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Simulation of the interaction between the working bodies of tillage machines and the soil in Simcenter STAR-CCM+

Abstract. The lack of simple analytical physical and mathematical models complicates the investigation of the interaction of tillage working bodies with the soil when designing new structures. To simplify these calculations within the framework of agricultural machinery engineering, it is necessary to use software that integrates the development of agricultural mechanics. The purpose of this study was to model and investigate the interaction of tillage working bodies with the soil using Simcenter STAR-CCM+. For this, the volumetric fluid method and the discrete element method were used. When creating the model, the main physical and mechanical properties of the soil were used. As a result, the simulation of the interaction of the most common tillage working bodies, such as a tooth of a duck-foot cultivator, a disc harrow on an elastic stand, a subsoil cultivator (chisel plough), a mouldboard plough, and a smooth roller, was modelled using volume-of-fluid method and discrete element method. The application of the volume-of-fluid method helped establish a non-primary flow of the soil relative to the working body, while the discrete element method determined the distributions of velocities and forces of interaction of soil particles. It was found that both proposed methods can be useful for modelling the interaction of the tillage working body with the soil in Simcenter STAR-CCM+. Complementing each other, they create a general picture of the physics of the interaction of the tillage tool with the soil. Using Simcenter STAR-CCM+, the interaction process was visualized and the height of the formed ridges and furrow depths and their location in space were

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determined. The application of the obtained models will enable the agricultural engineers to quickly develop innovative designs of tillage tools based on their interaction with the soil

Keywords: tools; numerical modelling; volumetric fluid method; discrete element method; velocity distribution; pressure

INTRODUCTION

To study the interaction of the working bodies of soil tillage machines with the soil, the latter should be formalized in the form of a physical and mathematical model of the environment in such a way that the properties of this model most fully correspond to the physical and mechanical properties of the real soil. A considerable number of studies investigate the interaction of tillage working bodies with the soil. Interaction models developed by V.P. Sysolin *et al.* (2001), Ya. Gukov (2007), O. Kozachenko *et al.* (2021a) and others deserve great attention. A.S. Kushnarev (2010) used the form of representation of the soil structure model and the types of deformations that occur during interaction as the basis of the classification of the interaction of tillage working bodies with the soil. As noted by V.P. Kovbasa (2006), V.F. Pashchenko & S.I. Kornienko (2016), this approach helped group the attempts made by many researchers to develop certain models of interaction of various working bodies according to certain characteristics. According to the form of presentation of the model of soil construction, all works related to the interaction of working bodies with the soil can be divided into four groups: solid body, continuous elastic medium, continuous incompressible fluid medium, continuous elastic-viscous-plastic medium.

Therewith, as an analytical apparatus, the following are used: methods of solid body mechanics, methods of the theory of elasticity and its simplified variants, methods of soil mechanics, methods of the theory of similarity and dimensions, methods of statistical mechanics (Hutsol & Kovbasa, 2016). Each of the presented studies is interesting in its approach to solving the technological problem of the interaction of the tillage working body with the soil environment. Thus, I.A. Shevchenko (2016) used the Mohr-Coulomb theory, which complements the theory of soil strength, in addition to the obtained equation of the movement of a material particle of soil on the surface of a tillage working body. Based on the results of experimental studies on the optimization of agrophysical properties of the arable horizon, I.A. Shevchenko (2016) considered the differentiated soil structure. M.V. Bakum & D.A. Yashchuk (2011) considered the issue of sketch geometry of determining the height of the ridges above the bottom of the furrow during tillage. O.P. Hutsol & V.P. Kovbasa (2016) presents the physical equations of the relationship between stresses and deformation rates for the soil environment when a soil-processing working body acts on it. Each of the presented models is used separately from each other, which leads to only a one-sided consideration of the scientific and technical difficulty of simulating the interaction of the working bodies of tillage machines with the soil.

J.B. Barr *et al.* (2019), K.A. Aikins *et al.* (2023), J. Zhang *et al.* (2023) stated that in the design and optimization of agricultural machinery, the discrete element method (DEM) has played a major role due to its ability to accelerate the design and production process due to the reduction of repeated prototyping, testing, and evaluation in experimental conditions. In the field of soil dynamics, DEM was mainly used in the design and optimization of soil tillage working bodies. This numerical method can capture the dynamic and volumetric behaviour of soils and soil-working body interactions (Xu *et al.*, 2022; Ucgul, 2023). The presented pool of information consolidates the available working approaches and helps identify model gaps that, if addressed, will advance the current soil dynamics modelling capability. The purpose was to simulate and investigate the interaction of tillage working bodies with the soil using the capabilities of Simcenter STAR-CCM+.

LITERATURE REVIEW

M. Ucgul *et al.* (2016) stated that modelling the soil-tool interaction is a complex process due to the variability of the soil profile, the nonlinear behaviour of the soil material, and the dynamic effects of soil flow. An approach that will provide further insight is the Discrete Element Method (DEM). In this study, topsoil subsidence during the soil-mouldboard interaction process was simulated using the 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 suggest that DEM has the potential to predict soil movement from tillage tools, including soil inversion and surface subsidence.

J. Zhang *et al.* (2023) built a model of the interaction of the rotary blade working body with the soil using the DEM. The modelling process reflects the blade-soil interaction law, and the accuracy of the simulation model is verified by field tests. The simulation model had good accuracy at all factor levels. The model built in this study can provide a theoretical framework and technical reference for the interaction mechanism of rotary tillage and soil, optimization of geometry, selection of working parameters.

A.A. Tagar *et al.* (2015) used the finite element method (FEM) to model soil failure patterns associated with consistency limits and soil sticking point, comparing the simulation results with soil failure patterns observed in a soil bunker and in the field. The results strongly suggested that the FEM is a useful tool for creating soil failure models, but the simulation models correlated better with the soil channel than with the field test results. It was concluded

that the FEM can provide accurate modelling of soil failure structures under soil hopper test conditions, but the soil hopper results do not meet the satisfactory results of field studies.

A. Ibrahim *et al.* (2015) illustrates the use of the FEM to model the interaction of a mouldboard plough. The Drucker-Prager elastoplastic model was used to model the behaviour of the sandy soil material. The mouldboard was considered as a discrete solid body with a reference point at the top, wherein three orthogonal components of forces (vertical, lateral, and sediment) were calculated. In this study, the influence of the blade cutting depth, work speed, cutting angle and elevation angle on soil tillage effort was investigated. It was concluded that the FEM can be used to understand the effects of mouldboard design and operating conditions on tillage forces, energy requirements and soil overturning quality. J.B. Barr *et al.* (2019) studied the interaction of plough shares using field experiments and modelling according to the DEM.

T. Okayasu *et al.* (2012) modelled the interaction of a tillage working body using a three-dimensional plough geometry and a soil layer modelled by the DEM particles. By introducing an element of bond between particles, the soil adhesion was arranged to simulate an actual cohesive soil. Soil cutting profiles were investigated in the context of variations in soil properties and tillage rates. Subsequent plough reaction forces were estimated from the simulation results. The simulated reaction forces were qualitatively consistent with the experimental data.

T. Xu *et al.* (2022) developed a precision seeding plant analysis model based on the DEM coupled with the MBD method (many body dynamics). The soil covering and compaction process was modelled and analysed. A comparison between the experimental results and the simulated results indicated that the trend was similar, and the two results were close. M. Ucgul (2023) modelled the interaction between the soil and a one-sided modified disc plough using the DEM. Since the disc plough is a passively driven tool, the rotating speed of the disc plough was modelled using the DEM-MBD combination. Our experience in numerical modelling of technological processes of agro-industrial production (Kozachenko *et al.*, 2021b; Aliyev *et al.*, 2022) allows us to assert the possibility of using the Simcenter STAR-CCM+ software package for simulating the interaction of the working bodies of tillage machines with the soil.

When designing new structures of tillage working bodies, agricultural engineers cannot investigate their interaction with the soil due to complex analytical physical and mathematical models developed by the above-mentioned renowned scientists and researchers. To simplify the calculations of this interaction within the framework of agricultural machine engineering, it is necessary to summarize the achievements of Ukrainian and foreign agricultural mechanics into a single software. Today, the use of numerical modelling of the interaction of the working bodies of soil tillage machines with the soil is already being practised in specialized software packages.

MATERIALS AND METHODS

Simcenter STAR-CCM+ allows using the Volume of Fluid method (VOF) and the Discrete Element Method (DEM) to model technological processes. VOF and DEM are two distinct methods for modelling physical processes. However, both were used to model the interaction of the tillage working body with the soil. The VOF is a numerical free-surface approximation method used to model fluid motion and its interaction with solids. The DEM is a numerical method used to model the behaviour of numerous discrete solids, such as particles of soil, sand, or rock. When modelling the work process of the tillage working body, the VOF can be used under the assumption that the soil is a liquid with appropriate physical and mechanical properties. On the other hand, the DEM can be used to model the interaction of a working body with individual soil particles that have varied sizes, shapes, and physical and mechanical properties.

The most common tillage implements for evaluating the use of VOF and DEM for simulating their interaction with the soil were chosen as follows: a tooth of a duck-foot cultivator, a disc harrow on an elastic rack, a subsoil cultivator (chisel plough), a mouldboard plough, and a smooth roller. The geometric dimensions of the specified tillage working bodies are presented in Figure 1.

In Simcenter STAR-CCM+, 3D models of working organs were transformed into a volume-surface mesh. Surface mesh generator and trimmer were picked as the 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 size of the mesh was taken as 0.01 m. The general appearance of the formed grids of working bodies is presented in Fig. 1.

The following physical models are selected for the VOF method in Simcenter STAR-CCM+: three-dimensional, non-stationary implicit, multiphase, multiphase interaction, separated flow, turbulent motion, $k-\epsilon$ turbulence model, the volume-of-fluid method, the volume-of-fluid waves, gravity. Air and soil were picked as Euler phases. A gas model with a constant density and a turbulent flow regime was picked for air. Physical and mechanical properties of air: density – 1.18415 kg/m³; dynamic viscosity – 1.85508·10⁻⁵ Pa·s. A liquid model with a constant density and a turbulent flow regime was picked for the soil. According to K.A. Aikins *et al.* (2023), the physical and mechanical properties of the soil are as follows: density – 1,500 kg/m³; dynamic viscosity – 10⁵ Pa·s. A random distribution of surface roughness is adopted for the VOF wave model. The general view of the modelling area with the specified geometric dimensions is presented in Figure 2.

The relative unevenness of the soil surface at rest of the VOF wave was within -0.02 m to 0.02 m, and its distribution is presented in Figure 3.

The following physical models were picked for the DEM in Simcenter STAR-CCM+: three-dimensional, non-stationary implicit, Lagrangian multiphase, multiphase interaction, gravity. The DEM particles with the following

models are chosen as the Lagrangian phase: spherical particle, solid, constant density. As physical and mechanical properties of soil particles according to O.P. Hutsol & V.P. Kovbasa (2016), I.A. Shevchenko (2016), the following were adopted: density – $1,500 \text{ kg/m}^3$; 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 was 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 was 0.61; normal and tangent coefficients of recovery – 0.5; no linear coupling. According to I.A. Shevchenko (2016), the fractional composition of the soil obeyed a normal Gaussian distribution within 10 mm to 36 mm. The accepted distribution of soil particles by size is presented in Figure 4. The soil was divided into 30 layers with a thickness of 0.02 m.

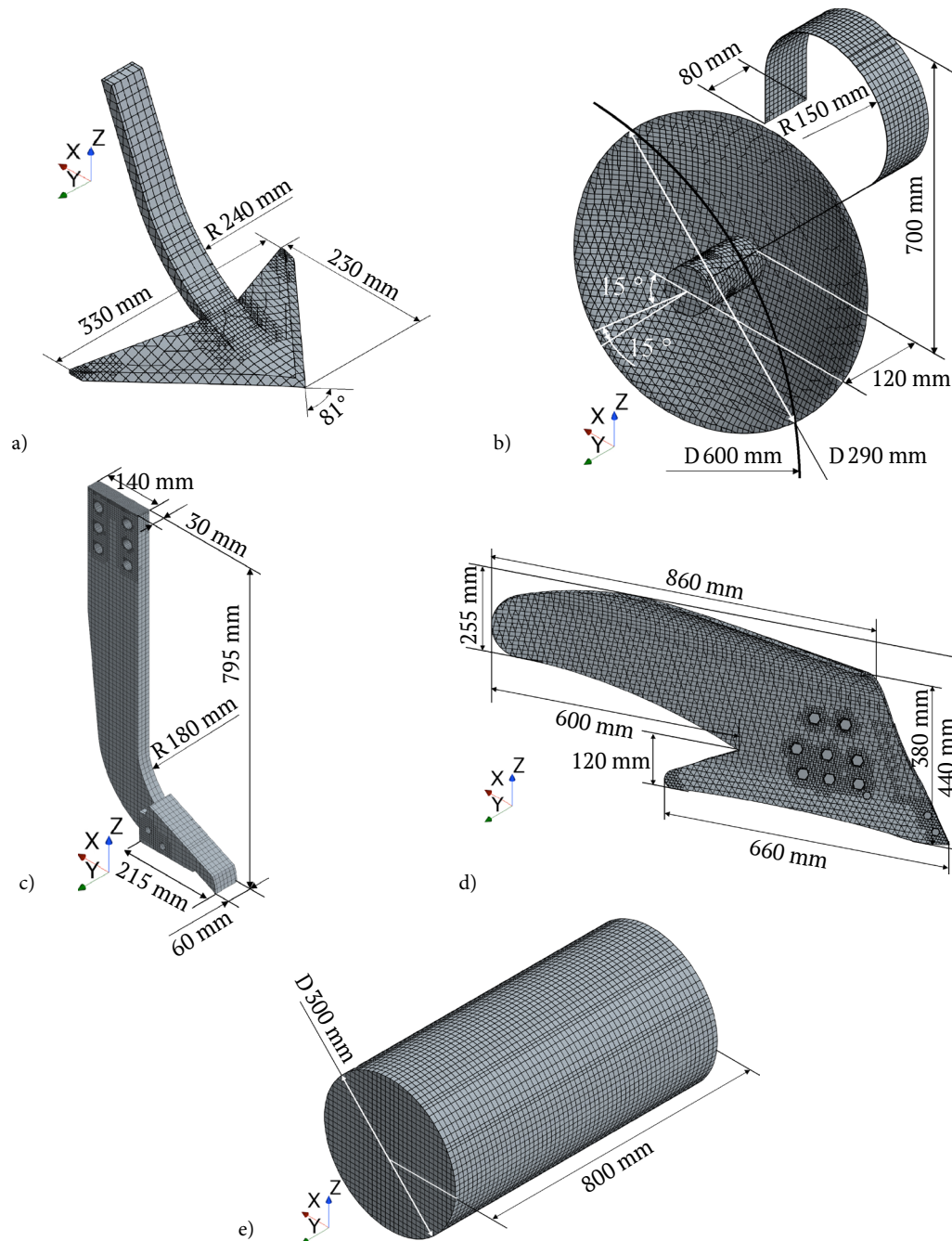


Figure 1. Geometric dimensions and formed grids of tillage working bodies

Notes: a) – tooth of a duck-foot cultivator; b) – disc harrow on an elastic rack; c) – subsoil cultivator; d) – mouldboard plough; e) – smooth roller

Source: developed by the authors

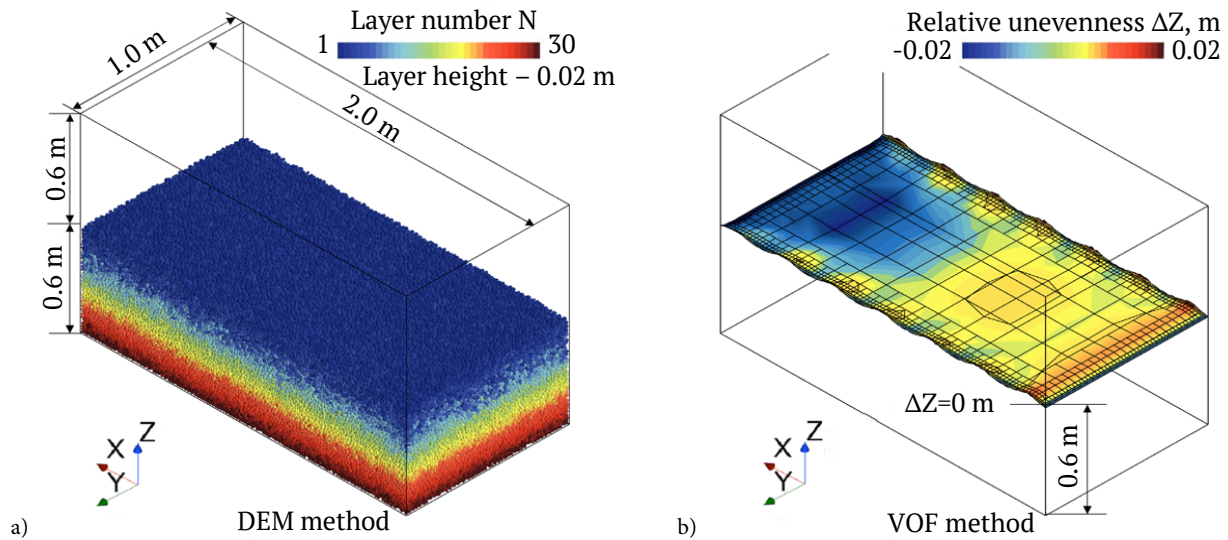


Figure 2. General view of the modelling area with specified geometric dimensions

Source: developed by the authors

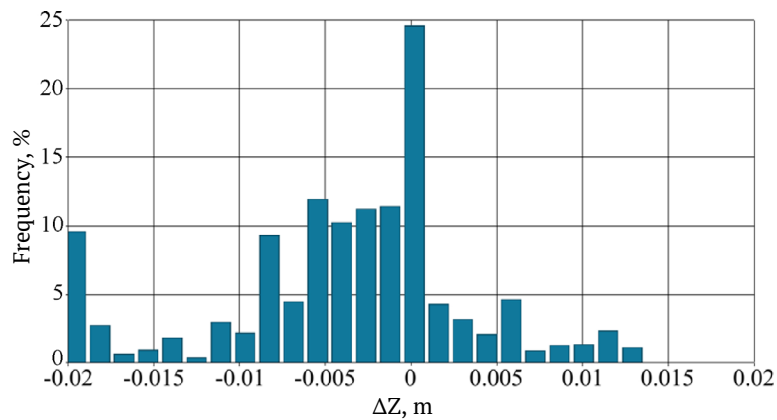


Figure 3. Distribution of the relative unevenness of the soil surface at rest of the VOF wave

