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IMPROVING THE WORK PROCESS EFFICIENCY OF A TILLAGE MODULE FOR PRE-SOWING TILLAGE

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The formation of a differentiated structure of the arable horizon during the pre-sowing processing of the grant is a relevant task that can be solved by designing appropriate soil-processing technical means.

A scientific hypothesis has been put forward, according to which increasing the efficiency of the process of forming a differentiated structure of the arable horizon can be achieved by improving the design and substantiating the structural and technological parameters of the tillage module for pre-sowing tillage. Numerical simulation was carried out in the Simcenter STAR-CCM+ software package using the Lagrangian multiphase model employing the discrete element method. Calculation of second-order regression equations and statistical processing of the obtained data was carried out in the Wolfram Cloud software package.

As a result of the simulation of the improved design of the tillage module, which includes one drum, plowshare, casing, and cleaner, it was found that it performs the operation of separation and redistribution of soil aggregates with almost the same efficiency as the basic design with 2 drums and plowshare.

As a result of the simulation of the work process of the improved tillage module, regression equations of the content of the 10–30 mm fraction in the 0–4 cm soil layer and the content of the 0–10 mm fraction in the 4–8 cm soil layer from the research factors were obtained. The chosen factors of influence were a casing outlet clearance, casing inlet clearance angle, cleaner inclination angle, drum rotation frequency, unit movement speed, and processing depth. Solving the problem of multi-criteria optimization, the rational structural and technological parameters of the tillage module for pre-sowing tillage were calculated

Keywords: soil environment, arable horizon, differentiated structure, pre-sowing treatment, simulation, modeling

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1. Introduction

A key aspect of soil condition as a medium for growing cultivated plants is its agrophysical properties. It is significantly influenced by such factors as moisture content, oxygen availability, soil strength, differentiated structure of the arable horizon, etc. [1]. As indicated in studies [2, 3], the optimal agrophysical properties of the arable horizon make it possible to reveal the genetic potential of cultivated plants. According to studies [4, 5], this optimization can be achieved as a result of mechanical processing, which is able to form a differentiated structure of the soil environment around the seed bed.

As stated in studies [6–8], the differentiated structure of the arable horizon should consist of three layers: above-cropped, cropped, and under-cropped. The purpose of the over-sowing layer is to preserve moisture in the sowing and sub-sowing layers, smooth out negative weather conditions, and protect the soil from erosion processes. The sowing layer should create optimal conditions for plants at the first stage of development, and the sub-sowing layer should create optimal conditions for the development of the root system of plants and storage of moisture in the arable and root-rich horizons [8].

Therefore, the formation of a differentiated structure of the arable horizon during the pre-sowing processing of the grant is an urgent problem that can be solved by developing appropriate soil processing technical means.

2. Literature review and problem statement

Studies [9, 10] show that machines with active working bodies are the most effective in the pre-sowing treatment of heavy soils. Most of the companies RAU (Germany), Pottinger (Austria), Struik (Netherlands), FPM Agromehanika (Serbia) manufacture various tillage units with active working bodies. Their processing width is from 0.2 to 9 m and power is from 0.3 to 250 kW. These machines make it possible to more efficiently load a tractor or other power tools even with a small width of capture [11].

To prepare the soil for sowing, soil tillers with a horizontal or vertical axis of rotation are mainly used, which allow preparing the soil for sowing and performing these operations in one pass [12, 13].

The use of rotary tillage machines with active working bodies driven by the power take-off mechanism of the tractor makes it possible to perform technological functions at speeds that are 3–8 times higher than the speed of the machine-tractor unit. This significantly reduces the cost of moving the mass of the unit, which does not participate in the performance of useful work and increases the efficiency of using the unit [14, 15].

As stated in study [8], in order to ensure the maximum yield in specific soil and climatic conditions, the following is necessary. Performance indicators of the machine for pre-sowing tillage must meet the requirements of agricultural plants regarding the under-sowing, in-sowing, and over-sowing layers of the arable horizon. The function of aggregates for pre-sowing soil preparation is the formation of a super-sowing layer with a predominant size of structural aggregates of 10–20 mm, a seed layer of 0.25–5 mm, and a soil density in a layer of 0–8 cm in the range of 1.21–1.24 g/cm^3.

Based on the above statement, a number of technological schemes of combined tillage units have been developed, which allow separation of soil particles in its surface layer [16, 17]. The disadvantage of the design [16] is low productivity and partial crushing of soil aggregates, which leads to the leveling of the above-sowing layer of the arable horizon. Designs [17] are practically the same. The difference lies in the ratio of angular velocities for the first and second drum. The disadvantage of these structures is their complexity and the impossibility of using them on wet soils, which is caused by the sticking of the space between the bars. More detailed theoretical and experimental studies on these technological schemes are reported in works [8, 18]. However, even with the high efficiency of using such devices, they were not mass-produced. This is caused by the complexity of the design (there are many rotating nodes) and a low level of reliability (very accurate execution of geometric dimensions, the deviation of which during operation can lead to the destruction of the tool). Therefore, further research is aimed at improving the known tillage module for pre-sowing tillage by simplifying its design (thereby increasing its reliability) while maintaining the given technological efficiency.

Also, in studies [18, 19], the equation of motion of a material point (soil particle) on the surface of a tillage working body and its flight in a two-dimensional coordinate system was obtained. In fact, the soil is a rather complex system of aggregates of different geometric size, density, mass, which interact with each other according to the elastic-viscous-plastic model.

The analysis of new structures of the tillage module, the study of their interaction with the soil and the substantiation of their structural and technological parameters will be carried out using modern methods of numerical modeling (simulation) in the automated design system (ADS system).

To study the process of interaction of the working bodies of tillage machines with the soil, the latter should be formalized in the form of a physical-mathematical model of the environment. The properties of this model should most fully correspond to the physical and mechanical properties of real soil [20, 21].

Our own experience [22, 23] related to the separation of seeds and milling of the manure-compost mixture showed the following. In Simcenter STAR-CCM+ (Siemens Digital Industries Software, USA, Germany) there is an opportunity to model environments by the discrete element method (DEM). A DEM is a numerical method used to model the behavior of a large number of discrete solids, such as particles of soil, sand, or rock. It is based on the use of the equations of motion of solid bodies and the laws of interaction between them. When modeling the work process of a tillage working body, DEM can be used to simulate the interaction of the working body with individual soil particles that have different sizes, shapes, and physical and mechanical properties.

This is confirmed in works [24–26].

For example, in [24] it is stated that the modeling of the soil-tool interaction is a complex process due to the variability of the soil profile, the nonlinear behavior of the soil material, and the dynamic influence of the soil flow. An approach that will provide further insight is the Discrete Element Method (DEM) technique. In this study, topsoil subsidence during the soil-dump interaction process was simulated using DEM. A procedure was developed to compare and quantify the ground motion and subsidence of the surface layer of DEM simulations with soil channel and field results. The results of the study show that DEM has the potential to predict soil movement from tillage tools, including soil inversion and surface subsidence.

In study [25], the simulation of the interaction of the tillage working body was created using the three-dimensional geometry of the dump plow and the soil layer modeled by DEM particles. By introducing an element of bond between particles, the soil adhesion was arranged to simulate an actual cohesive soil. In this simulation, soil cutting profiles were investigated due to variation in soil properties and soil processing speed. Subsequent plow reaction forces were estimated from the simulation results. The simulated reaction forces were qualitatively consistent with the experimental data.

In work [26], the analysis model of a precision seeding plant was created based on DEM (discrete element method) and MBDs (multibody dynamics) model. The soil covering and compaction process was modeled and analyzed. A comparison between the experimental results and the simulated results showed that the trend was similar, and the two results were close.

In study [27], the finite element method (FEM) was used to model soil failure models. It is related to the consistency limits and stickiness point of the soil. The results showed that FEM is a useful tool for modeling soil failure patterns; however, the simulation models correlated better with the soil channel than with the field test results. It is concluded that FEM can provide accurate modeling of soil failure structures under soil hopper test conditions, but the soil hopper results do not meet the satisfactory results of field studies.

The review of literary data makes it possible to formulate the problem, which implies the mechanized formation of a differentiated structure of the arable horizon. This problem can be solved by using tillage modules for pre-sowing tillage with active working bodies. In turn, the choice of the design of this module and the justification of its structural and technological parameters can be carried out by means of simulation and numerical modeling in specialized software packages using DEM.

3. The aim and objectives of the study

The purpose of this study is to increase the effectiveness of the process of forming a differentiated structure of the arable horizon by improving the design and substantiating the structural and technological parameters of the tillage module for pre-sowing tillage. This will make it possible to increase the productivity of cultivated plants.

To achieve the goal, the following tasks were solved:

– to create a model of interaction of the tillage module with the soil in the Simcenter STAR-CCM+ software package and check its adequacy;

– to improve the design of the tillage module for pre-sowing tillage by simulating its operation in Simcenter STAR-CCM+;

– to establish the dependence of changes in the quality indicators of the process of forming a differentiated structure of the arable horizon on the structural and technological parameters of the improved tillage module for pre-sowing tillage and substantiate their rational values.

4. The study materials and methods

The object of our research is the process of interaction of various structures of the tillage module for pre-sowing tillage with the soil environment, which is formalized by DEM in the Simcenter STAR-CCM+ software package.

A scientific hypothesis has been put forward, according to which increasing the efficiency of the process of forming a differentiated structure of the arable horizon can be achieved by improving the design and substantiating the structural and technological parameters of the tillage module for pre-sowing tillage.

The following physical models are selected for DEM in Simcenter STAR-CCM+: three-dimensional, non-stationary implicit, Lagrangian multiphase, multiphase interaction, gravity. DEM particles with the following models are chosen as the Lagrangian phase: spherical particle, solid, constant density. According to studies [8, 18, 19], the following are accepted as physical and mechanical properties of soil particles: density, 1230 g/cm^3; Poisson's ratio, 0.41; Young's modulus of elasticity, $1.5 \cdot 10^7$. For particle-particle interaction, the following coefficient of rest friction is accepted: 1.732; normal and tangent coefficients of recovery, 0.5; linear coupling factor, 1.5; work of cohesion, 0.5 N/m. For the interaction between the particle and the steel wall of the working body, the coefficient of friction at rest is 0.61; normal and tangent coefficients of recovery, 0.5; there is no linear coupling. According to studies [8], the fractional composition of soil aggregates by geometric size (from 1 mm to 30 mm) in layers (0–40 mm, 40–80 mm, 80–120 mm, 120–160 mm, 160–200 mm) was subject to the distribution, which is shown in Fig. 1.

The general view of the modeling area with the specified geometric dimensions is shown in Fig. 2. Schematically, the area is divided into two scalar scenes: the first is the distribution of aggregates by geometric dimensions (3 groups); the second is the distribution of aggregates by layers (5 layers). The geometric dimensions of the modeling area (2.0×0.6×0.2 m) were chosen from the analysis of studies [8, 18, 19].

The first stage of research, namely checking and verification of the model in Simcenter STAR-CCM+, was the numerical simulation of the structural and technological scheme proposed in [16, 17]. All geometric dimensions (Fig. 3) and operating modes (drum rotation frequency – 70 rpm, tillage depth – 0.08 m, movement speed – 1 m/s) of the combined tillage unit for pre-sowing tillage are taken from monograph [8].

The basic (control) design of the tillage unit for pre-sowing tillage includes 2 drums with bars and a plowshare. The low reliability of the machine is caused by the presence of a chain transmission between two drums, which can break under heavy loads. In addition, the presence of small gaps between the rods of the first and second drums (5–9 mm) can cause their destruction when stones fall, or significant backlash appears in the actuators.