Source: developed by the authors

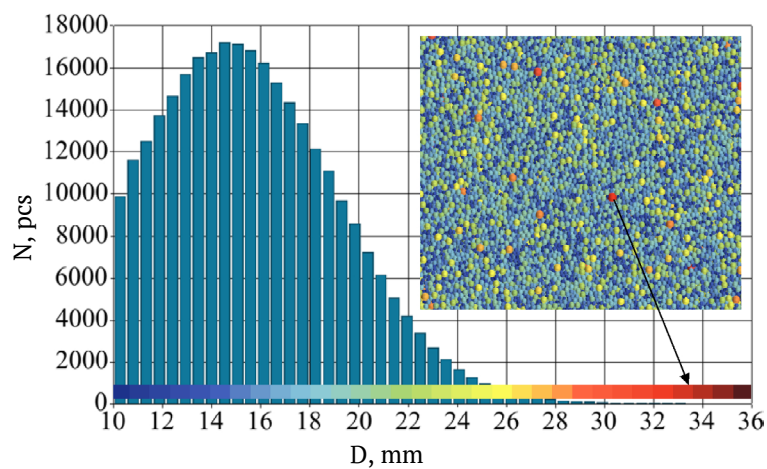


Figure 4. Distribution of spherical DEM soil particles by size

Source: developed by the authors based on I.A. Shevchenko (2016)

The parameters of the non-stationary implicit solver Simcenter STAR-CCM+ were as follows: time step – 0.01 s; the maximum number of iterations in one step – 5; 1st order of time sampling accuracy. The minimum and maximum Courant numbers – 0.2 and 0.5, respectively, – were chosen for Lagrangian multiphase. The total simulation time – 10 s.

RESULTS AND DISCUSSION

As a result of the simulation of the interaction of the tooth of a duck-foot cultivator with the soil, corresponding visualizations were built for the two methods, which are presented in Figure 5. The depth of cultivation – 0.08 m,

the speed of movement – 3 m/s. The distribution of the velocities of soil particles in the DEM modelling and non-primary soil flow relative to the working body in the VOF modelling are presented in Figure 6. Figures 5 and 6 clearly demonstrate the same nature of the change in the shape of the soil surface and its movement. Thus, according to the VOF, it is possible to determine the height of the formed ridge on the soil surface, which shows its loosening. In turn, DEM can be used to determine the trajectory of the movement of individual soil particles of different diameters and to investigate the displacement of horizontal layers in depth.

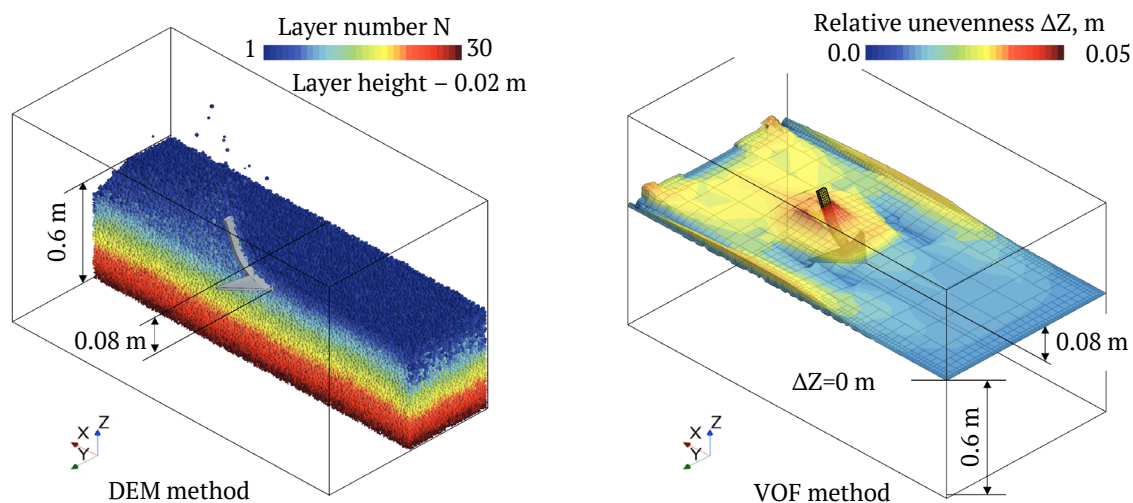


Figure 5. Visualization of the process of the interaction of the tooth of a duck-foot cultivator with the soil
Source: developed by the authors

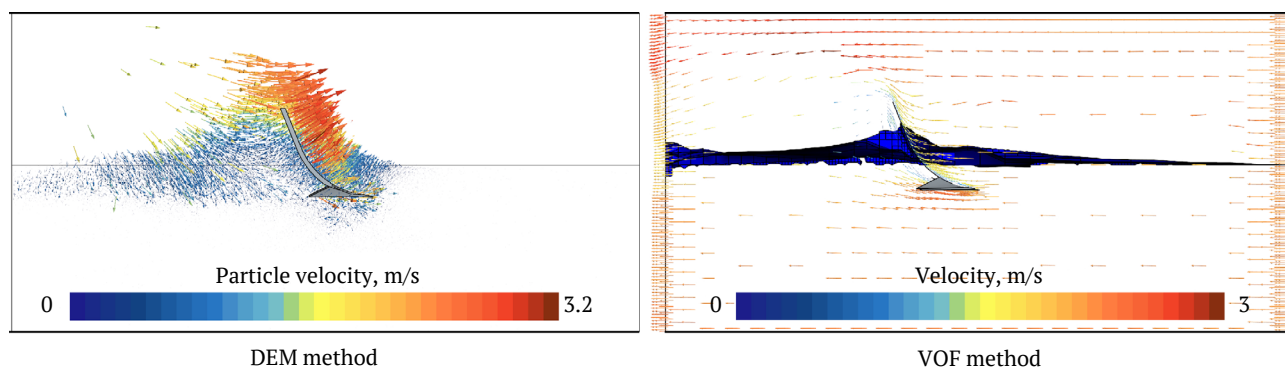


Figure 6. Distribution of soil particle velocities in DEM modelling and non-primary soil flow relative to the cultivator's arrow foot in the VOF modelling

Source: developed by the authors

Each of the methods plays a vital role in determining the numerical values of the interaction of the tooth of a duck-foot cultivator with the soil. Thus, Figure 7 shows the distribution of the forces of interaction of the duck-foot cultivator's tooth surface on individual soil particles according to the DEM. The force of interaction of soil particles varied up to 20 N. During VOF modelling, the pressure

distribution on the surface of the duck-foot cultivator's tooth was obtained. The pressure reached up to 144 kPa. The given two distributions complement each other in the numerical description of the interaction process. The use of both methods at the same time allows considering the interaction of the cultivating working body (duck-foot cultivator's tooth) with the soil considering the energy and

quality indicators of the work, which helps substantiate its geometric parameters. Minimizing normal stresses will help reduce the rate of wear of the working body. The best

loosening of the soil is carried out through deformations of stretching, displacement, and bending, which underlies the development of the criterion for optimizing this process.

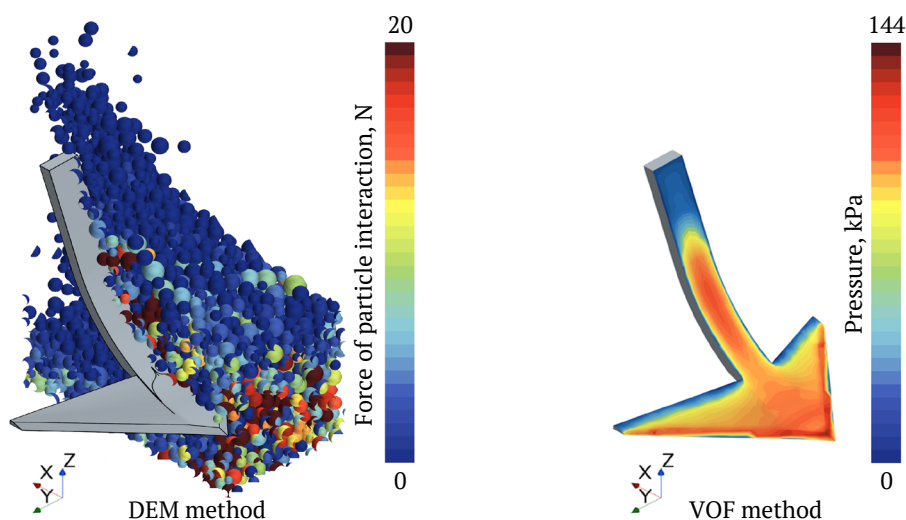


Figure 7. Distribution of the force of interaction of soil particles according to the DEM and pressure on the surface of the tooth of a duck-foot cultivator according to the VOF

Source: developed by the authors

Therefore, to achieve the criterion of strength, minimum rate of wear of the working body and uniform (isotropic) deformations in all directions, it is necessary to determine the geometric shape of the surface of the duck-foot cultivator's tooth, considering the conditions of interaction of the working body with the soil using Simcenter STAR-CCM+. The next working body is a disc harrow on an

elastic stand. The depth of cultivation – 0.18 m. The speed of movement – 3 m/s. The angles of attack and inclination of the disc are taken as 15°.

For two methods of modelling the process of interaction between the disc surface and the soil, corresponding visualizations were created based on the simulation results (Fig. 8).

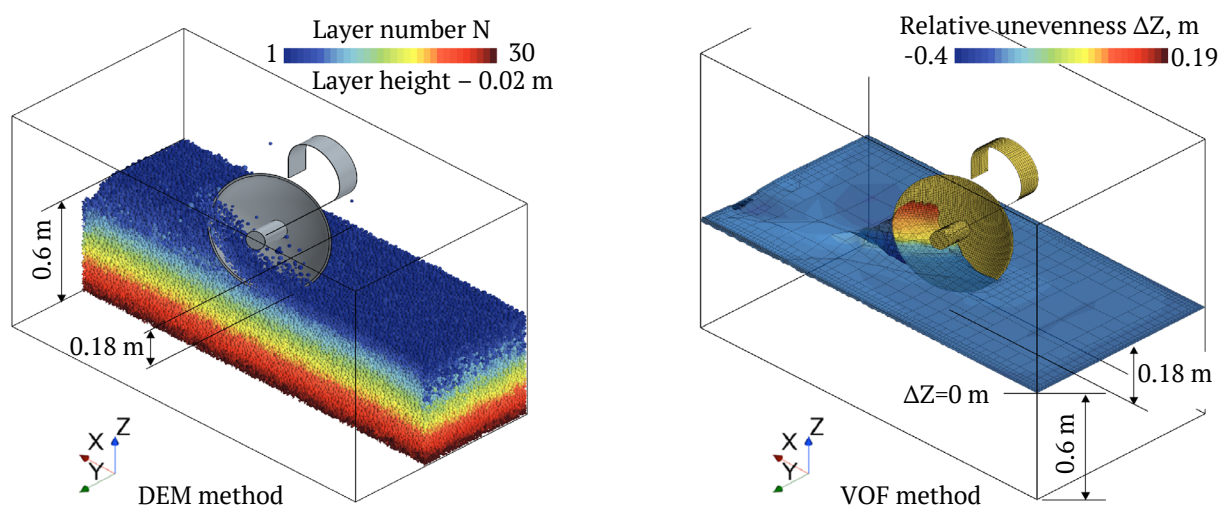


Figure 8. Visualization of the process of interaction of the disc with the soil

Source: developed by the authors

The distribution of soil particle velocities by the DEM and the VOF are presented in Figure 9. The visualizations demonstrate a similar change in the shape of the soil surface and its movement. Using the VOF, it is possible to

determine the height of soil creep on the disc (0.19 m) and the maximum furrow depth (0.04 m). In turn, DEM helps investigate the formation of ridges and furrows already after the passage of the disc.

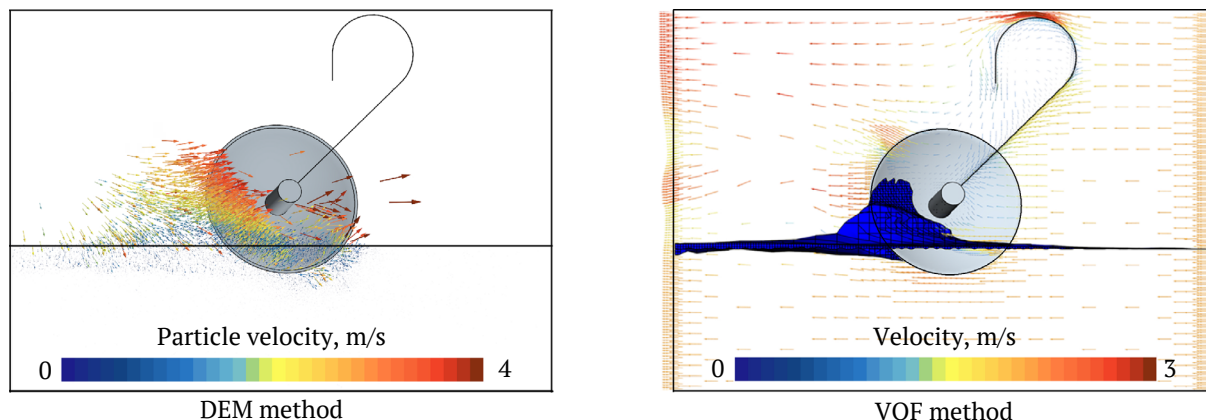


Figure 9. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the disc harrow in the VOF modelling

Source: developed by the authors

Figure 10 shows the distribution of interaction forces between the disc surface and individual soil particles according to the DEM. The force of interaction of soil particles varied up to 20 N. During the VOF modelling, the

pressure distribution on the disc surface was obtained (Fig. 10). Therewith, the pressure reached 112 kPa. These two distributions complement each other in the numerical description of the interaction.

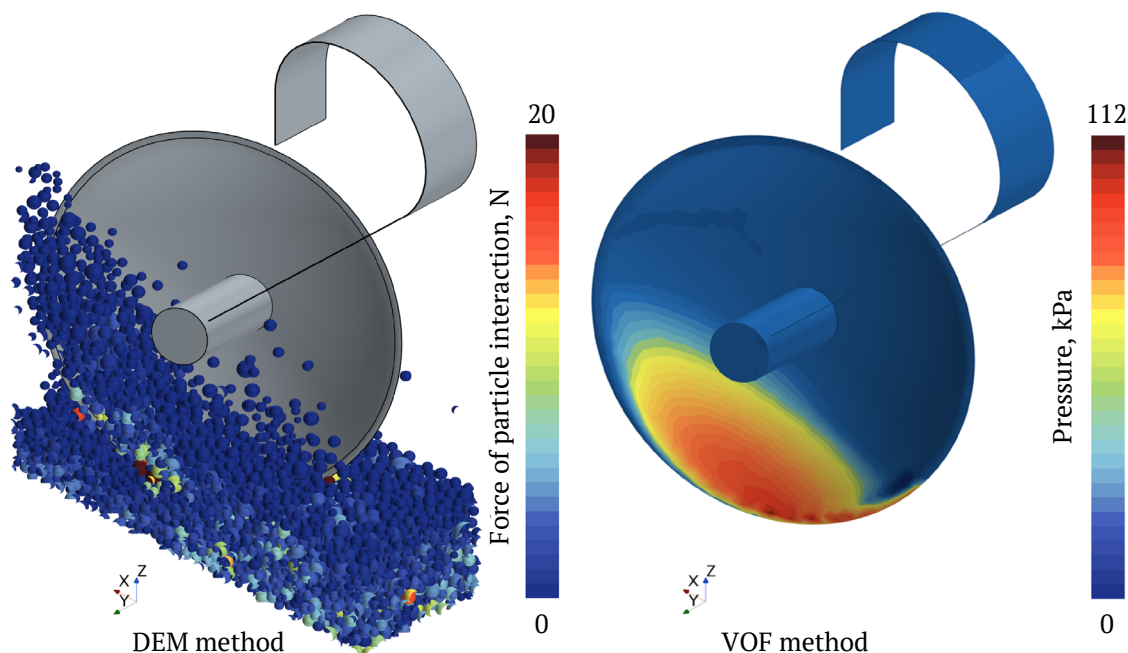


Figure 10. Distributions of interaction forces between soil particles according to the DEM and pressure on the disc surface according to the VOF

Source: developed by the authors

The use of the proposed DEM and VOF methods will allow substantiating the design and technological parameters of the disc harrow. To fulfil this purpose, it is necessary to conduct a study of soil movement on the surface of the disc harrow's working body and determine the line and area of contact with the soil environment. Subsequently, considering the stresses that arise in the soil under the action of the disk working body, it is possible to determine the components of the resistance forces. Proceeding from

the distribution of unevenness of the soil surface, it is possible to determine the coefficient of soil structure and the indicator of its looseness.