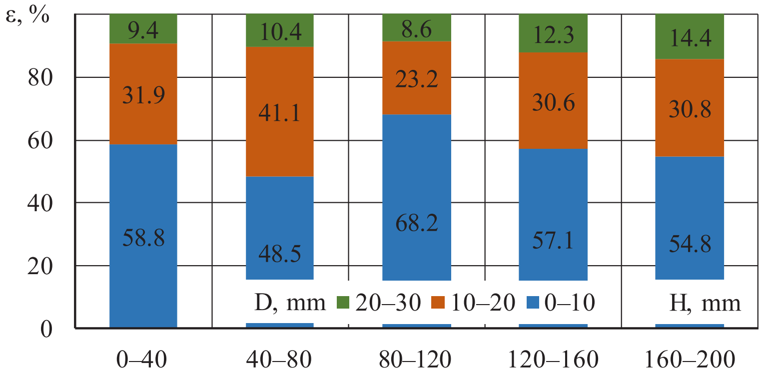


Fig. 1. Fractional composition of soil aggregates by geometric size in layers

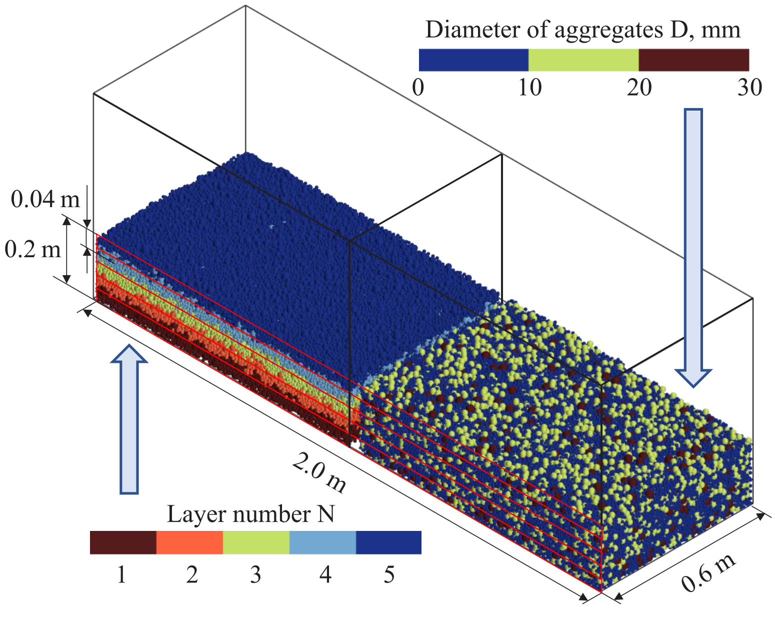


Fig. 2. General view of the modeling area with specified geometric dimensions

To analyze the process of simplifying the design of the tillage unit for pre-sowing tillage, let's consider its definition, which is given in Fig. 4. So, from the single-drum working body of the tillage unit by adding separate elements (ploughshare, casing, cleaning), we shall move to the complexity of the design. Therefore, the second stage of research is the numerical modeling of the process of interaction of the proposed structures with the soil.

In Simcenter STAR-CCM+, the 3D models of the working bodies were transformed into a volume-surface mesh. The surface mesh generator and trimmer were selected as mesh models. The 3D mesh model uses a template mesh that is constructed from hexagonal cells of the target size, from which it cuts or trims the base mesh using the initial input surface. The basic grid size was taken as 0.01 m.

For the third stage of modeling, a design with one drum, plowshare, casing, and cleaner was adopted. The scheme of the accepted design with geometric dimensions is shown in Fig. 5.

Two groups of factors were adopted for modeling. The first group – design parameters: casing outlet clearance H_c (0.08 m, 0.16 m, 0.24 m), casing inlet clearance angle α_c (10°, 30°, 50°), cleaner inclination angle β_o (10°, 20°, 30°). The second group is technological and mode parameters: drum rotation frequency n_r (60 rpm, 90 rpm, 120 rpm), unit movement speed V_r (1 m/s, 2 m/s, 3 m/s), working depth H_o (0.08 m, 0.10 m, 0.12 m).

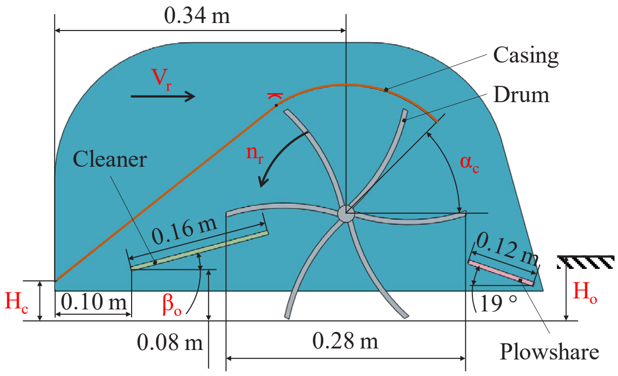


Fig. 5. Geometric dimensions of single-drum combined tillage unit with plowshare, casing and cleaner

For each group of factors, a full factorial experiment was conducted with a total number of experiments – $3^3=27$.

The content of the 10–30 mm fraction in the 0–4 cm layer $\left(\varepsilon_{0-4}^{>10}\right)$ and the content of the 0–10 mm fraction in the 4–8 cm layer $\left(\varepsilon_{4-8}^{<10}\right)$, were taken as a research criterion.

As a result of data processing in the Wolfram Cloud software package, it is necessary to establish the dependence of the above-mentioned criteria of the process of fractionation (separation) of the soil environment on research factors in the form of second-order regression equations. Statistical processing of the obtained data in the Wolfram Cloud software package consisted in determining the Student's criterion for each coefficient of the regression equation and comparing it with the table value. If the calculated value is less than the table value, then the coefficient of the regression equation is insignificant and can be ignored. The obtained regression equation was tested for adequacy using Fisher's test and Pearson's correlation coefficient.

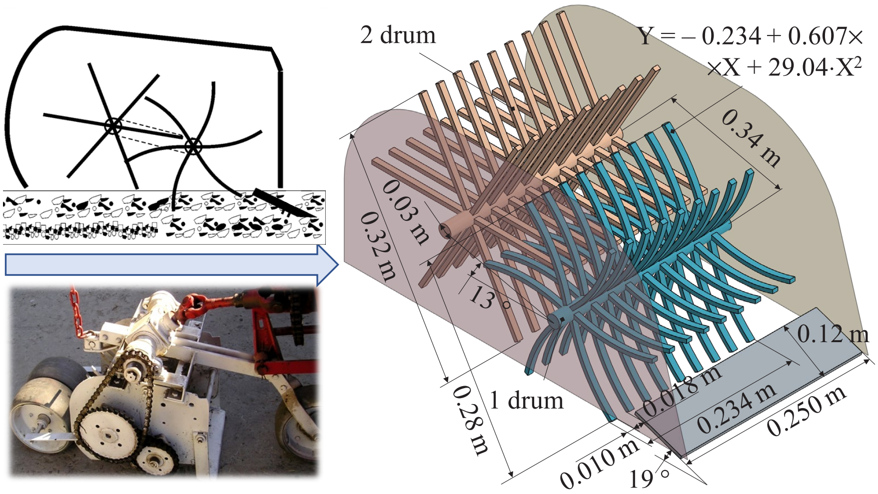


Fig. 3. Geometric dimensions of the combined tillage unit for pre-sowing tillage (compiled according to [8])

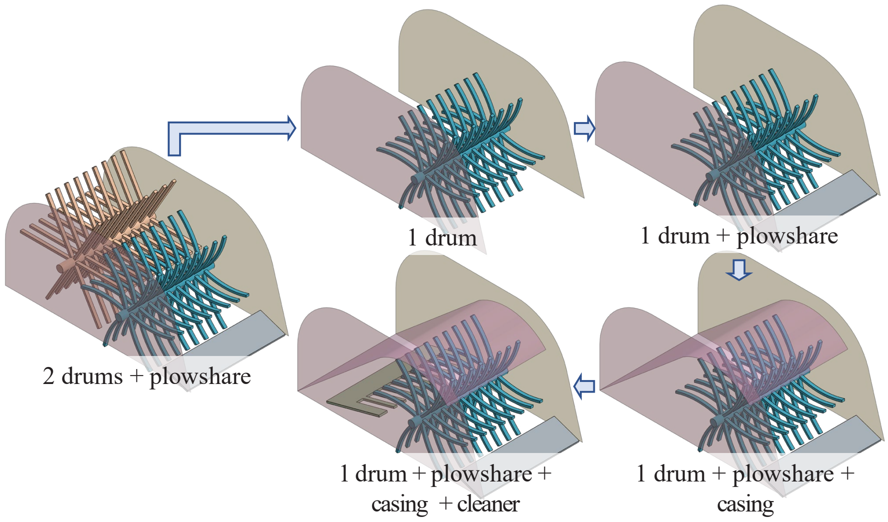


Fig. 4. Geometric dimensions of the combined tillage unit for pre-sowing tillage

5. Results of studying the process of interaction of the tillage module with the soil environment

5. 1. Verification of the interaction model of the tillage unit with the soil

As a result of the first stage of research, namely modeling of the basic (control) construction of the tillage unit (2 drums+ploughshare), a visualization of the scalar scene of the distribution of units according to their diameter and placement depth was obtained (Fig. 6).

A visual analysis shows that the basic design of the tillage aggregate redistributes the aggregates along the soil depth. This is confirmed by the histogram of the fractional composition of soil aggregates by geometric size in layers after processing (Fig. 6).

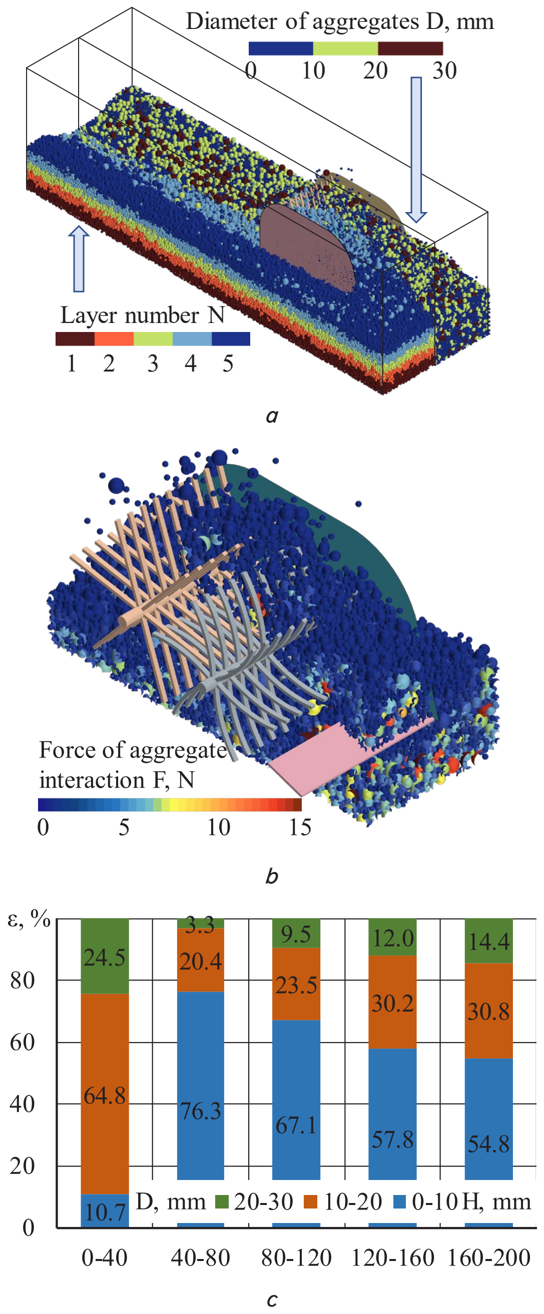


Fig. 6. Numerical simulation of the process of interaction of the tillage unit for pre-sowing tillage (2 drums+plowshare) with the soil: *a* – general view of the modeling area; *b* – force of contact interaction of aggregates; *c* – fractional composition of soil aggregates by geometric size in layers after treatment

Thus, it was established that after processing in the 0–4 cm layer, the content of the 10–20 mm fraction was 64.8±0.3 %, and the 20–30 mm fraction was 24.5±0.3 % (in total, 89.3±0.3 %); in the 4–8 cm layer, the content of the 0–10 mm fraction was 76.3±0.3 %. In turn, the histogram (Fig. 1) shows that the 0–4 cm layer contains the 10–30 mm fraction $\varepsilon_{0-4}^{>10}=41.3\pm0.3$ %, and the 4–8 cm layer contains the 0–10 mm fraction $\varepsilon_{4-8}^{<10}=48.5\pm0.3$ %. This indicates the redistribution of aggregates along the soil depth as a result of performing the separation process.

As indicated in [8], the content of fractions in the soil layers of field No. 1 (practically homogeneous dry soil) and field No. 2 (moistened and heterogeneous soil) after their processing by the basic (control) design of the tillage unit (2 drums+plowshare) corresponded to the expected one.

The following results were obtained for field No. 1: the content of the 10–30 mm fraction in the 0–5 cm layer – from 81.4 % to 83.6 %, the content of the 0.25–5 mm fraction in the 5–8 cm layer – from 80.6 % to 84.2 %. The following results were obtained for field No. 2: the content of the 10–20 mm fraction in the 0–5 cm layer – from 79.4 % to 84.7 %, the content of the 0.25–5 mm fraction in the 5–8 cm layer – from 78.3 % to 82.6 %.

Comparing experimental studies [8] and the results of numerical modeling shows that the fractional composition of soil aggregates by geometric size in layers after treatment is within acceptable limits.

This testifies to the adequacy of the numerical model created in Simcenter STAR-CCM+ and the correctness of accepting the physical and mechanical properties of the soil environment.

5. 2. Substantiation of the design of a combined tillage unit for presowing tillage

According to the second stage of research, the visualization of the scalar scene of the representation and the histogram of the distribution of the fractional composition of the aggregates according to their diameter and depth of placement after processing with the proposed structures were established (Fig. 7). A visual analysis of the scalar scenes made it possible to reveal the shortcomings of some of the proposed designs.

Thus, during soil treatment with a single-drum soil tillage unit, there is an insufficient load of the drum and a high height of throwing the units above the arable horizon. This leads to inefficient use of the structure. Adding a ploughshare and casing to the design made it possible to achieve uniform loading and obtain a controlled flight trajectory of the units. However, this structural implementation also contained a drawback, which is associated with the lack of clearing the gaps between the drum bars from aggregates. In the basic design, this problem was solved by adding a second drum. In order to simplify the design, the second active second drum was replaced by a passive cleaner.

For a more detailed comparison of the results of numerical modeling, we shall compile a corresponding table of changes in the fractional composition of aggregates by geometric size in soil layers after its treatment with the proposed structures (Table 1).

Analyzing Table 1, it can be argued that the structure with 1 drum, plowshare, casing, and cleaner performs the operation of separation and redistribution of soil aggregates with practically the same efficiency as the basic structure with 2 drums and plowshare. This is evidenced by the content of the 10–30 mm fraction in the 0–4 cm layer – 87.8±0.3 % and the 0–10 mm fraction content in the 4–8 cm layer – 83.5±0.3 %.

In order to improve the effectiveness of the proposed design of the tillage module for pre-sowing tillage, it is necessary to investigate its structural and operating parameters.