The next tool is a subsoil cultivator (chisel plough) with a working depth of 0.35 m and a movement speed of 3 m/s. For two methods of modelling the interaction of the disk surface with the soil, corresponding visualizations were created based on the simulation results, which are presented in Figure 11.

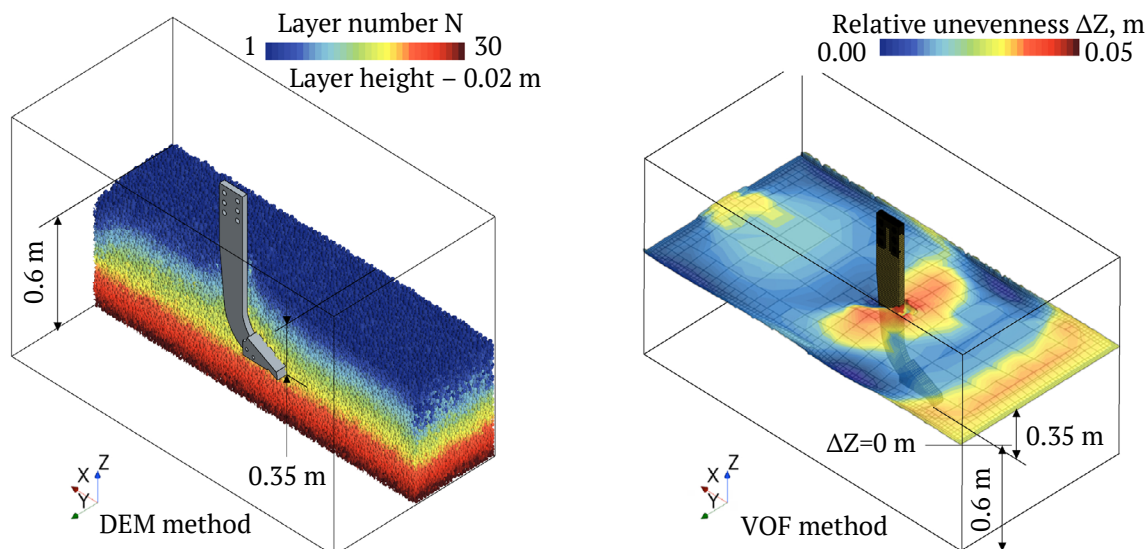


Figure 11. Visualization of the interaction of the subsoil cultivator (chisel plough) with the soil

Source: developed by the authors

Figure 12 shows the distribution of soil particle velocities according to DEM and VOF. Visualization shows a similar change in the shape of the soil surface and its movement. The use of DEM allows investigating the loosening

and formation of ridges because of the lifting of soil layers after the passage of a chisel plough.

The VOF allows determining the maximum height of ridges (0.05 m).

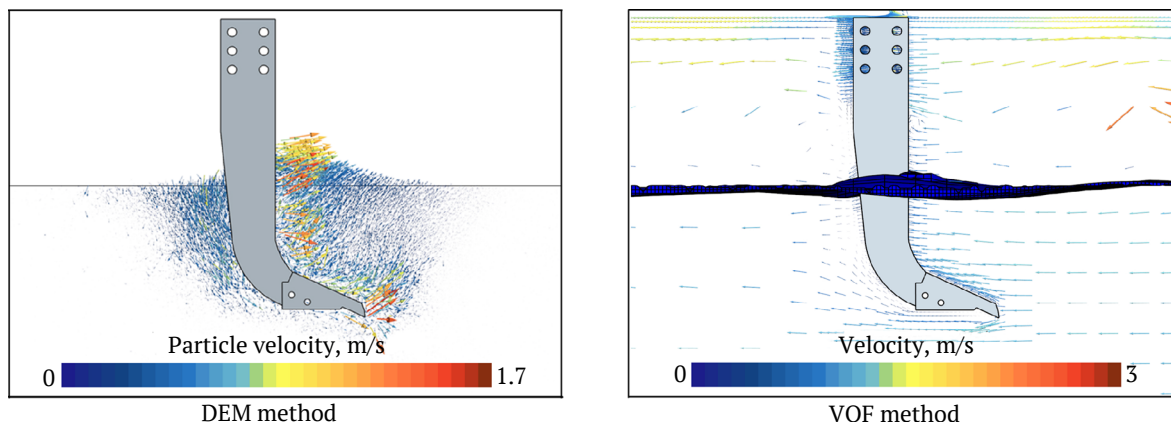


Figure 12. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the subsoil cultivator in the VOF modelling

Source: developed by the authors

Figure 13 shows the pressure distribution on the surface of the VOF chisel plough, the maximum value of which is 196 kPa. Using the DEM, the distribution of interaction forces between individual soil particles and the surface of the chisel plough was obtained. The force of interaction of soil particles varied up to 40 N.

The study of the interaction of the chisel plough with the soil allows determining the distribution of stress on the working body and the path of soil compaction. Furthermore, it is possible to calculate the soil loosening quality factor. As a result of the simulation of the interaction of the plough with the soil for the two methods, the corre-

sponding visualizations were built, which are presented in Figure 14. The depth of cultivation is 0.3 m. The speed of movement is 2 m/s. The distribution of velocities of soil particles in the DEM modelling and non-primary soil flow relative to the working body in the VOF modelling are presented in Figure 15. Figures 14 and 15 clearly demonstrate the same nature of the change in the shape of the soil surface and its overturning. Thus, the height of the formed ridge on the soil surface can be determined according to the VOF. In turn, the DEM can be used to determine the redistribution of layers of soil particles of different diameters along the cultivation depth.

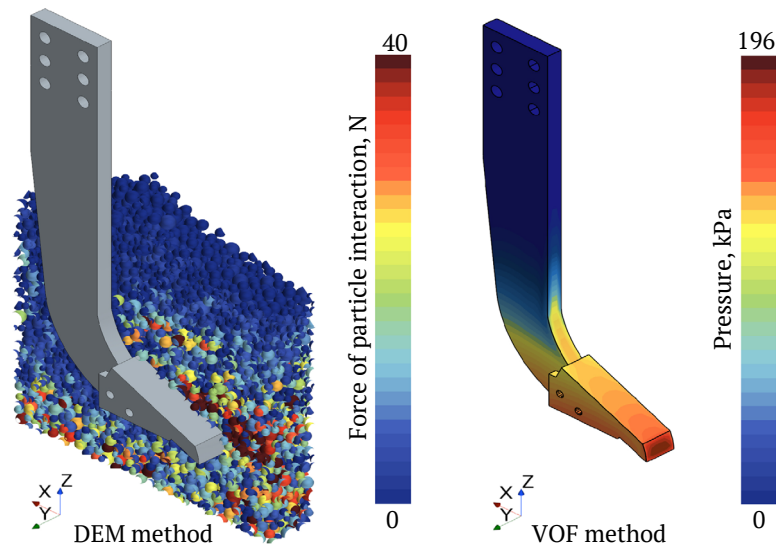


Figure 13. Distributions of interaction forces between soil particles according to the DEM and pressure on the chisel plough surface according to the VOF

Source: developed by the authors

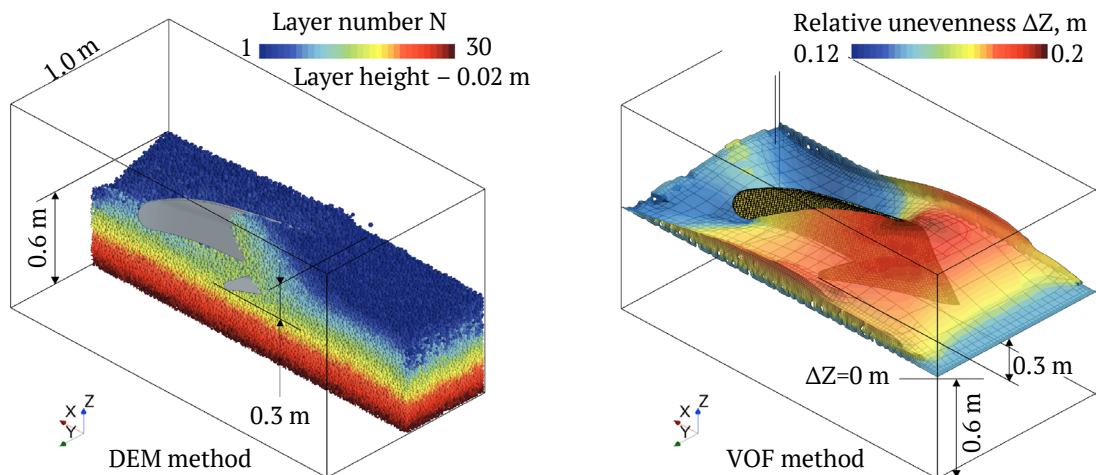


Figure 14. Visualization of the interaction between the plough and the soil

Source: developed by the authors

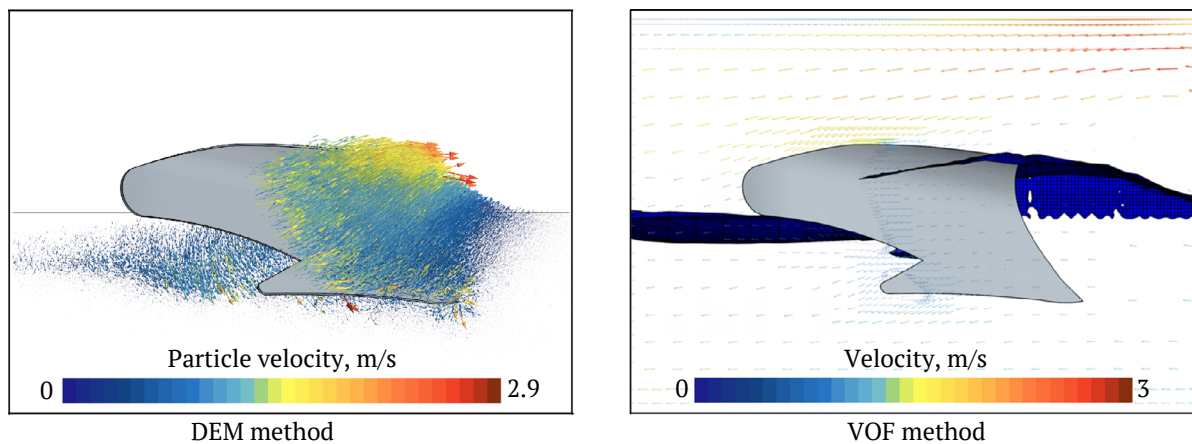


Figure 15. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the mouldboard plough in the VOF modelling

Source: developed by the authors

Figure 16 shows the distribution of the interaction forces of the plough surface on individual soil particles according to the DEM. The force of interaction of soil parti-

cles varied up to 40 N. During the VOF modelling, the pressure distribution on the surface of the plough was obtained (Fig. 16). The pressure reached up to 232 kPa.

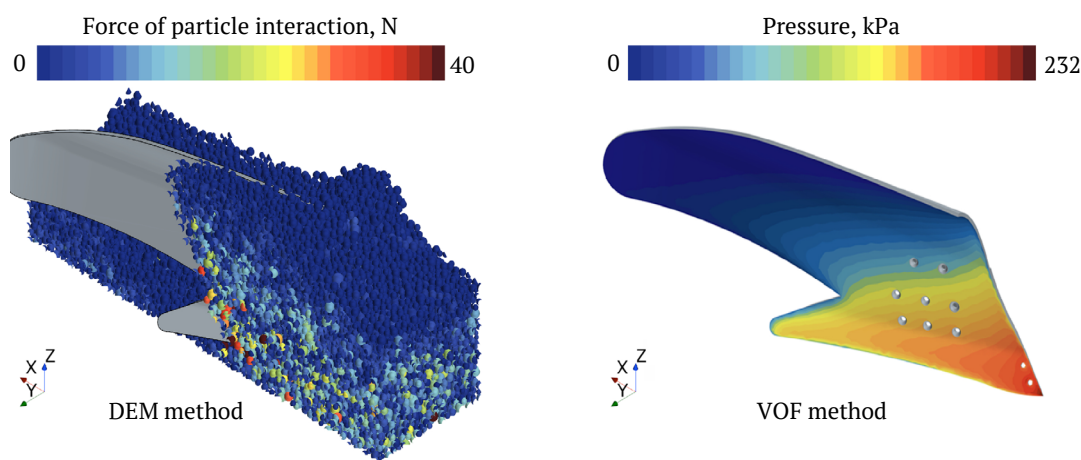


Figure 16. Distribution of forces of interaction of soil particles according to the DEM and pressure on the surface of the fallow plough according to the VOF

Source: developed by the authors

The last working body considered in this paper is a smooth roller. The speed of movement is 2 m/s. For two methods of modelling the interaction between the surface

of a smooth roller and the soil, the corresponding visualizations were created based on the simulation results (Fig. 17).

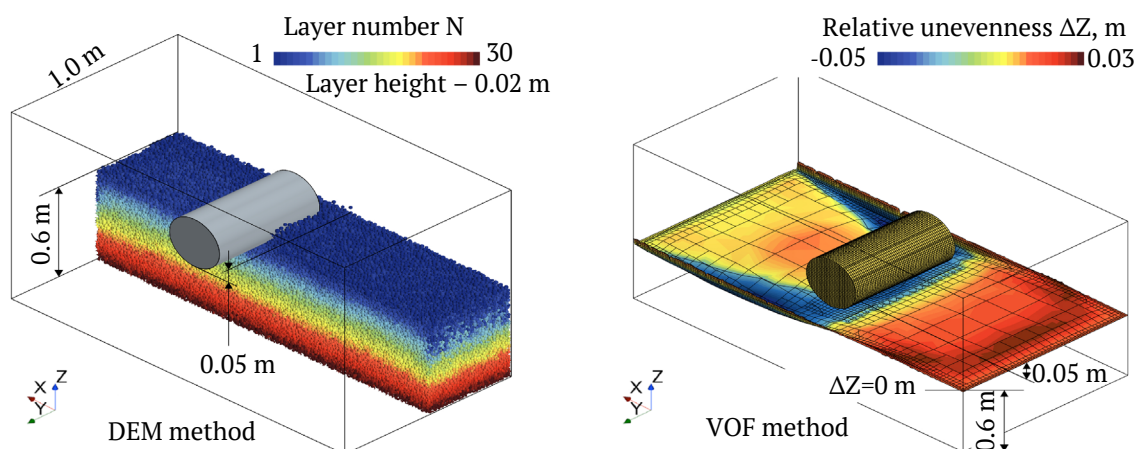


Figure 17. Visualization of the interaction between the plough and the soil

Source: developed by the authors

The distribution of soil particle velocities by the DEM and VOF is presented in Figure 18. Visualizations in Figures 17 and 18 demonstrate the deformation of the surface layer of the soil, which allows determining the degree of crushing of soil clods, destruction of the surface crust and compaction of the upper arable layer.

One of the main functions of rollers is to create a rational and uniform soil density in the soil. To fulfil these requirements by working bodies for rolling, it is necessary to know the pattern of pressure distribution at the “working body – soil” boundary. Figure 19 shows the distribution of interaction forces between the surface of a smooth roller and

individual soil particles according to the DEM. The force of soil particle interaction varied up to 40 N. During the VOF modelling, the pressure distribution on the surface of the roller was obtained. Therewith, the pressure reached 48 kPa.

Comparing the obtained results with classical analytical models of A.S. Kushnarev (2010), O.P. Hutsol & V.P. Kovbasa (2016) and I.A. Shevchenko (2016) established that the values of the maximum forces of interaction between the soil and the surface of the working bodies coincide. However, the presented models help obtain the distribution of this force on the surface of the tillage tool. This greatly expands the possibilities of numerical modelling

compared to classical analytical models. Furthermore, the time to calculate the forces in numerical modelling is much shorter than in the application of analytical models. The results of the study confirm the conclusions of solving the geometric problems of the sketch geometry of determining the height of the ridges above the bottom of the furrow dur-

ing soil cultivation, proposed by M.V. Bakum & D.A. Yashchuk (2011). However, the geometric problems in M.V. Bakum & D.A. Yashchuk (2011) are designed for standard tillage implements. That is, with specific forms of the surfaces of working bodies, they require correction, unlike numerical modelling according to the DEM and VOF methods.