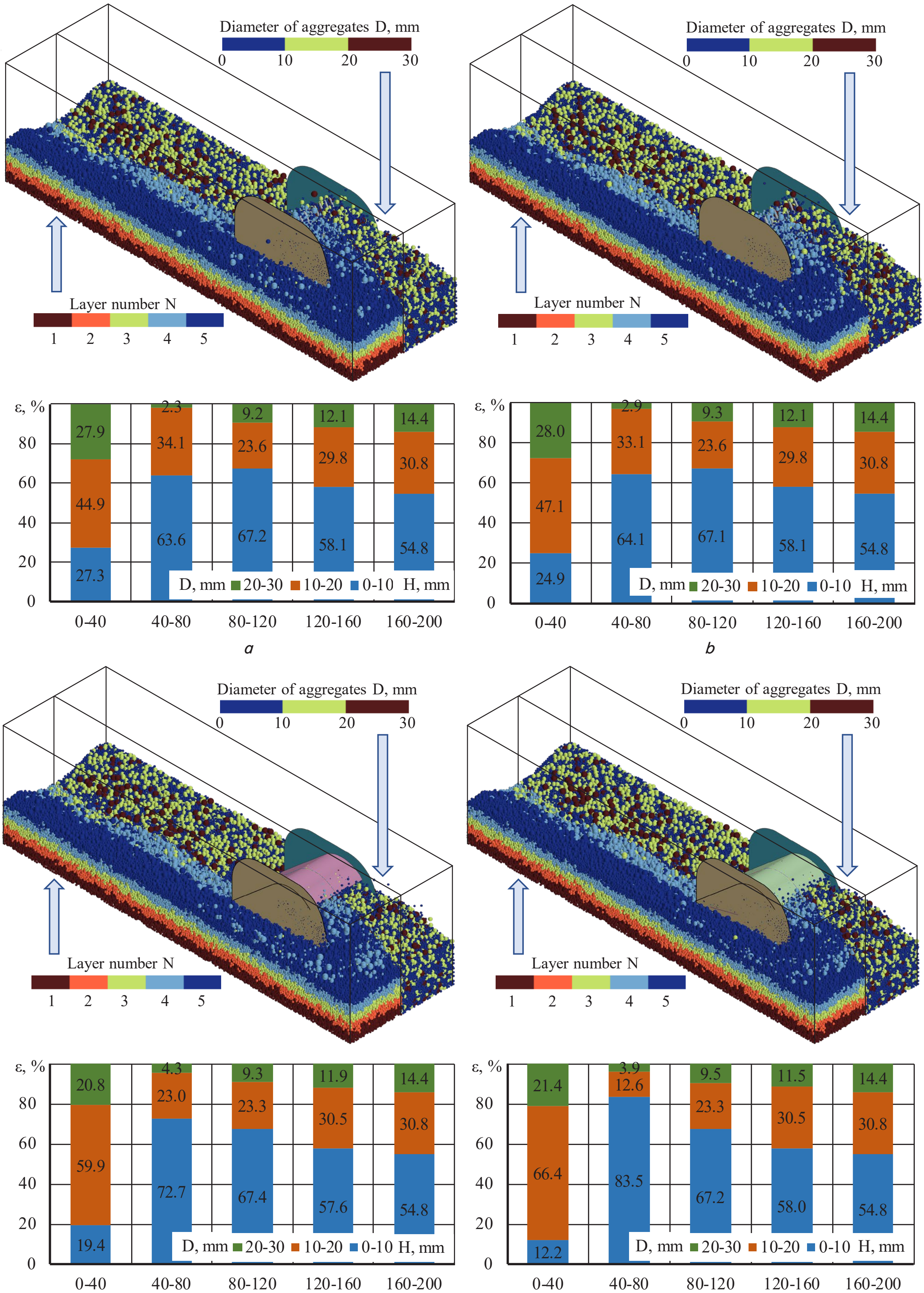


Fig. 7. Results of numerical modeling of the process of interaction of the proposed designs of the tillage unit with the soil: *a* – 1 drum; *b* – 1 drum+ploughshare; *c* – 1 drum+ploughshare+casing; *d* – 1 drum+ploughshare+casing+cleaner

Table 1

Fractional composition of aggregates by geometric size on soil layers after its treatment with the proposed structures

Structure	$\varepsilon_{0-4}^{>10}$, %	$\varepsilon_{4-8}^{<10}$, %
Before treatment (modeling)	41.2±0.3	48.5±0.3
Before treatment (experiment according to [8])	41.0±1.0	47.0±1.0
2 drums+ploughshare (simulation)	89.3±0.3	76.3±0.3
2 drums+plowshare (experiment according to [8])	81.4–83.6	80.6–84.2
1 drum (simulation)	72.7±0.3	63.6±0.3
1 drum+ploughshare (modeling)	75.1±0.3	64.1±0.3
1 drum+ploughshare+casing (modeling)	80.6±0.3	72.7±0.3
1 drum+ploughshare+casing+cleaner (modeling)	87.8±0.3	83.5±0.3

5. 3. Substantiation of structural and technological parameters of an improved tillage module for presowing tillage

As a result of the third stage of research, the drum rotation frequency n_r=60 rpm, unit movement speed V_r=1 m/s, and tillage depth H_o=0.08 m, were adopted for the first group of factors.

The simulation results are visualized in Fig. 8. For each pass of the improved soil treatment module for pre-sowing treatment, the fractional composition of soil aggregates is determined by geometric size in layers, which are shown in Fig. 8 in the form of histograms. As a result of processing the data from the histograms, the content of the 10–30 mm fraction in the 0–4 cm layer $\left(\varepsilon_{0-4}^{>10}\right)$ and the 0–10 mm fraction in the 4–8 cm layer $\left(\varepsilon_{4-8}^{<10}\right)$ were determined for each experiment.

After processing the data for the first group of factors in Wolfram Cloud, the regression equations of the content of the 10–30 mm fraction in the 0–4 cm layer $\left(\varepsilon_{0-4}^{>10}\right)$ and the content of the 0–10 mm fraction in the 4–8 cm layer $\left(\varepsilon_{4-8}^{<10}\right)$ from the research factors were obtained in a decoded form with rejected non-significant coefficients of regression:

$$\begin{aligned}\varepsilon_{0-4}^{>10} &= 43.2974+0.760414\alpha_c-0.00978301\alpha_c^2+\\&+282.804H_c+0.667797\alpha_c H_c-816.872H_c^2;\end{aligned}\qquad(1)$$

$$\begin{aligned}\varepsilon_{4-8}^{<10} &= 63.6102+0.238605\alpha_c-0.00260979\alpha_c^2+\\&+0.575363\beta_o-0.0157494\,\beta_o^2+105.726H_c-\\&-292.686H_c^2.\end{aligned}\qquad(2)$$

Graphical interpretation of equations (1), (2) is shown in Fig. 9, 10, respectively.

Statistical analysis of equations (1) and (2) in the studied variation range showed that the Pearson correlation coefficient is 0.87 and 0.91, respectively. In turn, Fisher's criterion is $F_{(1)}=2.33<F_t=2.49$ and $F_{(2)}=2.12<F_t=2.49$, respectively. This confirms the adequacy of our models.

A condition for the efficiency of the process of separation of aggregates of the soil environment by layers is to achieve the maximum values of the criteria $\varepsilon_{0-4}^{>10}$ and $\varepsilon_{4-8}^{<10}$ at the same time. Visual and computational analysis in Wolfram Cloud of equations (1) and (2) showed that the optima of the given regression equations do not coincide, so it is necessary to solve the problem of multi-criteria optimization.

Multi-criteria optimization refers to the process of simultaneous optimization of two or more conflicting objective functions of optimization criteria in a given scope:

$$\begin{cases}\varepsilon_{0-4}^{>10}\left(H_c,\alpha_c,\beta_o\right)\to\max;\\ \varepsilon_{4-8}^{<10}\left(H_c,\alpha_c,\beta_o\right)\to\max;\\ 0.08\le H_c\le 0.24;\\ 10\le\alpha_c\le 50;\\ 10\le\beta_o\le 30.\end{cases}\qquad(3)$$

The normalization of the private objective functions of the optimization criteria (3) involves bringing them to a single dimensionless form and changing their values within a unit interval:

$$\begin{cases}\varepsilon_{0-4}'^{>10}=\dfrac{\varepsilon_{0-4}^{>10}-\min\left[\varepsilon_{0-4}^{>10}\right]}{\max\left[\varepsilon_{0-4}^{>10}\right]-\min\left[\varepsilon_{0-4}^{>10}\right]};\\ \varepsilon_{4-8}'^{<10}=\dfrac{\varepsilon_{4-8}^{<10}-\min\left[\varepsilon_{4-8}^{<10}\right]}{\max\left[\varepsilon_{4-8}^{<10}\right]-\min\left[\varepsilon_{4-8}^{<10}\right]}.\end{cases}\qquad(4)$$

As a new multiplicative objective function ε' we accept:

$$\varepsilon'=\varepsilon_{0-4}'^{>10}\cdot\varepsilon_{4-8}'^{<10}.\qquad(5)$$

Then task (3) is reduced to painfully simple:

$$\begin{cases}\varepsilon'\left(H_c,\alpha_c,\beta_o\right)\to\max;\\ 0.08\le H_c\le 0.24;\\ 10\le\alpha_c\le 50;\\ 10\le\beta_o\le 30.\end{cases}\qquad(6)$$

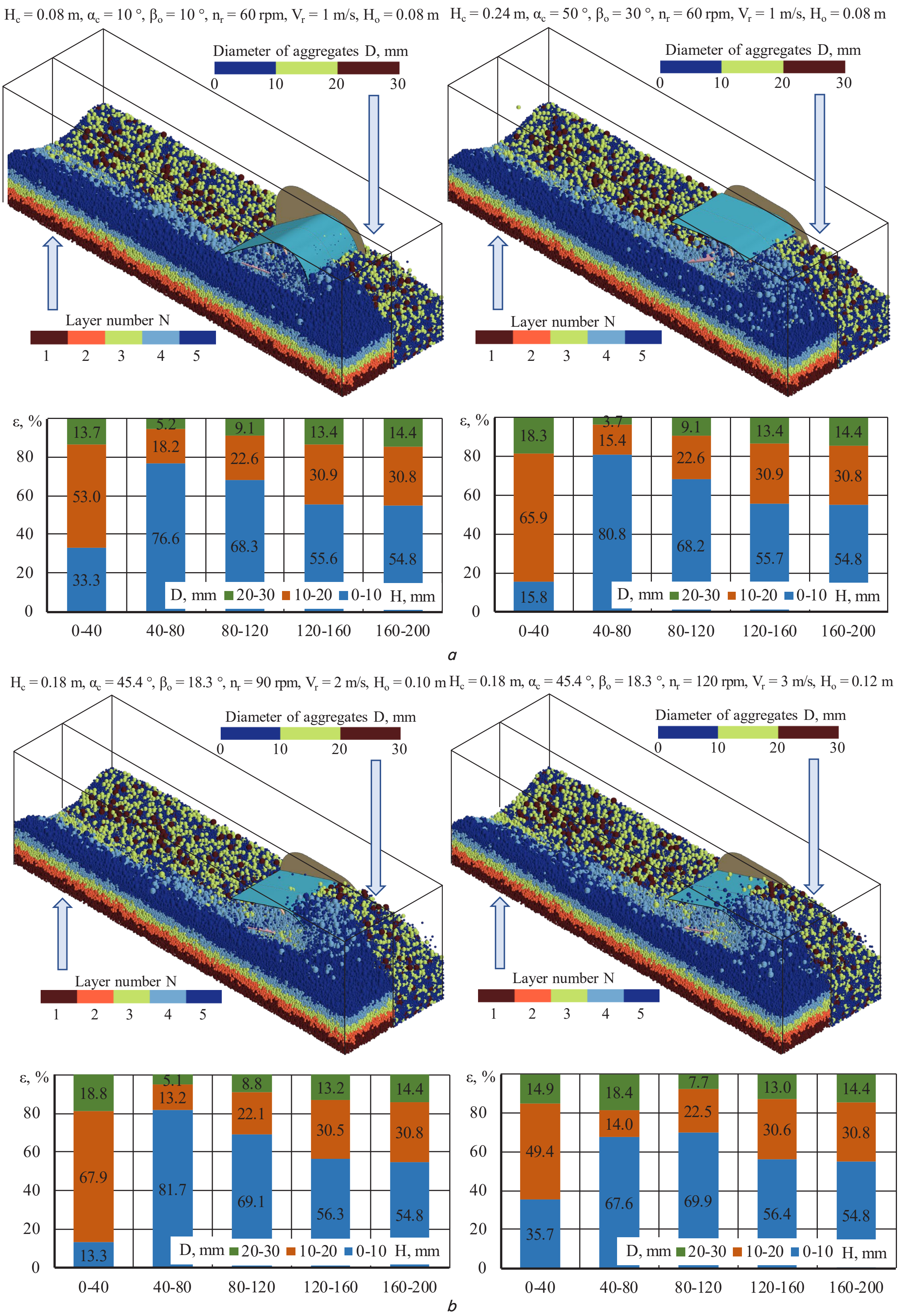
Solving problem (6) together with (1) and (2) in the Wolfram Cloud using the «FindMaximum» feature, the optimal values of the factors at which this is possible were calculated: H_c=0.18 m, α_c=45.4°, β_o=18.3°. At the same time, $\varepsilon_{0-4}^{>10}=87.6\,\%$ and $\varepsilon_{4-8}^{<10}=83.8\,\%$.