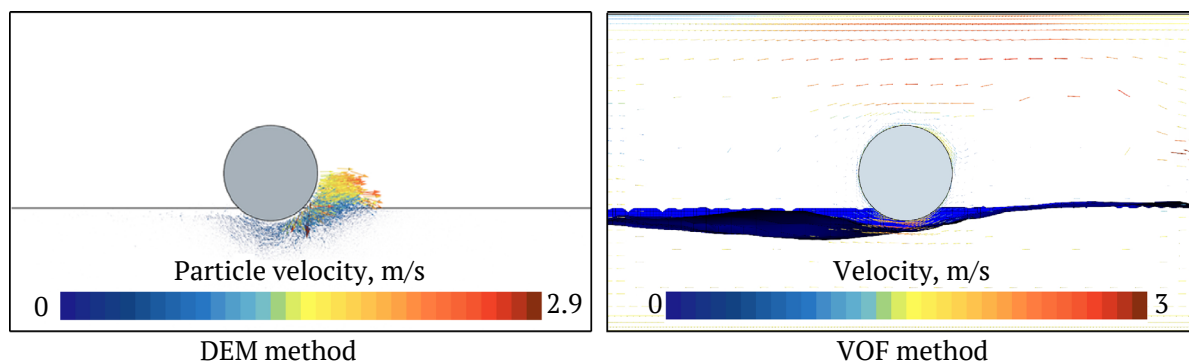


Figure 18. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the roller in the VOF modelling

Source: developed by the authors

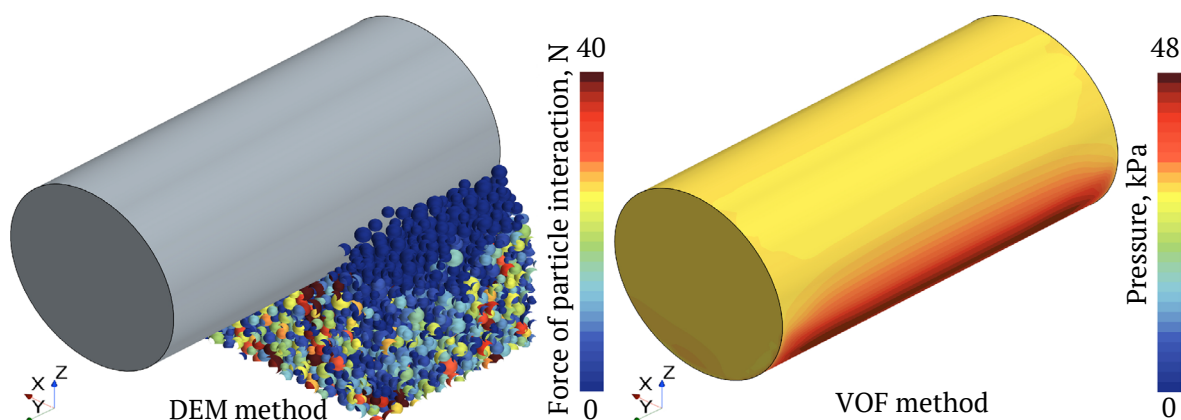


Figure 19. Distribution of the force of interaction of soil particles according to the DEM and pressure on the surface of a smooth roller according to the VOF

Source: developed by the authors

Comparison of the obtained results with those obtained by T. Okayasu *et al.* (2012), M. Ucgul *et al.* (2016), J.B. Barr *et al.* (2019) confirm the possibilities of using the DEM method for modelling the interaction of working bodies with the soil. However, as in the mentioned studies, as well as in the conducted ones, there is a need to determine the pressure on the surface of the working body. This can be done using the VOF method, which complements the picture of the physics of the interaction of the tillage working body with the soil. The models and simulations that were built by A. Ibrahim *et al.* (2015) and J. Zhang *et al.* (2023) are confirmed by field experiments. However, the high accuracy of the models and the truth of their verification is possible only when the physical and mechanical properties of the soil, the initial and boundary conditions of modelling, which fully correspond to the field conditions, are speci-

fied. Therefore, in the presented materials, an emphasis is placed on conducting more laboratory studies to determine the physical and mechanical properties of the soil, which will allow bringing the soil model closer to real conditions.

Comparing the obtained results with the study by A.A. Tagar *et al.* (2015) reveals one drawback of the DEM and VOF soil modelling – the breakdown 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” model as a phase interaction, 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 the VOF model is used alongside a Lagrangian multiphase (LMP) model. This modelling

strategy allows maintaining Euler's phase accuracy in areas where it is needed locally, while using the more computationally efficient LMP model for DEM particle tracking.

CONCLUSIONS

Modelling and review of the interaction of the most common tillage working bodies (tooth of a duck-foot cultivator, disc harrow on an elastic rack, subsoil cultivator (chisel plough), mouldboard plough, and smooth roller) with the soil using the capabilities of Simcenter STAR-CCM+ according to the volume-of-fluid method (VOF) and the discrete element method (DEM). When creating the model, the main physical and mechanical properties of the soil were used (density, Poisson's ratio, Young's modulus of elasticity, coefficient of rest friction between soil particles, normal and tangent coefficients of recovery, coefficient of linear coupling, work of cohesion, coefficient of rest friction of soil particles against the surface of the working body, fractional composition of the soil). To improve the accuracy of the soil model of several types, it is necessary to conduct more laboratory studies to determine their properties and compare them with the parameters specified in Simcenter STAR-CCM+.

Simcenter STAR-CCM+ simulation of the interaction of tillage working bodies with the soil helps visualize it, determine the speed distributions of soil particles in the DEM modelling and non-primary soil flow relative to the

working body in the VOF modelling. Furthermore, it is possible to determine the distribution of the force of interaction of soil particles using the DEM method, the pressure on the surface of the working body using the VOF method, the height of the formed ridges and the depth of furrows and their location in space.

In general, both DEM and VOF methods can be useful for simulating the interaction of the tillage working body with the soil in Simcenter STAR-CCM+, depending on the particular situation and the problem to be solved. The VOF can be accurate for modelling large-scale processes but does not always accurately describe small-scale motion. On the other hand, the DEM method can be accurate for modelling discrete soil particles but does not always accurately describe large-scale processes. They complement each other and create a general picture of the physics of the interaction of the tillage working body with the soil. The purpose of further research is to achieve the best density of the soil, ensuring minimal normal stresses and uniform deformations in all directions using the working body of the tillage tool.

CONFLICT OF INTEREST

None.

ACKNOWLEDGEMENTS

None.

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**Симуляція процесу взаємодії робочих органів
ґрунтообробних машин із ґрунтом в Simcenter STAR-CCM+**

Анотація. Відсутність простих аналітичних фізико-математичних моделей ускладнює дослідження процесу взаємодії ґрунтообробних робочих органів із ґрунтом при проєктуванні нових конструкцій. Для того, щоб спростити ці розрахунки в рамках інжинірингу сільськогосподарського машинобудування, необхідно використовувати програмне забезпечення, яке об'єднає напрацювання землеробської механіки. Метою дослідження було моделювання та дослідження процесу взаємодії ґрунтообробних робочих органів із ґрунтом за допомогою Simcenter STAR-CCM+. Для цього було використано метод об'ємної рідини та метод дискретних елементів. В процесі створення моделі використанні основні фізико-механічні властивості ґрунту. В результаті було проведено моделювання процесу взаємодії найпоширеніших ґрунтообробних робочих органів, таких як стрілчата лапа культиватора, дискова борона на пружній стійці, глибокорозпушувач (чизельний плуг), відвальний плуг і гладкий коток, за допомогою методів об'ємної рідини та дискретних елементів. Застосування методу об'ємної рідини дозволило встановити непервинний потік ґрунту відносно робочого органу, а метод дискретних елементів дозволив визначати розподіли швидкостей та сил взаємодії частинок ґрунту. Встановлено, що обидва запропонованих методи можуть бути корисними для моделювання взаємодії ґрунтообробного робочого органу з ґрунтом в Simcenter STAR-CCM+. Доповнюючи один одного, вони створюють загальну картину фізики процесу взаємодії ґрунтообробного знаряддя із ґрунтом. За допомогою Simcenter STAR-CCM+ була зроблена візуалізація процесу взаємодії і визначено висоту сформованих гребнів і глибин борозн та їх розташування у просторі. Застосування отриманих моделей дозволить агроінженерам швидко проєктувати нові конструкції ґрунтообробних знарядь спираючись на процесі їх взаємодії із ґрунтом.

Ключові слова: знаряддя; чисельне моделювання; метод об'ємної рідини; метод дискретних елементів; розподіл швидкостей; тиск

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Improvement of the design of the motorized filter respirator

Abstract. Working conditions often do not meet the regulatory requirements for hygienic indicators, specifically, there are violations regarding the presence of harmful impurities in the air of the working area. In such cases, motorized filter respirators are used to protect respiratory organs, which require the development of a suitable system for managing operational indicators for effective operation. The purpose of this study was to improve the control system of a motorized filter respirator to increase protective efficiency. To create a suitable control system, a structural-parametric synthesis of performance indicators' management was applied, based on the relationships between the main variables (outgoing regulated variables, controlling influences and disturbances). A new working scheme of the control object with selected design elements of the blower was developed, the main difference of which is the use of the Arduino Uno R3 board, the LCD Keypad Shield module with a two-line display for controlling the airflow modes, according to the change in the resistance of the filter considering the accumulation of dust sediment assuming that the transfer function can be represented by an aperiodic link of the 1st order with sufficient accuracy for practice. To work out the operating modes and determine the duration of the protective effect, a software model of the operation of the motorized filter respirator was created, which

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helped evaluate the influence of the dust concentration on the change in airflow through the filter elements, considering the accumulation of dust sediment on the protective effectiveness. Recommendations were developed to ensure the effective functioning of the protective device pursuant to the requirements under the most adverse conditions. The practical significance of this study is that thanks to the improvement of the control system of the motorized filter respirator, more comfortable and effective protection is provided, specifically in conditions of severe or hazardous working environments

Keywords: fan; pressure; rotation speed; dust concentration; air flow; pulse width

INTRODUCTION

Working conditions, according to the hygienic indicator (harmful impurities in the air of the working zone), quite often do not meet the regulatory requirements (Kramchaninova *et al.*, 2020). Even with the application of collective means of protection of workers, it is frequently not possible to ensure the maximum permissible levels of hazardous substances in the air of working zones (Aggarwal *et al.*, 2020). M.J. Antonini *et al.* (2021) noted that in such cases, filtering means of individual respiratory protection (hereinafter – IRP) are typically used. However, they are characterized by rather low protective properties. A.N. Bui *et al.* (2021) investigated that this is due, foremost, to the mismatch of the IRP to the anthropometric parameters of the user's face, the presence of hair or scars, which leads to the emergence of a significant suction of unfiltered air due to the lack of tightness between the IRP mask and the face. Motorized filter respirators were developed to solve this issue. A.K. Cramer *et al.* (2021) proved that the main difference between them and ordinary filtering IRP is the creation of excess pressure in the space under the mask, which makes it impossible for harmful impurities to enter the user's respiratory organs, due to leakage, behind the obturation strip (the strip of adhesion of the half mask to the face). However, the emergence of such motorized IRP led to the emergence of new urgent problems, which are related to the correspondence of air supply to the under-mask space to the physiology of breathing, which depends on the pace, rhythm, and difficulty of work (Golinko *et al.*, 2020). Furthermore, it is necessary to provide convenient design parameters (weight of the filtering respirator, breathing resistance, fogging of the mask), which would not lead to other inconveniences during their operation. To solve these problems, a control system is used for the operational parameters of motorized filter respirators: the amount of air supply, the resistance of the filters, the charge of the power battery. However, the main issue of such control systems is the speed of ensuring the necessary operating mode, the lack of control over the duration of the protective effect of the filters, which will ultimately affect the protective efficiency. The conclusion made is reflected in the latest scientific research.

M.Y. Kim *et al.* (2021) presented the results of a study on the influence of the amount of airflow on the level of air purification in the filter elements of motorized filter respirators. Specifically, the authors considered the possibility of cleaning filters from settled dust by applying a reverse flow of air. The study determined the time to ensure an

acceptable level of airflow resistance. However, as the authors themselves note, this procedure requires a fairly considerable period of time, which does not allow for the appropriate exploitation of such IRP. In addition, for such motorized filter respirators, combined filters are mostly used to protect against dust and harmful gases. Unfortunately, purging the filters is ineffective for restoring the gas component of the latter. In another study, V. Jayan *et al.* (2020) set out to develop an innovative design of a motorized filtering respirator with a low cost. To reduce the cost of the design, it was suggested to use a flexible plastic headband, a hood made of polypropylene non-woven fabric, as well as to abandon the control systems for the movement mode of the airflow, which in the final version does not allow this respirator to be used for work that is characterized by a different pace and rhythm of work because the amount of air supplied by the fan under the hood is constant.

T.S. Alderman *et al.* (2016) addressed the issue of the reduction of protective effectiveness in case of incorrect installation of filters, e.g., when replacing during work, in an uncomfortable position. As a result, the conditions were determined when the IRP does not provide adequate protective effectiveness. The lack of evaluation of the effectiveness of control systems for the operation of such respirators should be attributed to the shortcomings of this study. Thus, the existing pressure drop sensors must necessarily report, through corresponding signals, about depressurization of the system, in case of incorrect placement of the filter in the blower or the use of a filter of the wrong design. A. Licina *et al.* (2020) made a powerful analysis of over 50 studies on the effectiveness of the designs of motorized filter respirators, which strongly suggested that the main disadvantages of such respirators are overheating, reduced mobility, limitation of the field of vision, fogging, which are related to the inefficiency of the control system in motorized filter respirators. For instance, regarding overheating or fogging of the glass, M.Z. Chaari *et al.* (2020) claimed that it is possible to predict the mode of cooling or dehumidification of the air. Based on the analysis of the latest publications, it can be concluded that the task of ensuring the control of motorized filter respirators, which will ensure the suitable protective efficiency during the given period of operation, is still relevant. Furthermore, the presence of an uncomfortable feeling can also be prevented by the possibility of controlling the mode of air movement, which requires the suitable development of software models.

The purpose of this study was to improve the control system of the motorized filter respirator to increase the protective efficiency, by developing an innovative parametric scheme of the control object considering the functional relationships between the operating mode, airflow, filter resistance, and the term of protective action.

To fulfil the purpose, it was necessary to perform the following tasks: develop a structural diagram of the control object and select all the structural elements of the blower of the motorized filter respirator; conduct a parametric synthesis of the information and control system of the motorized filter respirator to improve the management system of operational indicators; determine the modes of movement of the airflow in the blower of the motorized filter respirator according to the change in the resistance of the filter, considering the accumulation of dust deposits to determine the term of protective action and protective efficiency.

MATERIALS AND METHODS

To perform the scientific research, a structural-parametric synthesis of a motorized filter respirator was used, which allowed to choose a variant of the working scheme. For this, a certain rank of the control system was synthesized at each level of development of its design. Firstly, a general control scheme for the work of the filtering IRP was formed, then a functional scheme of the interaction of structural elements, which helped pick the suitable components of the motorized filtering respirator. For the latter, a heuristic

method was used, which relied mainly on the erudition and intuition of the designer. Therewith, the experience and knowledge of previous developments and analogues underlay the development of the design of the motorized filter respirator (Cheberyachko *et al.*, 2022). Thanks to the parametric synthesis of the motorized filtering respirator, the task of improving the management system of operational indicators was solved based on establishing the main interrelationships of its constituent elements of the filtering IRP design. Therewith, to ensure the performance of the automatic control system (hereinafter – ACS) of the blower, it was necessary to define a mathematical model that required the definition of the relationships between the main variables (output adjustable variables, controlling influences and disturbances) and the restrictions imposed on them. There are various (static and dynamic) types of mathematical models, but in practice, transfer functions are most widely used to determine which analytical and experimental methods of identification are used. Creating a mathematical model of the blower control system assumes that the transfer functions of all its components are already known. The use of transfer functions of individual constituent elements of the control object to obtain its mathematical model is a rather challenging task and cannot guarantee the correspondence of the obtained result to the real object. For the convenience of the identification procedure, all components of the control object were combined into one transfer function (Fig. 1).

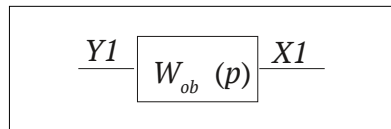


Figure 1. Simplified structural diagram of the blower control object

Note: $W_{ob}(p)$ – the transfer function of the motorized filter respirator control object; $X1$ – air pressure in the mask, Pa; $Y1$ – task signal for the control object – fan rotation speed, rpm

Source: developed by the authors

The transfer function of a W_{ob} object combines the transfer functions of a blower motor, a fan blade, a flexible pipe, a mask, and a filter. With this simplification in mind, the task of identifying a motorized filtering respirator was described as determining the functional relationship between the task signal to the fan speed regulator $Y1$ and the air pressure in the respirator mask $X1$. Considering the design of the motorized filter respirator, which is similar to ventilation systems, it was possible to suggest that the transfer function with sufficient accuracy for practice can be represented by an aperiodic link of the 1st order (Kadhim & Obed, 2018; Jovanović *et al.*, 2022):

$$W(s) = \frac{Y(s)}{X(s)} = \frac{k}{Ts+1}, \quad (1)$$

where k is the amplification factor, which is the ratio of the output value to the input value in the static (steady) mode, Pa/rpm.; T is the time constant characterizing the

inertia of the object (duration of the transient process), $T > 0$, time, s; s is the independent complex variable, $s = \sigma + j\omega$. σ is the real part of a complex number, $j\omega$ is the complex frequency domain, ω is the frequency variable Fourier transform, j is the imaginary unit, a number that, when squared, gives a negative unit: $j^2 = -1$. The aperiodic link of the 1st order has a mathematical description in the form of a differential equation:

$$T \cdot \frac{dy(t)}{dt} + y(t) = k \cdot x(t), \quad (2)$$

where $y(t)$ is the initial value (coordinate) of the system, pressure, Pa, $x(t)$ is the system input coordinate fan rotation speed, rpm; k is the amplification factor, Pa/rpm; T is the time constant, s.

To obtain the transfer functions for the aperiodic units of the first order of the motorized filter respirator, the Process Models in System Identification Toolbox method was

used in the MATLAB Online software. Subsequently, the obtained transfer functions were used to develop a software model in the SolidWorks software environment. The task of identification was performed through an active experiment with the blower of a motorized filter respirator. The method of active experiment (transient characteristics) is based on the use of artificial disturbances affecting the delta momentum of the object according to a plan created in advance (Vladov *et al.*, 2020).

Identification of signals from blower sensors of a motorized filter respirator according to the method of transient characteristics has several advantages: the test step signal is a typical control signal of comparable objects; the prevalence of parametric object identification methods based on this type of signal; the experiment using the method of transient characteristics does not require a change in the physical structure of the experimental sample of the motorized respirator.

To control the value of air pressure in the rarefaction zone and in the mask of the motorized respirator, pressure sensors were used – MPXV7002DP (piezoresistive differential pressure sensor), with a measurement range from -2 kPa to +2 kPa, sensitivity 1.0 V/kPa, analogue output: 0.5 V-4.5 V and a response time of 1 m (manufacturer: NXP Company, Netherlands). To rotate the centrifugal fan, an electric motor model BFB1012VH-AF00 (manufacturer: RTS-Ukraine Company, Ukraine) was used. To reduce air pressure fluctuations in the specified zones (changes in air flow due to fan rotation), a brushless electric motor of the BLDC – Brushless DC Motor model, BL 2208/8 Brushless Outrunner 2200 kv, with a speed of up to 18,000 rpm and a voltage of up to 11.1 V (manufacturer: Hobby Star Company, Taiwan). The speed of rotation of the motor rotor was

controlled using an electronic speed controller – model ESC – Electronic Speed Controller – Skywalker 40A. Speed control was based on pulse width modulation (Manufacturer: Hobbywing Technology Co., Ltd, China). The collection of information from the sensors and the change in the speed of rotation of the fan was provided by the controller model Arduino Uno R3 (Manufacturer: Arduino Company, China), which is loaded with the corresponding software, developed by the author of this study.

To monitor the current state of the sensors and select the required motor speed, an LCD Keypad Shield module compatible with the Arduino Uno R3 controller was connected with a two-line display (16 characters in each line) and 6 buttons (only 5 can be engaged of them, the 6 button is responsible for the hardware reset of the controller) (Manufacturer: DF Robot Company, China).

Excel Microsoft 365 program was used to process the experimental data, to construct approximation curves of the dependences of the fan blade rotation speed on the pulse width of pulse width modulation (PWM) and the filter resistance on the fan rotation speed.

RESULTS AND DISCUSSION

To develop a structural diagram of the control object of a motorized filter respirator and to select the design elements of the blower, the main relationships of its constituent elements, which are different in nature – pneumatic (related to air movement: filter, fan blade, flexible pipe, with connected mask, inhalation/exhalation valves) and electrical (speed controller and fan motor) and is quite a complex object. Thusly, it was presented the structure of the researched control object – a motorized filter respirator (Fig. 2).

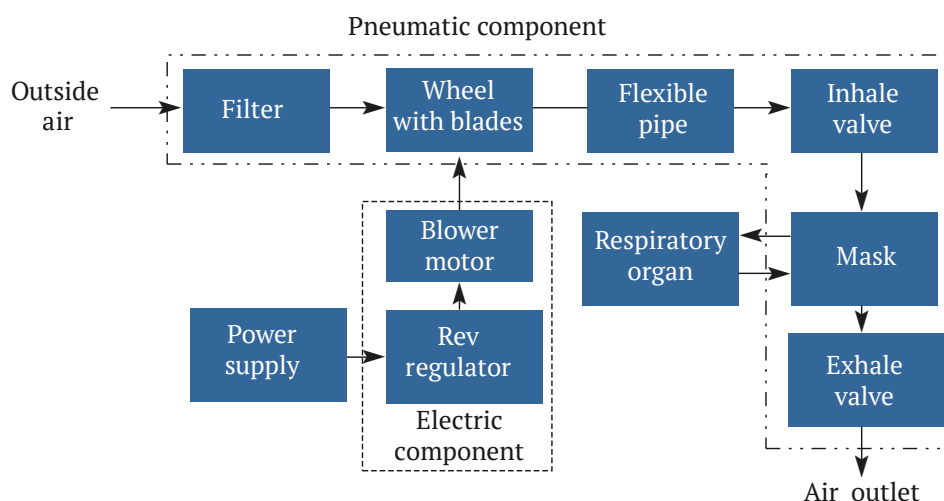


Figure 2. Structural diagram of the control object

Source: developed by the authors

The development of the structural diagram of the motorized filter respirator helped present the design of its blower (Fig. 3), the main difference of which is the use of a centrifugal fan for air supply, which will provide a much

better aerodynamic performance in terms of the airflow/pressure ratio, compared to the axial fans used in analogous motorized filter respirators (Johnson & Johnson, 2018; Tran *et al.*, 2021; Nagel *et al.*, 2021). Furthermore,

the proposed design provides the possibility, thanks to ACS, to operate with various input parameters (breathing resistance, temperature, air humidity, amount of air supply) to determine the pressure drop in the zone (1, 2) and the fan (3) and excess pressure in full-face mask with an assessment of the effect on the protective properties of the IRP.

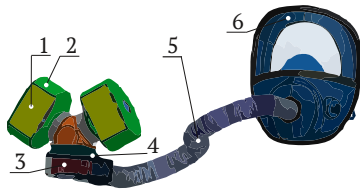


Figure 3. Design of the air supply unit:

filter (1), filter box (2); centrifugal fan (3); housing (4); corrugated duct (5); full-face mask (6)

Source: developed by the authors

The connection diagram of the electronic components of the experimental sample of the blower is presented in Figure 4.

For the convenience of performing experiments and checking the operation of the fan motor, data on the change in fan rotation speed from the width of the PWM pulses were obtained. The required value of the pulse width was supplied to the input of the electronic speed controller of the brushless motor, the rotation speed was controlled using a non-contact laser tachometer. The dependence of the fan blade rotation speed on the PWM pulse width is presented in Figure 5.

The initial value of the test signal is the value of the PWM pulse width, which is supplied to the electronic speed controller, can be left zero (for the electronic speed controller of the brushless motor, this signal ranges from 800 μ s to 2,300 μ s at a frequency of 50 Hz) (Kothakonda *et al.*, 2021).

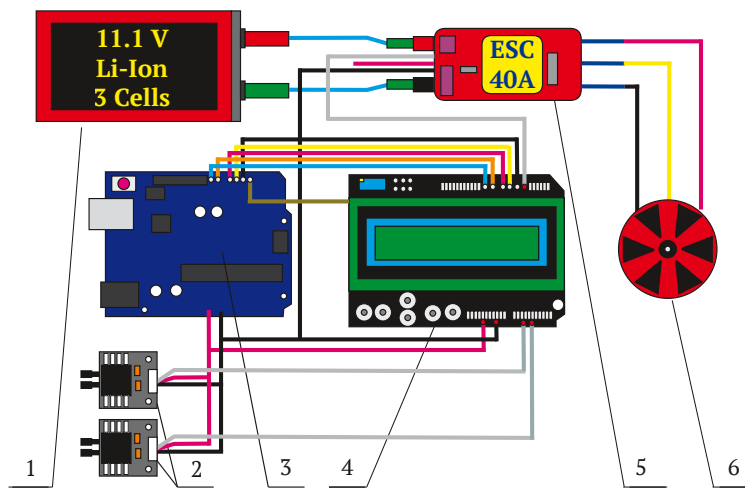


Figure 4. Connection diagram of the electronic components of the blower

Note: 1 – rechargeable battery Li-Ion 11.1 V; 2 – differential pressure sensors MPXV7002DP; 3 – board based on micro-controller ATmega328p – Arduino Uno R3; 4 – LCD Keypad Shield module; 5 – electronic speed controller ESC Skywalker 40A; 6 – brushless electric motor BL 2208/8

Source: developed by the authors

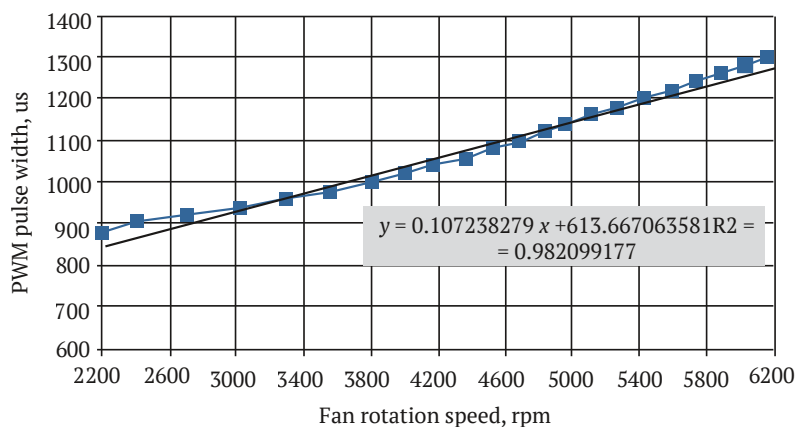


Figure 5. Dependence of fan blade rotation speed on PWM pulse width

Source: developed by the authors

The final value of the test signal is selected considering the permissible value of the air pressure in the mask (up to 370 Pa, accordingly). If the air pressure exceeds the permissible value, it is necessary to repeat the experiment, reducing the value of the control influence on the executive device.

For further experiments, using the obtained dependence (Fig. 5), using linear approximation in Microsoft Excel 365, an equation of the following form was obtained:

$$y = 0.107238279 \times x - 613.667063581, \quad (3)$$

where x is the fan blade rotation speed, rpm; y is the PWM pulse width, μs .

The coefficient of determination of the obtained equation was $R^2 = 0.9821$, i.e., the equation over 98% corresponds to the experimental dependence of the rotation speed of the fan blade on the PWM pulse width. When performing an experiment, the main task is to determine the parameters of the test signal – the control effect on the executive device. For the test step effect, the parameters are as follows: the initial value of the signal, the final value of the signal, and the time of the signal (switch-on moment). Considering the specific features of the operation of the electronic speed regulator, the range of adjustment of the speed of rotation of the fan motor was chosen within 0–6,200 rpm (Fig. 6).

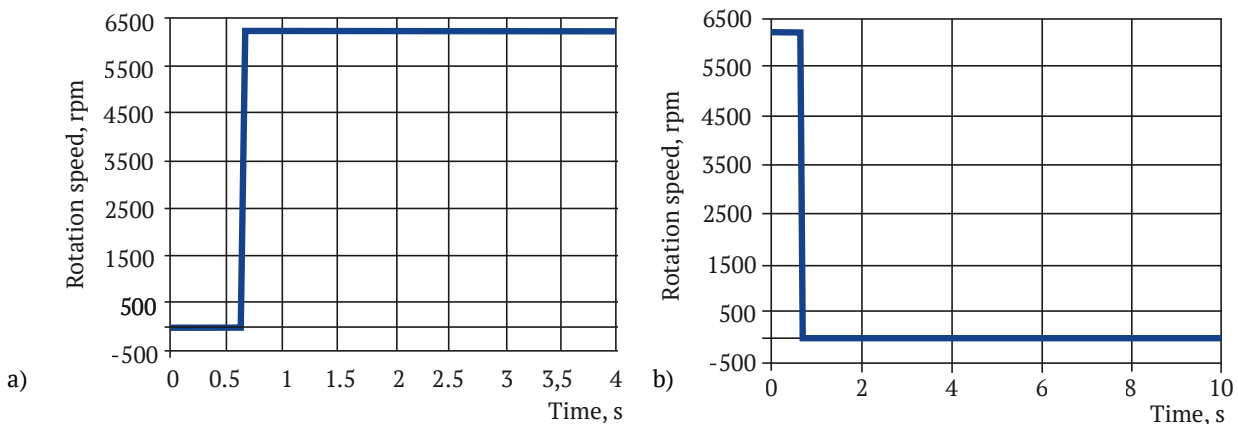


Figure 6. Step test signal

Note: a) – from 0 to 6,200 rpm, b) – from 6,200 to 0 rpm

Source: developed by the authors

The transient characteristics presented in Figures 7a, 7b were used to obtain the transfer functions of the motorized filter respirator using the Process Models in System Identification Toolbox method in the MATLAB Online software for first-order aperiodic units:

transfer function when sending a signal to increase the control influence (Fig. 7a, increasing fan speed):

$$0.59287 \cdot \frac{dy(t)}{dt} + y(t) = 0.22866 \cdot x(t) \quad (4)$$

transfer function when sending a signal to reduce the control influence (Fig. 7b, reduction of fan speed):

$$0.6542 \cdot \frac{dy(t)}{dt} + y(t) = 0.21038 \cdot x(t) \quad (5)$$

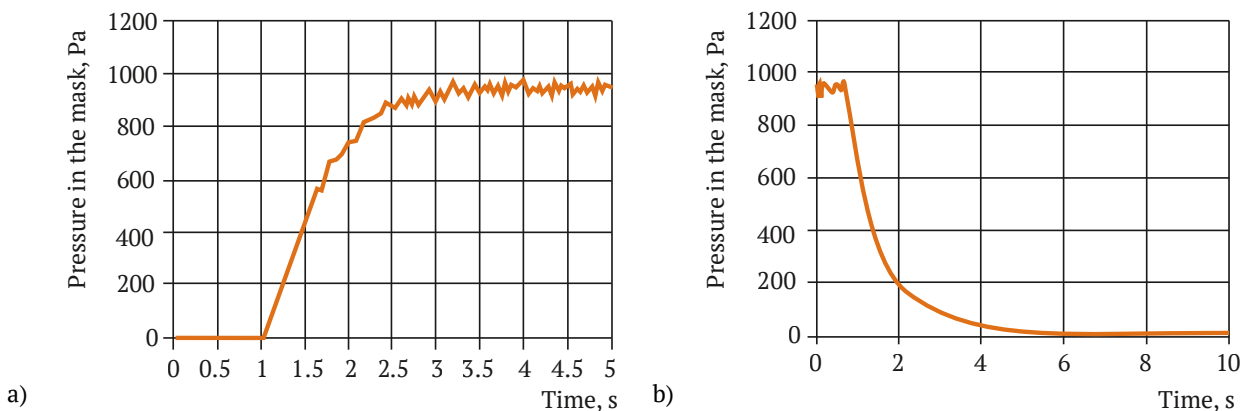


Figure 7. Averaged transient characteristics when applying a test signal

Note: a) – on increasing the controlling influence, b) – on decreasing the controlling influence

Source: developed by the authors

The difference between the time constants when the controlling influence increases and decreases is explained by the technical features of the electronic speed controller. Using the obtained transfer functions, a software model was developed in the SolidWorks software

environment, which helped conduct a series of experiments to investigate the influence of dust concentration and changes in airflow through the filter elements on the resistance of the filter, considering the accumulation of dust sediment (Fig. 8).

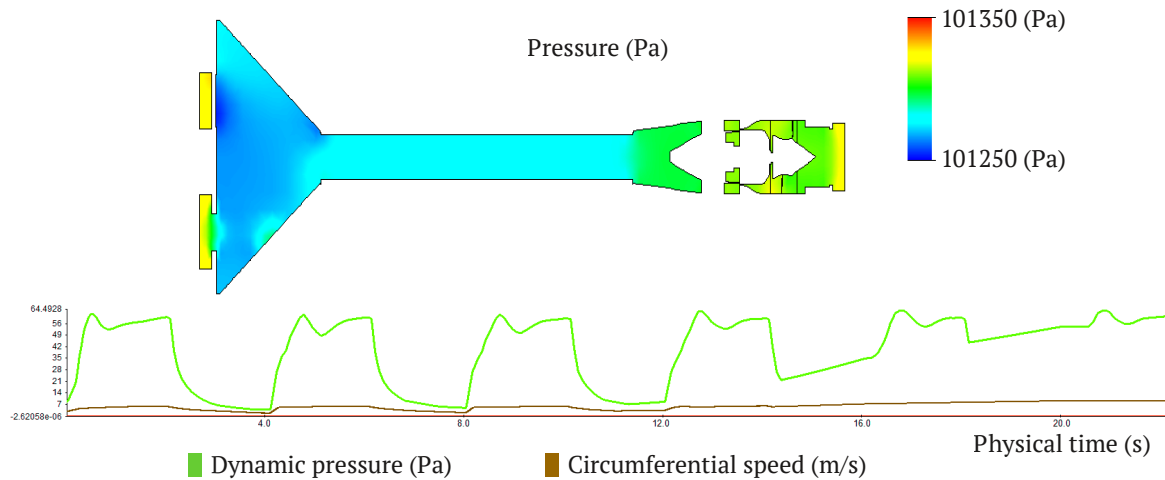


Figure 8. Software (software model) for investigating the operation of a motorized filter respirator

Source: developed by the authors

As a result of the processing and calibration of the received signals, the dependence of the filter resistance on the speed of rotation of the fan was determined (Fig. 9, Fig. 10), which allows controlling the required amount of air in the sub-mask space of the full-face mask of the motorized filter respirator. To determine the effect of dust concentration and airflow on the increase in filter resistance during a certain time (5 hours), an empirical relationship was used (Worker Health & Safety 2020). The obtained

results indicate that in the most unfavourable operating conditions: the maximum concentration of dust and the maximum necessary airflow, when using one filter, the total resistance to air movement at the end of the work shift is 1,016 Pa, exceeding the norm, and when two filters are working, it is equal to 756 Pa, which fully satisfies the requirements. If it is necessary to increase the service life of the filter respirator, it is necessary to use filters with a larger filtering surface.