After processing the data for the second group of factors in Wolfram Cloud, the regression equations of the content of the 10–30 mm fraction in the 0–4 cm layer $\left(\varepsilon_{0-4}^{>10}\right)$ and the content of the 0–10 mm fraction in the 4–8 cm layer $\left(\varepsilon_{4-8}^{<10}\right)$ were obtained from the research factors in a decoded form with rejected non-significant coefficients regressions:

$$\begin{aligned}\varepsilon_{0-4}^{>10} &= 4.83262+836.0H_o-2866.32H_o^2+\\&+0.686684n_r-0.00458603n_r^2+18.6236V_r-\\&-36.0931H_oV_r-0.0521419n_rV_r-4.47247V_r^2;\end{aligned}\qquad(7)$$

$$\begin{aligned}\varepsilon_{4-8}^{<10} &= 73.471+674.456H_o-4897.39H_o^2-\\&-0.137562n_r-2.17676V_r+55.8551H_oV_r-1.51068V_r^2.\end{aligned}\qquad(8)$$

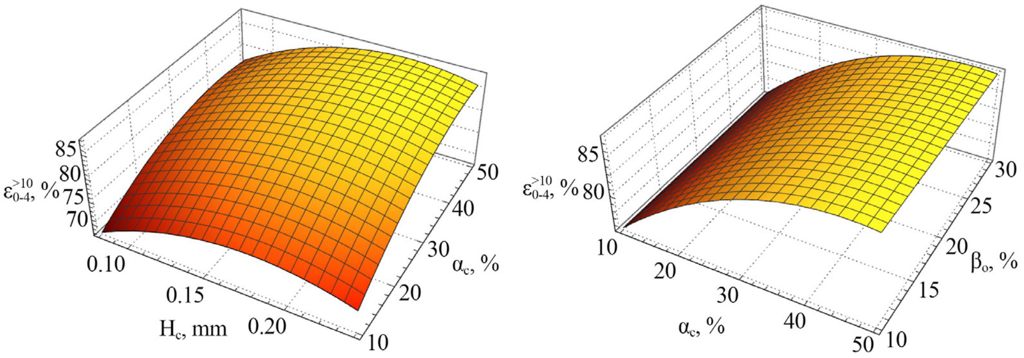
The graphical interpretation of equations (7), (8) is shown in Fig. 11, 12, respectively.



a

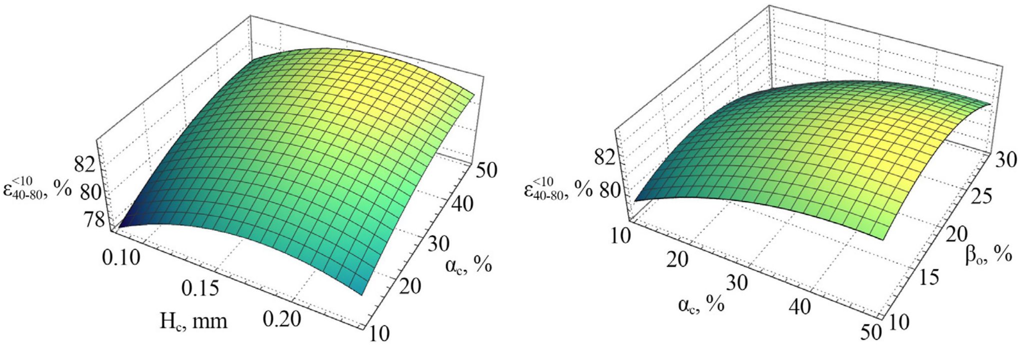
b

Fig. 8. Results of the numerical modeling of the process of the interaction of the improved tillage unit with the soil at different structural and technological parameters: *a* — the first group of factors; *b* — the second group of factors



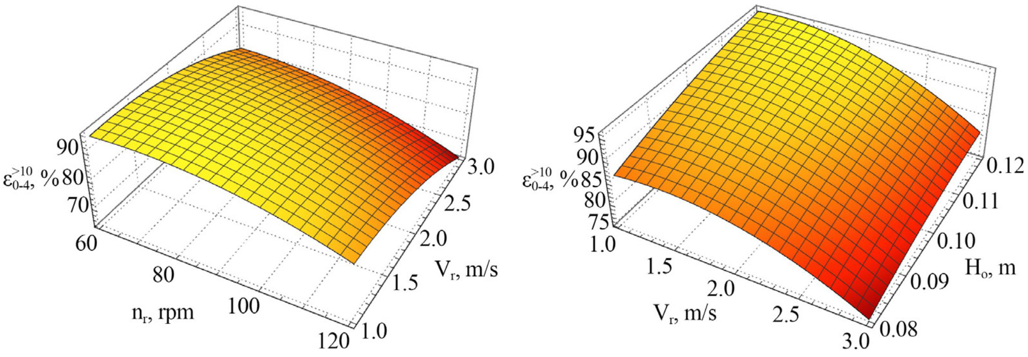
a *b*

Fig. 9. Dependence of the content of the 10–30 mm fraction in the 0–4 cm layer $\left(\varepsilon_{0-4}^{>10}\right)$ on the outlet gap of the casing H_c, the angle of the inlet gap of the casing α_c and the angle of inclination of the cleaner β_o: *a* – at β_o=20 °; *b* – at H_c=0.19 m



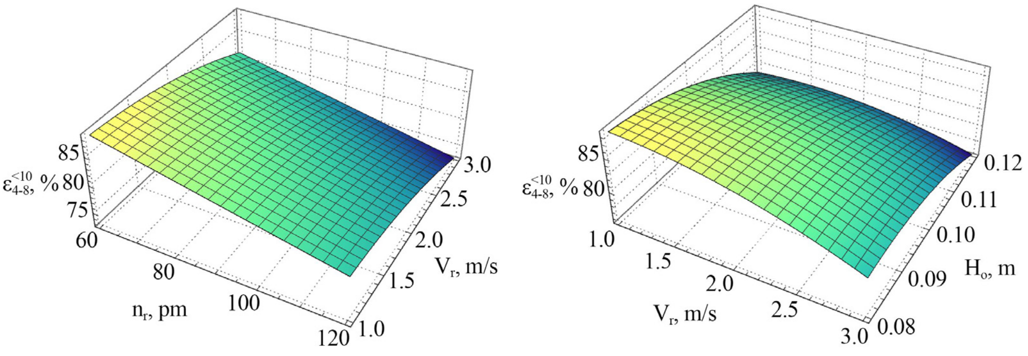
a *b*

Fig. 10. Dependence of the content of the 0–10 mm fraction in a layer of 4–8 cm $\left(\varepsilon_{4-8}^{<10}\right)$ on the outlet clearance of the casing H_c, the angle of the inlet clearance of the casing α_c and the angle of inclination of the cleaner β_o: *a* – β_o=18.3°; *b* – at H_c=0.18 m



a *b*

Fig. 11. Dependence of the content of the 10–30 mm fraction in the 0–4 cm layer $\left(\varepsilon_{0-4}^{>10}\right)$ on the drum rotation frequency n_r, unit movement speed V_r, depth of processing H_o: *a* – at H_o=0.12 m; *b* – at n_r=68 rpm



a *b*

Fig. 12. Dependence of the content of the 0–10 mm fraction in a layer of 4–8 cm $\left(\varepsilon_{4-8}^{<10}\right)$ on the frequency of rotation of the drum n_r, the speed of movement of the unit V_r, the depth of cultivation H_o: *a* – at H_o=0.12 m; *b* – at n_r=68 rpm

Statistical analysis of equations (7), (8) in the studied variation range showed that the Pearson correlation coefficient is 0.93 and 0.96, respectively. In turn, Fisher's criterion is $F_{(7)}=2.01<F_t=2.49$ and $F_{(8)}=1.97<F_t=2.49$, respectively. This confirms the adequacy of our models.