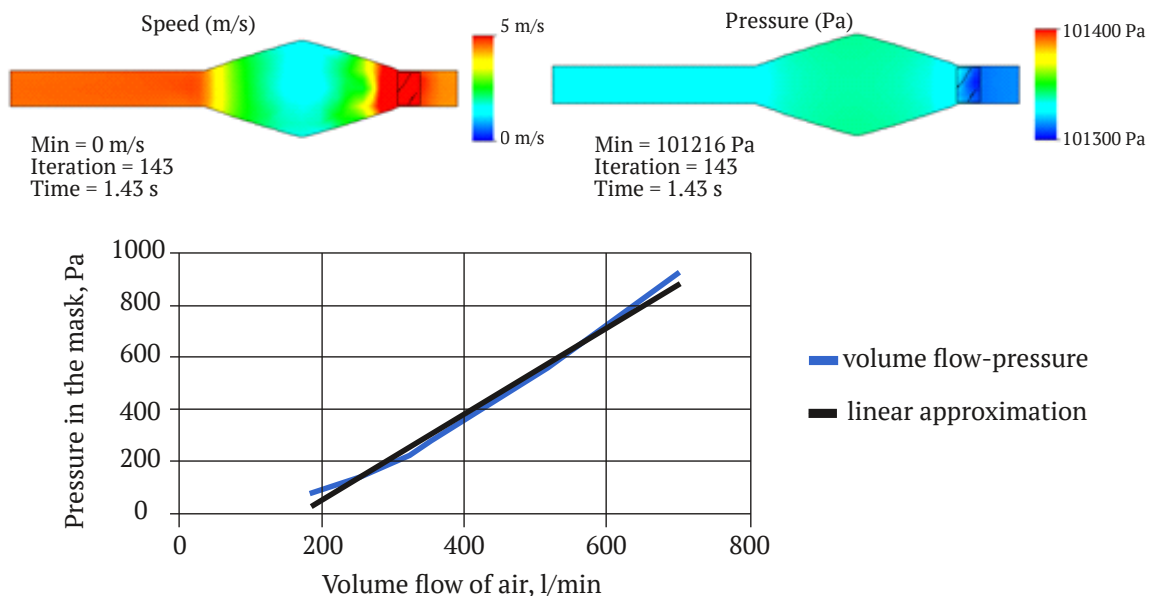


Figure 9. Dependence of filter resistance on fan rotation speed

Source: developed by the authors

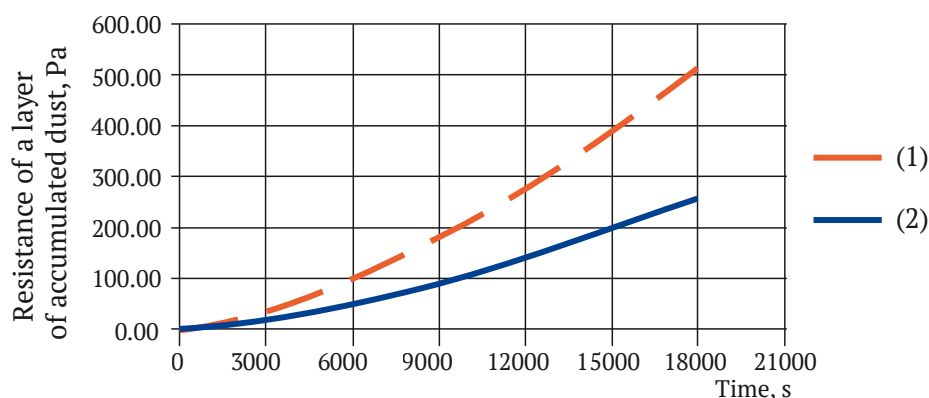


Figure 10. Change of the added resistance of the motorized filter respirator

Note: (1) – with flow rate: 260 l/min and dust concentration of 500 mg/m³ when using one filter, (2) – two filters

Source: developed by the authors

The conducted studies showed that when using a motorized filter respirator, there is a gradual increase in the resistance of the filter elements due to the accumulation of a layer of dust sediment, depending on the speed of rotation of the fan blades. Based on empirical dependences, the possibility of calculating the added resistance of the filter due to the accumulation of a layer of dust sediment was added to the simulation model, which affects the possibility of determining the term of protective action.

The developed structural diagram of the blower control facility allowed to select all the structural elements of the specified structural element of the motorized filter respirator (fan motor, electronic speed controller, number of filters), which allows ensuring prominent efficiency and modern technical level of individual respiratory devices per the international standards, which specify the requirements for the main indicators. Thus, the key element is protective efficiency, which is determined by maintaining all operational parameters of motorized filter respirators within the specified limits (pressure drop level no more than 370 Pa, flow rate no less than 115 l/min). A. Licina & A. Silvers (2021) discuss the necessity of its control through the equipping of such respirators with more advanced control systems that provide appropriate control over the protective effectiveness during operation. A newly developed software model of the movement of airflow through the air blower channels allows evaluating the impact on the protective properties of the respirator and the concentration of dust and changes in airflow through the filter elements due to the increase in filter resistance.

Furthermore, as noted by R. Weiss *et al.* (2021), it is essential to ensure the functionality of the motorized filter respirator so that its indicators also meet ergonomic requirements (breathing resistance, proportion of carbon dioxide and oxygen inhaled, dimensions of the face of half masks, viewing angles, speech intelligibility, etc.). Ensuring the mentioned requirements are implemented using the Arduino Uno R3 board, the LCD Keypad Shield module with a two-line display allows quickly processing input signals and maintaining the set parameters of the blower according

to the physical load and dustiness of the air, air humidity, and ambient temperature. The obtained simulation results suggest that the developed device is characterized by considerably lower breathing resistance compared to known analogues described in the work of T. Vo *et al.* (2022). The refusal to use motorized filter respirators is noted due to profuse sweating and fogging of the sight glass. S. Wood *et al.* (2019) argue that in this regard, it is important to provide users with the ability to adjust the amount of air supplied to the mask to remove moisture, which can be implemented through the speed of rotation of the fan to obtain the desired value (at least 115 l/min), as well as through the possibility of adjusting the dimensions of each element of the design of the protective device, based on the requirements of the customers and equipped with an airflow control system, which, according to the design, should ensure the appropriate amount of air in the space under the mask.

Another critical indicator of a motorized filter respirator is the time of protective action under various loads, which is determined by the content of harmful impurities in the air atmosphere of the working area. D.E. McMahon *et al.* (2020) investigated that for this, the given scheme makes provision for the collection of signals from the relevant sensors, the information from which is processed based on the transfer function. In the future, the modes of movement of the airflow are determined, according to the change in the resistance of the filter, considering the accumulation of dust deposits and data from the environment: temperature and air humidity, which considerably affect the possibility of the filter functioning. According to K. Yamazaki *et al.* (2018), the duration of protective action also depends on the reliability of the motorized filter respirator to provide the required properties during a timed work shift. There is a need to test and control the charge of the battery, the discharge of which at a critical moment can impair the degree of user protection. Thus, M.Z. Chaari *et al.* (2020) devoted considerable attention to the development of a motorized respirator with a lightweight rechargeable battery to reduce the weight of IRP. However, a small charge of the battery led to a simplified control

system, which provides only three modes of airflow, which leads to limitations in the use of such IRP, considering that the operation at high fan speeds also leads to a rapid discharge of the battery and stopping of air supply. Comparable conclusions were reached by O. Bazaluk *et al.* (2021), who recommended to abandon ventilators with a voltage of 12 V and switch to models powered by a voltage of 24 V. However, this requires an increase in the capacity of the battery, and therefore its weight, which will affect the performance of the user of the motorized filter respirator. There is a need to create a suitable algorithm for testing various modes of operation of a motorized filter respirator to establish clear time frames for its operation in diverse production conditions. In this regard, the development of a software model of the operation of a motorized filter respirator allows conducting the necessary experiments to investigate the effect of changing various parameters on the reliability of the IRP. Furthermore, the program allows reducing the time and costs of setting up the system in real operating conditions.

The promising nature of such developments is discussed by S. Sekoguchi *et al.* (2020), S. Sekoguchi *et al.* (2022). Adding a cooler to the blower design requires working out different airflow modes to ensure a suitable level of protection in heated professional environments.

CONCLUSIONS

The structural diagram of the control object was developed and all the structural elements of the blower of the motorized filter respirator were selected, which differs from the existing ones in that it uses a centralized fan for air supply, which has significantly better aerodynamic characteristics in terms of the airflow/pressure ratio, compared to axial ones fans. An experimental sample of the blower of a motorized

filter respirator was developed, considering the functional relationships between the main variables (output adjustable variables, controlling effects and disturbances) and the restrictions imposed on them to ensure the control of the current state of operation and the term of protective action.

The modes of airflow were determined, according to the speed of rotation of the fan blade from the width of the PWM pulses, which depend on the resistance of the filter, the accumulation of dust deposits based on the transfer function. A software model of the blower of a motorized filter respirator was created, which allowed conducting a series of experiments to investigate the influence of dust concentration and changes in airflow through the filter elements on the value of the protective action period. It is proposed to ensure the effective functioning of a motorized filter respirator in the most adverse conditions. For this, it is necessary to use 2 filter elements to ensure a pressure drop level of no more than 370 Pa, a flow of air inhaled by the user of no less than 115 l/min during the entire work shift of six hours. In the perspective of further research, it is planned to work out the ACS mode in combination with a cooling device to reduce body temperature during production activities.

CONFLICT OF INTEREST

None.

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Удосконалення конструкції моторизованого фільтрувального респіратора

Анотація. Умови праці часто не відповідають нормативним вимогам щодо гігієнічних показників, зокрема виявляються порушення щодо наявності шкідливих домішок у повітрі робочої зони. В таких випадках, застосовуються моторизовані фільтрувальні респіратори для захисту органів дихання, які для ефективної роботи потребують розробки відповідної системи управління операційними показниками. Метою статті було удосконалення системи управління моторизованим фільтрувальним респіратором для підвищення захисної ефективності. Для створення відповідної системи управління застосовано структурно-параметричний синтез керування операційними показниками, на основі взаємозв'язків між основними змінними (вихідні

регульовані змінні, керуючі впливу та обурення). Розроблено нову робочу схему об'єкту керування з підібраними конструктивними елементами повітродувки, основною відмінністю якої є використання плати "Arduino Uno R3" модуль "LCD Keypad Shield" з дворядковим дисплеєм для контролю режимів руху повітряного потоку, у відповідності до зміни опору фільтра з урахуванням накопичення пилового осаду на основі припущення, що передаточна функція з достатньою для практики точністю може бути представлена аперіодичною ланкою 1-го порядку. Для відпрацювання режимів роботи та визначення терміну захисної дії створена програмна модель роботи моторизованого фільтрувального респіратора, яка дозволила оцінити вплив концентрації пилу на зміну витрати повітря крізь фільтрувальні елементи з урахуванням накопичення пилового осаду на захисну ефективність. Розроблені рекомендації для забезпечення ефективного функціонування захисного пристрою згідно з вимогами при найбільш несприятливих умовах. Практичне значення полягає в тому, що завдяки удосконаленню системи управління моторизованим фільтрувальним респіратором забезпечується більш комфортний та ефективний захист, зокрема в умовах важких або шкідливих робочих середовищ

Ключові слова: вентилятор; тиск; швидкість обертання; концентрація пилу; повітряний потік; ширина імпульсів

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Screw electromechanical hydrolyser for processing poultry by-products

Abstract. The use of keratin-containing products in various industries, including agriculture, cosmetics, and biomedicine requires solving the urgent problem of improving the methods and means of hydrothermal hydrolysis of keratin waste. The purpose of this study is to examine the screw electromechanical hydrolyser to provide modes of efficient conversion of keratin waste into a useful product with added value. The study is based on the basic principles of electrodynamics, heat and mass transfer, mathematical modelling by the finite element method, and experimental verification of the multiphysical parameters of the electromechanical hydrolyser. The experimental model of the electromechanical hydrolyser was used to determine the optimal conditions for hydrothermal hydrolysis of keratin waste in terms of thermal conditions, raw material transportation, pressure, and magnetic field effects. After undergoing the processing, a bulk of brown feather flour was obtained, which had been hydrolysed and possessed a distinct odour. According to the size of the electromagnetic system of the experimental sample, a mathematical model for observing thermal and electromagnetic processes was built. The patterns of magnetic induction distribution were determined for the cross-section, axial distribution on the screw surface, and the upper faces of the screw winding in an electromechanical hydrolyser. Three-dimensional images of the heating of the screw and the screw electromechanical hydrolyser itself were obtained. By comparing the results of mathematical modelling and empirical studies, the adequacy of the mathematical model was confirmed. The findings of the study can be applied in the field of animal husbandry in the production of feed additives of increased digestibility for feeding agricultural animals and poultry

Keywords: keratin material; feather flour; finite element method; Maxwell's equation; energy saving

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INTRODUCTION

The activities of various industries generate billions of tonnes of keratin waste (Bhari *et al.*, 2021). The accumulation or destruction of this waste leads to an aggravation of the environmental problem. Keratin is a structural protein found in hair, feathers, nails, hooves, and wool. This type of material has a high potential for use in the medical, pharmaceutical, cosmetic, and biotechnology industries (Luo *et al.*, 2016; Arshad *et al.*, 2016). The products of these industries are innovative but, currently, feather flour has a narrow range of practical applications (Nurdiawati *et al.*, 2018), which is mainly due to the complexity of feather processing. Chicken feathers consist of 92% keratin, which makes them a valuable source of minerals, amino acids, and peptides (Bhari *et al.*, 2021). B. Wang *et al.* (2016) noted that keratin is remarkable for its ability to withstand a range of physical and chemical stresses. The processing method used greatly impacts the worth of keratin material. The polypeptide chains' amino acid residue count and their arrangement determine the material's chemical and physical characteristics. Intramolecular and intermolecular disulfide bonds, hydrogen bonds, and crystal structure jointly determine the structural stability of the keratin material (Saha *et al.*, 2019). These properties distinguish keratins from other fibrous proteins, such as myofibrillar and collagen proteins (Saha *et al.*, 2019). The disintegration of disulfide covalent bonds and hydrogen bonds within the material's structure is necessary for the successful extraction of keratin. The main methods of extracting keratin from down and feather waste are hydrothermal, acid, alkaline, and enzymatic hydrolysis.

Through deep acid hydrolysis of feather keratin, all molecular bonds are disrupted, and the resulting mixture contains free amino acids. This process is particularly destructive to tryptophan and partially affects serine and threonine. According to Y. Ji *et al.* (2014), asparagine and glutamine are transformed into aspartic and glutamic acid, and free ammonia creates an ammonium salt. The breakdown of methionine into cysteine and cystine occurs during deep alkaline hydrolysis, which also causes partial racemisation of amino acids and the creation of cyclopeptides. Additionally, alkaline hydrolysis produces ammonia and aldehydes that interact with amino groups. Sinkiewicz *et al.* (2017) documented these phenomena. The study by A.K. Nadda & S. Sharma (2019) showed that severe chemical processing conditions result in the depletion of crucial amino acids, racemisation of amino acids within protein hydrolysates, the creation of cyclopeptides, and a decrease in the biological value of the end product. Therefore, discovering sustainable and ecologically sound methods for recycling keratin waste is vital.

R. Bhari *et al.* (2021) found out that conventional methods of feather hydrolysis require high energy consumption and reduce the amino acid content and amount of pure protein. One of the most effective methods of processing down and feather waste on an industrial scale is the hydrothermal hydrolysis method. Hydrothermal hydrolysis

is a method of processing keratin waste that involves the use of water under high pressure and at high temperatures to destroy the protein structure. As a result of this process, hydrolysates are formed – mixtures of amino acids, peptides, and other organic compounds. Increasingly, the hydrothermal hydrolysis of poultry by-products is performed in screw conversion devices. In the studies (Singha & Muthukumarappan, 2016; Mazlan *et al.*, 2019; Feng, 2019), the use of a screw converter is preferred because of its versatility in processing various kinds of materials, regardless of the pace of the technological process.

The purpose of this study was to examine a screw electromechanical hydrolyser for the efficient conversion of keratin waste into a useful product – protein flour using the hydrothermal hydrolysis method. To achieve this purpose, the following objectives were set: to investigate the optimal conditions for the hydrothermal hydrolysis of keratinous waste – chicken feathers, namely, the multiphysical parameters of the reaction; to analyse the properties of the resulting hydrolysate.

LITERATURE REVIEW

Numerous publications exist that focus on electromechanical converters utilising screwing mechanisms. Studies conducted by P. Singha & K. Muthukumarappan (2016), F. Campuzano *et al.* (2019), and P. Brassard *et al.* (2017) examined the torque of screw-based electromechanical converters. The studies mentioned highlighting the crucial role of torque in determining operating expenses. Therefore, optimizing time-varying hydrolysis procedures, such as screw speed and processing medium temperature, is vital for efficient industrial processing and controlled energy consumption. The impact of hydrolysis parameters on mixing torque was examined using single- and twin-screw electromechanical converters in the works of M. Mazlan *et al.* (2019), P. Singha & K. Muthukumarappan (2016), and C. Feng *et al.* (2019). The parameters studied include the temperature of the processing medium, screw rotation speed, and moisture content of the raw material. Surface response regression models were developed in this study to establish a correlation between system parameters and time-varying parameters. The results indicated that an increase in the processing temperature beyond the recommended levels resulted in a reduction in the viscosity of the raw material, pressure within the processing medium, and specific mechanical energy. Furthermore, M. Mushtuk *et al.* (2020) investigated the issue of high energy costs associated with processing in an electromechanical screw converter. In this study, mathematical modelling was performed and the power and energy parameters of the technical system were determined. X. Shi *et al.* (2019), S. Jalalifar *et al.* (2020), G. Fülöp *et al.* (2021) described vibrations occurring in screw electromechanical converters. These publications analysed the oscillation process of an electromechanical screw transducer with the materials placed within it, constructed an equivalent device circuit, determined

the differential equations of system oscillation, and obtained their analytical solution using numerical methods.

Among the existing publications, there are many papers devoted to thermal processes occurring in screw converter devices. F. Campuzano *et al.* (2019) investigated the effects of heat transfer on the processing material. It was established that the heat transfer effect in a twin-screw converter is better than in a single-screw converter. Insufficient attention has been paid to the influence of the screw blade geometry on the output and quality of raw material processing. F. Qi & M.M. Wright (2020) performed mathematical modelling of the processes of hydrodynamics, heat transfer, and chemical reactions of particles in a twin-screw converter. The publication used the method of discrete elements to build a mathematical model. It was found that biomass processing in a twin-screw mechanism is considerably affected by the heat of the reaction parameters in the kinetic model. The disadvantages of the proposed model include the complexity of its use, which is associated with the need for careful calibration of the heat of reaction parameters to improve the kinetic model. A. Funke *et al.* (2018) observed the inefficiency of the screw converter in the initial mixing area, which leads to uneven heat transfer under suboptimal conditions. A mathematical model was constructed to eliminate these inefficiencies and, accordingly, increase the initial average heat transfer coefficient compared to the original design of the screw converter. E. Aliiev *et al.* (2022) explored the influence of design and technological parameters of the equipment on the productivity and technical and economic efficiency of the feed preparation line. The publication presented analytical calculation methods that accounted for the geometry of the ripper auger, incorporated mechanisms of solid movement and

destruction, utilised the discrete element method to describe the solid component movement, improved the physical and mathematical understanding of solid component movement in the screw channel, and developed a numerical modelling approach.

MATERIALS AND METHODS

The screw electromechanical hydrolyser is a simplified implementation of the twin-screw electromechanical hydrolyser presented by (Zablodskiy *et al.*, 2021a; Zablodsky *et al.*, 2021b). The screw electromechanical hydrolyser consists of a feedstock loading unit, a screw, a deaerator for air removal, an outer shell of the working medium, a heating and magnetic field effect unit, a feedstock unloading unit, a metal profile structure, an electric drive, and a vacuum pump. The outer shell of the working chamber is made of aluminum pipe.

In this hydrolyser, the loaded feather raw material passes through two impact zones. In the first working area of the screw, the feathers are preheated to 60°C and exposed to a magnetic field with a frequency of 1-50 Hz and an induction of 0.025 T. The raw material in the first working zone is compacted to form a raw material seal (plug) by reducing the auger cross-section shown in Figure 1. At a compaction pressure of 1-20 MPa, the raw material is fed into the second working zone, where it is loosened by a reduced diameter part of the screw turns, moved at a temperature of 180-260°C, exposed to a magnetic field with a frequency of 1-50 Hz with an induction of 0.065 T for 110 s, and vacuum is applied at the outlet of the second working zone every 10-60 s. For the installation of the vacuum pump, the HS-115 R-134 HongSen charging hose, HS-466NAH valve manifold, the universal hose for charging freon, and the Universal crane were used.



Figure 1. The screw of an electromechanical hydrolyser

Source: developed by the authors

The following measuring devices were used during the empirical studies: Analog spring universal dynamometer NK-300, designed to measure screw forces and torque, accuracy class 0.5%; Tenmars TM-191 Magnetic Field Meter, designed to measure ultra-low frequency electromagnetic fields from 30 Hz to 300 Hz; Tenmars TM-190 Multi Field EMF Meter, a compact device for measuring high-frequency electromagnetic fields in the frequency range from 50 MHz to 3.5 GHz and low-frequency electric and magnetic fields in the frequency range of 50-60 Hz; infrared, optical pyrometer BENETECH GM533A, measuring range – 50-530°C, visibility index 12:1, thermal radiation coefficient 0.1-1, spectrum 5-14 microns. The magnetic

field is applied using two single-phase stators with starting capacitors of 720 W each – HCSE 0.5-40U (Fig. 2).

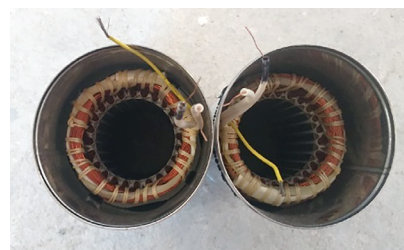


Figure 2. HCSE 0,5-40U, 720 W single-phase stators

Source: developed by the authors

The raw material is preheated to 60°C in the first working area using a self-regulating heating cable SRF 30-2CR with a power of 30 W/m and a length of 1 m. The main heating of the raw material to a temperature of 180-260°C is achieved using a heating device EHKM 52×200, 1.2 kW, 230 V – a micanite ring with a heating temperature of up to 350°C. The temperature control and regulation in the raw material compaction zones, ranging from 180 to 260°C, are accomplished using a TENSE DT-36E digital thermostat equipped with a J-type thermocouple.

The experimental sample of the screw electromechanical hydrolyser is shown in Figure 3. The examination of thermal properties was conducted indoors with an ambient temperature of 24°C. The temperature was measured with an infrared, optical pyrometer BENETECH GM533A at a distance of 0.5 m from the object of study. The heat sources were connected to the network in turn, and before the next measurement, a time delay was performed to cool the object of study to ambient temperature.



Figure 3. Screw electromechanical hydrolyser

Source: developed by the authors

To understand in detail the full picture of the temperature and magnetic fields in the screw electromechanical hydrolyser, a finite element simulation was performed in the Comsol Multiphysics software environment. The electromagnetic field is analysed based on Maxwell's system of equations. The vector potential was formulated according to the following equations (1)-(4) (Zablodsky et al., 2021b):

$$\nabla \times H = J, \quad (1)$$

where H – is the magnetic field strength vector, A/m; J – is the current density vector, A/m².

$$B = \nabla \times A, \quad (2)$$

where B – is the magnetic field density vector, T; A – is the vector magnetic potential, Wb/m.

$$E = -\frac{\partial A}{\partial t}, \quad (3)$$

where E – is the electric field intensity vector, V/m.

$$J = \sigma E, \quad (4)$$

where σ – is the electrical conductivity, S/m.

The equation of the scalar potential is (Zablodsky et al., 2021b):

$$\nabla \cdot B = 0. \quad (5)$$

Magnetic isolation as a separate type of magnetic potential boundary condition equates the tangential component of the magnetic potential to zero (Zablodsky et al., 2021b):

$$n \cdot B = 0. \quad (6)$$

The B-H curve describes the magnetisation of the rotor and is determined from the equation (Zablodsky et al., 2021b):

$$B = f(|H|) \frac{H}{|H|}. \quad (7)$$

Homogenised multi-turn coils are used as a boundary condition, a current source simulating a bundle of wires wound together and separated by insulation (Zablodsky et al., 2021b):

$$J_e = \frac{NI_{coil}}{A} e_{coil}, \quad (8)$$

where N – is the number of turns in the winding; A – is the total cross-section, the area of the winding domain, m²; I_{coil} – is the current, A; e_{coil} – is a vector variable for visualising the direction of turns in the winding.

The heating model of the screw electromechanical hydrolyser is developed by combining principles from magnetic field physics, solid heat transfer, and electromagnetic heating. The model is solved within the frequency-transition domain of the study. The heat transfer equation is formulated based on Fourier's law in differential form and incorporates an additional term for the heat source (Zablodskiy et al., 2021a):

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p u \cdot \nabla T + \nabla \cdot q = d_z Q + q_0 + d_z Q_{ted}, \quad (9)$$

where d_z – is the thickness of the domain in the nonplanar direction, m; ρ – is the density, kg/m³; C_p – is the specific heat capacity at constant pressure, J/(kg·K); T – is the temperature, K; t – is the time, s; u – is the velocity vector, m/s; q – is the heat flux, W/m²; Q – is the heat source, W/m³; q_0 – is the internal heat flux, W/m²; Q_{ted} – is the thermoelastic damping, W/m³.

$$q = -d_z k \nabla T, \quad (10)$$

where k – is the thermal conductivity, W/(m·K).

Thermal insulation is applied to the outer borders of the model (Zablodskiy et al., 2021a):

$$-n \cdot q = 0, \quad (11)$$

where n – is the refractive index.

The heat flux from the surfaces is determined from the equation (Zablodskiy et al., 2021a):

$$-n \cdot q = d_z q_0, \quad (12)$$

$$q_0 = h(T_{ext} - T), \quad (13)$$

where h – is the heat transfer coefficient, W/(m²·K); T_{ext} – is the outdoor temperature, K.

The radiation from the model surface to the environment is determined from the equation (Zablodskiy *et al.*, 2021a):

$$-n \cdot q = d_z \varepsilon \sigma (T_{amb}^4 - T^4), \quad (14)$$

where ε – is the surface emissivity; σ – is the Stefan-Boltzmann constant, W/(m²·K⁴); T_{amb} – is the ambient temperature, K.

Electromagnetic heating is determined from equations (Zablodskiy *et al.*, 2021a):

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_e, \quad (15)$$

where Q_e – is the electromagnetic heat source, W/m³.

$$Q_e = Q_{rh} + Q_{ml}, \quad (16)$$

where Q_{rh} – is the resistive loss, W/m²; Q_{ml} – is the magnetic loss, W/m².

$$Q_{rh} = \frac{1}{2} Re(J \cdot E^*), \quad (17)$$

$$Q_{ml} = \frac{1}{2} Re(i\omega B \cdot H^*), \quad (8)$$

where Re – is the Reynolds number; E^* – is the vector of electric field intensity at a given frequency and time, V/m; H^* – is the vector of magnetic field intensity at a given frequency and time, A/m.

RESULTS AND DISCUSSION

The results of the study show that the temperature increase is linear. An electric micanite ring heater EHKm 52×200, 1.2 kW, 230 V, reached the process temperature in 2 minutes, after which the temperature was maintained at the set upper limit of 250°C using a TENSE DT-36E digital thermostat. The SRF 30-2CR heating cable reached a temperature of 85°C in 15 minutes. The HCSE 0,5-40U, 720 W stators reached a temperature of 90°C in 15 minutes.

Mathematical modelling of the processes within the screw electromechanical hydrolyser was conducted to facilitate comparisons with the results obtained from experimental studies. The finite element mesh was created as a physics-controlled mesh. The grid parameters are shown in Table 1. The modelling was performed under the assumption that the main components of the screw electrical hydrolyser, namely, the SRF 30-2CR heating cable, the EHKm 52×200 micanite ring, and the HCSE 0.5-40u single-phase stators, operate at the rated load without additional adjustment. The modeling results are presented in Figures 4-8.

Table 1. Finite element mesh parameters

Grid parameters	Value
Mesh vertices	523509
Tetrahedra	3007747
Prisms	36784
Hexahedra	3072
Triangles	453692
Quads	4288
Edge elements	47708
Vertex elements	1622
Number of elements	3047603
Minimum element quality	0.07147
Average element quality	0.6584
Element volume ratio	1.464E-6
Mesh volume	4.986E7 mm ³

Source: developed by the authors

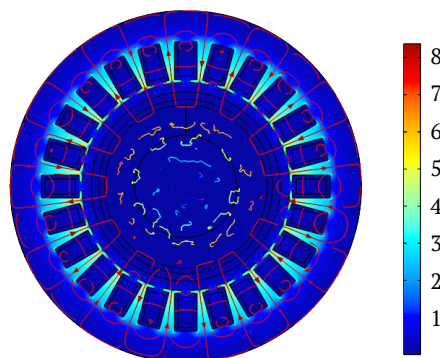


Figure 4. Spatial representation of the magnetic induction distribution for the cross-section of the screw electromagnetic hydrolyser geometry, t

Source: developed by the authors

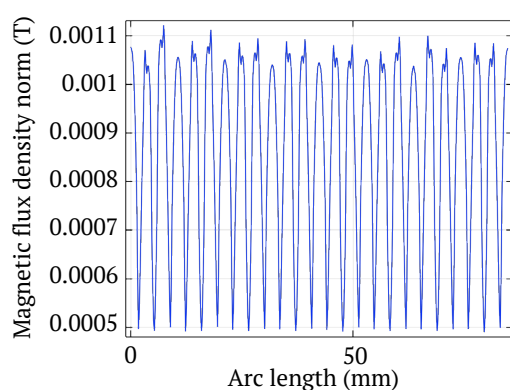


Figure 5. Graph of the distribution of magnetic induction on the surface of the screw of an electrochemical hydrolyser, t

Source: developed by the authors

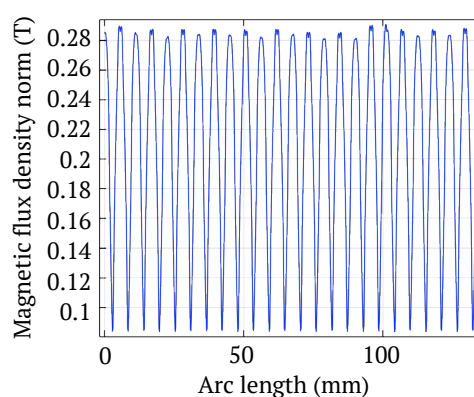


Figure 6. Graph of the distribution of magnetic induction along the upper face of the screw blades of the screw mechanical hydrolyser, t

Source: developed by the authors

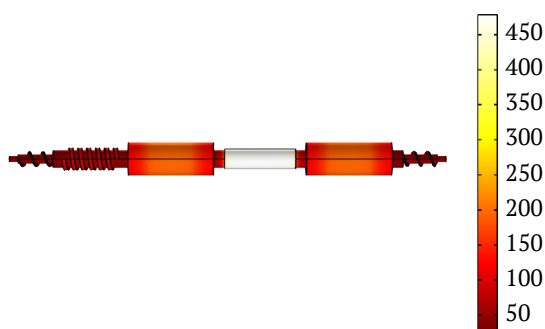


Figure 7. Three-dimensional image of heating of the screw electromechanical hydrolyser, side view, °C

Source: developed by the authors

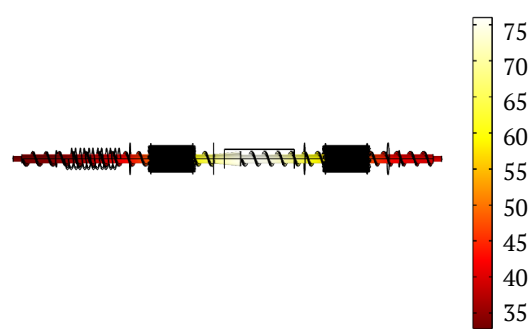


Figure 8. Three-dimensional image of the heating of the screw of an electromechanical hydrolyser, °C

Source: developed by the authors

Based on empirical studies and the results of mathematical modelling of the screw electromechanical hydrolyser, the processing of chicken feathers according to the method of hydrothermal hydrolysis was analysed. The working areas of the screw electromechanical hydrolyser were preheated for 20 minutes. For this purpose, the self-regulating heating cable SRF 30-2CR was connected directly to the 220 V network, and the single-phase stators

of the HCSE 0,5-40U were connected to the 220 V network using CBB60-G 25 μ F capacitors. The electric micanite ring heater EHKМ 52×200 was connected to a 220 V network using a TENSE DT-36E digital thermostat. The maximum temperature value was set at 220°C, the temperature was controlled by a J-type thermocouple. Upon completion of the preheating of the working chambers, the shredded chicken feathers were fed in small, loosened portions, 163400 mm³

(6.25 g), to the raw material loading unit until the first working area was filled. By investigating the movement of chicken feathers in the working area of a mock-up sample of an electromechanical screw hydrolyser using a borosilicate glass pipe as the outer shell of the working area, it was found that the feathers travel from the raw material loading unit to the sealing cylinder in 300 revolutions. The volume of the first working area was 158300 mm³. The initial working zone is filled with feather raw materials through the compaction caused by the mechanical motion of the screw and the weight of the material, involving the loading of 12 small portions of fluffed feathers, totalling 75 g. The compacted feather raw material is transferred to the second working zone under a pressure of 1–20 MPa, where it is exposed to a magnetic field with a frequency of 1–50 Hz and an induction of 0.065 T for 110 seconds at a temperature of 180–260°C. Figure 8 shows the effect of induction heating on the auger of the prototype of the screw electromechanical hydrolyser, which, when acting simultaneously with other heating equipment, creates conditions for comprehensive heating of the processing raw material – chicken feathers in the processing environment.

Further, the keratin raw material is loosened and continues to move to the raw material unloading unit and is exposed to vacuum pulses every 60 seconds using a Leeto XZ-1A vacuum pump. Using a prototype of an electromechanical screw hydrolyser with the dimensions and characteristics described in this paper, 1.17 kWh of electrical energy was consumed to produce 8500 mm³ (642 g) of hydrolysed feather meal. The results of empirical studies and mathematical modelling of the electromagnetic system of a screw electromechanical hydrolyser are close to those obtained during the study of the electromagnetic system of a twin-screw electromechanical hydrolyser (Zablodskiy *et al.*, 2021a; Zablodsky *et al.*, 2021b). As a result of processing, a brownish, loose, hydrolysed feather meal with a specific odour was obtained. Figure 9 shows a sample of hydrolysed feather meal.



Figure 9. Hydrolysed feather meal

Source: developed by the authors

The use of the influence of an electromagnetic field is one of the trends in the search for ways to increase the efficiency of processing keratin-containing raw materials and breaking disulfide bonds. Y.S. Lee *et al.* (2016) proposed

a complex hydrothermal and microwave treatment using sodium hydroxide, which substantially reduces feather hydrolysis. Yet the applicability of this method is limited by high cost and significant energy consumption. Microwave alkaline treatment at a frequency of 2450 MHz and power level of 800 W consumes more than 66.5 kWh per kg of raw material, which is considerably higher than the consumption (1.3 kWh/kg) recorded for the experimental sample of the screw electromechanical hydrolyser. When comparing the energy costs with the findings of the study conducted by Vavrova *et al.* (2022), it is important to highlight that modifications to the method of hydrothermal hydrolysis of bird feathers using electricity were analysed. The energy consumption for electric heating of the reactor during hydrolysis using malic acid amounted to 1.6 kWh/kg.