Similar to the previous problem of multi-criteria optimization, a system of equations is built:

$$\begin{cases} \varepsilon'(n_r, V_r, H_o) \to \max; \\ 60 \le n_r \le 120; \\ 1 \le V_r \le 3; \\ 0.08 \le H_o \le 0.12. \end{cases} \tag{9}$$

Solving problem (9) together with (4), (5), and (7), (8) in Wolfram Cloud using the «FindMaximum» feature, the optimal values of the factors where this is possible were calculated: $n_r=60$ rpm, $V_r=1.27$ m/s, $H_o=0.097$ m. At the same time, $\varepsilon_{0-4}^{>10}=91.8\,\%$ and $\varepsilon_{4-8}^{<10}=86.0\,\%$.

6. Discussion of research results into the process of interaction of the tillage module with the soil environment

Comparing our results with classical analytical models [8–10], it was established that the latter do not provide a complete picture of the process of interaction of active working bodies of tillage machines with the soil environment. This is primarily due to the accepted assumptions and simplifications based on solving the equation of motion of the soil aggregate as an independent material point. In turn, the obtained results of numerical modeling are based on the method of discrete elements, which makes it possible to consider the soil as a system of aggregates that have certain physical and mechanical properties and geometric dimensions. This increases the accuracy of calculations and makes it possible to bring the obtained process simulation results closer to real conditions.

A comparison of our results with works [26–28] reveals one drawback of soil modeling by DEM – the destruction of soil aggregates into smaller particles and dust. This drawback can be solved by applying the Euler-to-Lagrangian transition model. Simcenter STAR-CCM+ provides the «Resolved Eulerian-Lagrangian Transition» transition model as a phase interaction model, which allows capturing the breakup of a liquid with the formation of droplets separating from a free surface. This model is intended to be used as part of a hybrid multiphase approach where a volume of fluid (VOF) model is used alongside a Lagrangian multiphase (LMP) model. It can be explained as follows. The reported modeling strategy allows maintaining Eulerian phase accuracy in areas where it is needed locally, while using the more computationally efficient LMP model for DEM particle tracking.

A comparison of the results of the first stage of research, namely the modeling of the basic (control) structure of the tillage unit (2 drums+plowshare) with works [8, 18, 19], allows us to assert the adequacy of the created physical model in the Simcenter STAR-CCM+ software package. This is primarily explained by the similarity of the values of the fractional composition of the aggregates by geometric size in the soil layers after its treatment, both according to the results of numerical modeling (Fig. 6, *c*) and according to the results of experimental studies [8].

In addition, we should note that the simplification of the design of the tillage module, by switching from two rotating drums [8, 18, 19] to one rotating drum with passive elements (cleaners and casings), makes it possible to obtain a better fractional composition of aggregates in terms of geometric size in soil layers (Table 1, Fig. 7). The substantiation of the structural and technological parameters of the selected design, using equations (1)–(2), (7)–(8), (6) and (9), made it possible to further improve the fractional composition of the arable horizon aggregates (Fig. 9, 10) when compared with experimental data [8] (Table 1).

This will make it possible to obtain a greater increase in the productivity of cultivated plants, which is explained by the results of experimental studies [6–8]. However, this hypothesis must be verified in further experimental field studies. It is further experimental research that will make it possible:

– to investigate in more detail the process of interaction of the working bodies of the tillage module with the soil;

– to check and refine the developed model in the Simcenter STAR-CCM+ software package;

– to justify the mode parameters of the working bodies of the tillage module for different types of soils.

7. Conclusions

1. Numerical simulation was carried out in Simcenter STAR-CCM+ of the process of interaction of different designs of tillage modules for pre-sowing cultivation: 2 drums+plowshare, 1 drum, 1 drum+plowshare, 1 drum+plowshare+casing, 1 drum+plowshare+casing+ +cleaner. Visualizations of the scalar scene and a histogram of the distribution of aggregates by their diameter and placement depth were obtained. A two-drum-plowshare separator was chosen as the basic (control) structure. Its numerical modeling made it possible to establish that after treatment in the 0–4 cm layer, the content of the 10–20 mm fraction was 64.8±0.3 %, and the 20–30 mm fraction was 24.5±0.3 % (total 89.3±0.3 %), in the 4–8 cm layer the content of the 0–10 mm fraction was 76.3±0.3 %. Our data are confirmed by the experiment [8], which testifies to the adequacy of the created numerical model in Simcenter STAR-CCM+ and the correctness of accepting the physical and mechanical properties of the soil environment.

2. The structure of the tillage module, which includes 1 drum, ploughshare, casing, and cleaner, has been improved. As a result of its modeling, it was established that it performs the operation of separation and redistribution of soil aggregates with practically the same efficiency as the basic design. This is evidenced by the content of the 10–30 mm fraction in the 0–4 cm layer – 87.8±0.3 % and the 0–10 mm fraction content in the 4–8 cm layer – 83.5±0.3 %.

3. We have built regression equations of the content of the 10–30 mm fraction in the 0–4 cm soil layer $\left(\varepsilon_{0-4}^{>10}\right)$ and the content of the 0–10 mm fraction in the 4–8 cm soil layer $\left(\varepsilon_{4-8}^{<10}\right)$ from the research factors: casing outlet gap H_c, casing inlet gap angle α_c, cleaner inclination angle β_o, the rotation frequency of the drum n_r, the movement speed of the unit V_r and the depth of processing H_o. The problem of multi-criteria optimization was solved, accord-

ing to which $\varepsilon_{0-4}^{>10} \to \max$, $\varepsilon_{4-8}^{<10} \to \max$. We have calculated rational structural and technological parameters of the soil tillage module for pre-sowing tillage at which it is possible: $H_c = 0.18$ m, $\alpha_c = 45.4°$, $\beta_o = 18.3°$, $n_r = 60$ rpm, $V_r = 1.27$ m/s, $H_o = 0.097$ m. At the same time, $\varepsilon_{0-4}^{>10} = 91.8\,\%$ and $\varepsilon_{0-4}^{>10} = 91.8\,\%$.

Conflicts of interest

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

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Data availability

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

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