Currently, the experimental sample of the screw electromechanical hydrolyser is not yet completely developed in terms of thermal insulation. The addition of a protective housing with the necessary thermal insulation layer should substantially reduce heat radiation to the environment. This can increase the efficiency of the device by up to 95%. In this regard, the ratio of energy consumption to the weight of processed chicken feathers can be reduced for an industrial model of an electromechanical screw hydrolyser.

It is worth noting an important aspect of the proposed method and means, namely the strategy of successive changes in the physical properties of keratin-containing raw materials before hydrothermal hydrolysis. The proposed design has unique properties in terms of the effect on keratin-containing raw materials. In the sealing cavity of the working part of the screw unit, the down and feather raw material is compacted 8–10 times, heated at a pressure of 0.5–5.0 MPa to a temperature of 60°C, and exposed to a gradient magnetic field with a frequency of 1–50 Hz and an induction of up to 0.025 T to inhibit the process of moisture evaporation. Moreover, the down and feather raw materials are deaerated in the sealing cavity using a deaeration chamber, where high magnetic intensity is created to suck in paramagnetic oxygen, thus, in the sealing cavity of the working area of the screw unit, voids are removed from the down and feather mixture as much as possible, in which water can be converted into steam and further, due to the removal of oxygen, the quality of the resulting product is impacted due to oxidation. The sequential hydrolysis strategy was also incorporated by N.D.A. Pedrosa *et al.* (2022) using three reactors. The disadvantage of this technology is the use of alkaline dissolution, a long process duration (more than 10.5 hours), and significant energy consumption of 4.0 kWh/kg.

N. Zablodskiy *et al.* (2021a), N. Zablodsky *et al.* (2021b) investigated a twin-screw electromechanical hydrolyser for processing poultry by-products. Such a hydrolyser is based on the principles of using the dissipative energy component and integrating the functional features of the technological process in one device. N. Zablodskiy *et al.* (2021a), N. Zablodsky *et al.* (2021b) conducted several studies on electromagnetic, electromechanical, thermal, vibration,

and some other processes that occur in this kind of device. The screw electromechanical hydrolyser presented in this paper is characterised by a simple design compared to the twin-screw hydrolyser: it is easy and quick to disassemble, which substantially speeds up the maintenance process. Despite the simplicity of the design, the screw electromechanical hydrolyser can provide identical hydrothermal hydrolysis parameters as the twin-screw hydrolyser but is inferior in energy efficiency and the ability to narrowly control the hydrolysis parameters.

CONCLUSIONS

According to the results of the examination of thermal characteristics, the screw electromechanical hydrolyser is capable of providing the necessary thermal conditions for the hydrothermal hydrolysis of poultry by-products. The level of the oscillating electromagnetic field is sufficient to exert a magnetic field effect on the raw material for processing – chicken feathers. The results of the mathematical modelling of the thermal characteristics correspond to the data obtained during empirical studies of a prototype of a screw electromechanical hydrolyser, so this mathematical model can be considered adequate.

The use of a magnetic field source and induction heating in conjunction with other heating equipment creates conditions for a comprehensive impact on the raw material and expands the ability to control the hydrolysis process to apply the optimal mode depending on the properties

of the feedstock and the quality requirements of the final product. The proposed method and means of processing keratin-containing raw materials are focused on the use of environmentally friendly energy for conversion into value-added products. The ratio of energy consumption to the weight of processed chicken feathers at the level of 1.3 kWh/kg makes this method attractive for investment.

The scientific and technical originality of this study lies in the application of an electromagnetic field source to induce a magnetic field effect on keratin-based raw materials, the utilisation of the dissipative energy component, and the implementation of induction heating in the screw of the electromechanical hydrolyser. Simultaneous operation with other heating devices enables comprehensive heating of the processed raw materials.

The results obtained can be used in further studies on the development of structures and control systems for industrial models of an electromechanical screw hydrolyser. In addition, the findings present promising opportunities for future investigations into the physicochemical analysis of the final product, feather meal, to determine in detail the impact of the magnetic field on the raw material.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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None.

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**Шнековий електромеханічний гідролізер
для переробки побічних продуктів птахівництва**

Анотація. Використання продуктів переробки кератин-вмісних речовин в різних галузях, включаючи, зокрема, сільське господарство, косметику та біомедицину, потребує вирішення актуальної задачі удосконалення способів і засобів гідротермічного гідролізу кератинових відходів. Метою даної роботи було дослідження шнекового електромеханічного гідролізера для забезпечення режимів ефективного перетворення кератинових відходів у корисний продукт з доданою вартістю. Дослідження ґрунтуються на основних положеннях електродинаміки, тепломасообміну, математичного моделювання методом скінченних елементів і експериментальній перевірці мультифізичних параметрів електромеханічного гідролізера. На експериментальному зразку електромеханічного гідролізера здійснено визначення оптимальних умов гідротермічного гідролізу кератинових відходів щодо забезпечення теплового режиму, транспортування сировини, тиску та впливу магнітного поля. Як результат переробки було отримано сипуче, гідролізоване пір'яне борошно коричневого кольору, що володіє специфічним запахом. Згідно розмірів електромагнітної системи експериментального зразка побудована математична модель для досліджень теплових і електромагнітних процесів. Визначено закономірності просторового розподілу магнітної індукції для поперечного перерізу, осевого розподілу на поверхні шнеку та верхніх гранях шнекової навівки електромеханічного гідролізера. Отримані тривимірні зображення нагріву шнеку та безпосередньо самого шнекового електромеханічного гідролізера. Порівнянням результатів математичного моделювання та емпіричних досліджень підтверджена адекватність математичної моделі. Результати дослідження можуть знайти застосування в галузі тваринництва при виготовленні кормових добавок підвищеної засвоюваності на потреби годівлі сільськогосподарських тварин та птиці

Ключові слова: кератинова сировина; пір'яне борошно; кінцево-елементний метод; рівняння Максвелла; енергозбереження

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**Agent-based simulation model
of multimodal iron ore concentrate transportation**

Abstract. Most global supply chains are implemented through the use of different types of transport. This especially applies to general cargo: iron ore, oil, grain. As the number of participants in the transport process grows, the risks of delays, disruptions which can impact interoperability, and delays in deliveries increase. Therefore, the improvement of multimodal cargo transportation remains an urgent scientific and applied problem. The purpose of the study is to cover the technical and operational parameters of the multimodal supply chain of cargo delivery (on the example of iron ore concentrate). The purpose was achieved by the development of an agent-based simulation model. The AnyLogic Research Edition environment with Java SE was used to implement the simulation model, as it enables the integration of discrete-event and agent-based methodologies in the simulation concurrently. The experimental findings using the developed simulation model revealed the following: 1) around 40% of the delivery time is spent on waiting: 8% for the transport unit to load and 33% for the collection of freight until it reaches the loading rate into the transport unit. 2) the sensitivity

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experiment conducted on the model identified that among all the variable technological parameters in the base model, the difference in the loading rate between the railway train and the sea vessel has the most impact on the average delivery time of freight. 3) there is a strong linear relationship between the vessel capacity (with a constant rate of mass shipment into the railway train) and the average time required for collecting and loading the freight onto the vessel in the event of accidental arrival of freight by rail at the transshipment terminal. The results of the study can be used to improve the logistics chains for the delivery of iron ore concentrate from Ukraine to other countries

Keywords: technological system; optimisation of terminals; Java-code; rail-sea supply chain, system analysis

INTRODUCTION

Globalisation considerably expands the economic and financial capabilities of producers and consumers and leads to an increase in the number of participants in the transportation process. These factors have a detrimental effect on the efficiency of transport production: firstly, unproductive delays occur at transshipment points due to the necessity of collecting shipments for loading onto transport units; secondly, conflicts arise within the transport system due to the technological differences between various transportation modes involved in the multimodal supply chain.

Maritime transport remains the backbone of globalised trade and the manufacturing supply chain. According to the Review of Maritime Transport (UNCTAD, 2022), four-fifths volume of the world merchandise trade is carried by sea. Total volumes grow continually and reached 11 billion tonnes in 2022. Dry bulk commodities contributed considerably to this growth. In 2022, ships spent a median time of 24.2 hours in port. Dry bulk carriers spent 2.11 days in port. Inland distribution, such as railway link, is a vital factor in the performance of global maritime transportation. Given this, the search for optimal parameters in multimodal transportation to minimise delivery time is an urgent scientific and applied task of today. N.Y. Shramenko & O.V. Shramenko (2018) proposed a model for the delivery of bulk cargo by rail transport considering the principles of logistics and system analysis. The optimised technological parameters related to the operation of the whole production and transport chain were justified: the size of the freight shipment, the technical equipment of the freight fronts, and the delivery interval. However, the current model lacks the capability to simulate different scenarios for organising transmitting trains in a transportation junction, specifically for collection up to the required standard, following a strict schedule, and employing a combined approach.

X. Fang *et al.* (2020) proposed to solve multimodal transportations planning problem of inter-organisational coordination by developing an evaluation model of the synergy degree index of container sea-rail transportation actors based on synergy theory. The model enables to produce recommendations to logistics service providers on how to improve their activities to contribute to multimodal transport synergy. The model does not directly address the stochastic nature of multimodal transportation nor give a numerical assessment of its parameters. The competitive advantage of distant hinterland ports is general costs and quality of service. A pricing model, utilising game theory,

was proposed by C. Qu *et al.* (2020) to determine the initial equilibrium state of competition among seaports. The proposed model has some limitations because of various business contexts and regulations applied in different countries.

B. Yan *et al.* (2020) addressed the transshipment operation problem through a rolling horizon-based modelling approach that considered the direct transshipment number, storage time, and dwell time of inbound containers. The proposed solution contributes to the minimisation of delivery time in the supply chain but leads to an increase in port service time of trains and supply chain costs. T. Lelke *et al.* (2023) proposed to build the agent-based model using open-source transport statistics. The approach can be applied to different areas and regions of transport services. The study is focused on modelling individual mobility and traffic in the city. combined the agent-based and discrete-event approaches in a simulation model to investigate a two-stage optimisation of intermodal terminal parameters, specifically focusing on the operation of handling equipment and rolling stock (Muravev *et al.*, 2021). The optimisation process aims to minimise container handling costs, which serves as the objective function in this study.

To conclude, modern studies are devoted to solving specific issues of multimodal transport such as operations management, planning, and site location. Besides, they cannot adequately reflect the delivery process in the “rail – sea – rail” system, i.e., from the point of departure to the point of destination, considering the minimum transportation time. The purpose of the study is to analyse the technical and operational parameters of a multimodal supply chain involving a mixed rail-waterborne link for bulk cargo delivery to identify optimal solutions based on the criterion of minimising the delivery time. To address this scientific and practical problem, the proposed approach involves the following steps: developing an agent-based simulation model that represents the transport-technological line of the multimodal railway-waterborne link within the supply chain; conducting experiments using the simulation model to determine the technical and operational parameters that have the most impact on the average delivery time of freight.

MATERIALS AND METHODS

The study considered the rail-sea-rail freight process line, which is a technological system with three interconnected technological elements: the first railway line, the sea line, and the second railway line.

The entire process of freight transportation can be divided into two subsets: the sub-process of freight collection

until the required shipment is attained and the sub-process of transporting the corresponding shipment (Fig. 1).

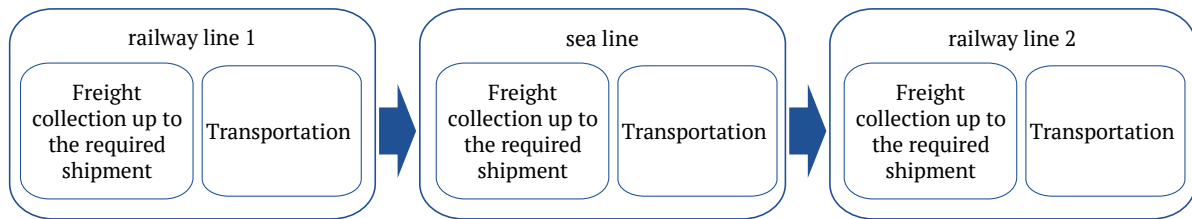


Figure 1. Structural and logical scheme of the simulation model

Source: developed by the authors

The functioning of the third type of agent (Fig. 1) represents the set of sub-processes for both collecting (including the formation of the information order of

readiness for shipment dispatch by Agent 2, Table 1) and transportation (involving the operation of the rolling stock by Agent 4, Table 1).

Table 1. Set of simulation model agents

No.	Agent name	Agent function	Simulation - correspondence to the real process
1	The flow of shipment orders	Interaction with other agents as a unit of commodity mass (freight). Fixation of the moment of tracking of a freight shipment of each control point of the simulation	Simulation of advancement of freight through a supply chain, incorporating elements of collecting the freight up to the required level for transportation by a specific mode of transport
2	Information order for a shipment dispatching	Formation of the order for service by the agent of freight transportation	Simulation of the formation of a ready-to-ship consignment by a transport unit – a train or a ship
3	The transport system of a certain type of transport mode (rail or sea) – supply chain	Organization of the transportation process at a certain stage of the supply chain	Simulation of transport production, including freight collection, freight production operations, and freight transportation.
4	Transport unit	Interaction with an information order and a specific transport system	Simulation of transporting a shipment at a certain stage of the supply chain. These sets of agents simulate the direct freight delivery by trains and ships

Source: developed by the authors

The total delivery time of a freight unit is determined by the combined duration of its stay at the collecting point and the transit time during direct transportation:

$$t_{del} = t_{collect.rail1} + t_{tr.rail1} + t_{collect.sea} + t_{tr.sea} + t_{collect.rail2} + t_{tr.rail2}, \quad (1)$$

Where $t_{collect.rail1}$, $t_{collect.sea}$, $t_{collect.rail2}$ – delay time at the freight collecting point to the required shipment and waiting time for the train, respectively, on railway line 1, sea line and railway line 2; $t_{tr.rail1}$, $t_{tr.rail2}$ – shipping time of freight by trains on railway line 1 and railway line 2, respectively; $t_{tr.sea}$ – shipping time of freight by ships on sea line.

One of the crucial aspects of optimising the organisation of a multimodal supply chain, considering the cost of shipment, is the minimisation of the average freight delivery time which, obviously, with constant technical parameters of rolling stock (average speed, capacity and other physical and technical parameters) can be achieved by reducing the time of freight collection up to the

required shipment and the waiting time of the freight to be shipped by a train:

$$\overline{t_{del}} \rightarrow \min,$$

where $\overline{t_{del}}$ – average time of cargo delivery, provided:

$$\sum t_{collect} \rightarrow \min,$$

where $\sum t_{collect}$ – the total time of the freight collection up to the required volume (at the point of departure and re-loading).

In turn, the waiting time for train when dispatching completed shipments decreased with the growth of the rolling stock:

$$\overline{t_{del}} \rightarrow \min,$$

provided:

$$\begin{cases} Z \rightarrow \max, \\ M \rightarrow \max, \end{cases} \quad (2)$$

where Z – fleet of railway rolling stock, trains; M – fleet of water transport vessels (bulk carriers).

On the other hand, increasing the fleet of trains and bulk carriers, while keeping all other factors constant, leads to an increase in the downtime of the rolling stock as it waits for transport orders. Additionally, the loading of the rolling stock is reduced. However, in this context, these changes can be interpreted as improvements in efficiency. The expression (2) was formulated as follows:

$$\sum t_{collect} \rightarrow \min,$$

provided

$$\begin{cases} \frac{\sum t_{inv.rail1}}{24} \rightarrow \min, \\ \frac{\sum t_{inv.rail2}}{24} \rightarrow \min, \\ \frac{\sum t_{inv.vessels}}{24} \rightarrow \min. \end{cases} \quad (3)$$

where $\sum t_{inv.rail1}$, $\sum t_{inv.rail2}$, $\sum t_{inv.vessels}$ – the average daily time of engagement for a unit of rolling stock in railways and water transport, respectively.

Minimisation of loading was achieved by increasing the operational fleet of rolling stock, which is economically inefficient. Hence, the utilisation limit of rolling stock was constrained to a rational limit of 0.5. Formally, the task of finding a rational way of transport production

in a multimodal supply chain was to find a solution to the objective function:

$$\overline{t_{del}} = f(Z, M) \rightarrow \min$$

Provided:

$$\begin{cases} \frac{\sum t_{inv.rail1}}{24} \geq 0,5; \\ \frac{\sum t_{inv.rail2}}{24} \geq 0,5; \\ \frac{\sum t_{inv.vessels}}{24} \geq 0,5. \end{cases} \quad (4)$$

Other limitations and assumptions of simulation also included:

1. the incoming freight flow to the first collection point is the simplest distribution, which follows a Poisson process;

2. the configuration of the infrastructure of railway and sea (port) transport systems is rational and does not considerably affect the time delay in receiving and dispatching trains and vessels;

3. when selecting a server, service channel or service order, the FIFO principle is used (first in – first out) – the server, channel or order being in the longest waiting state is selected;

4. the flow of transportation is one-way: the rolling stock moves in the loaded state in one direction, in the opposite – it is empty.

In this study, the simulation-based approach was employed to analyse the multimodal supply chain of iron ore concentrate (pellets) between Poltava Mining and Processing Plant in Ukraine and Krupp in Germany during 2018-2020, Table 2.

Table 2. Initial parameters of the multimodal supply chain of iron ore concentrate from Ukraine to the EU (Germany)

No.	Parameter	Value
1	Annual volume of shipment, thousands of tonnes	500
2	Railway station of departure in Ukraine	Zolotonneishyne
3	Port of departure (Ukraine)	Southern
4	Port of destination	Amsterdam (Netherlands)
5	Railway station of destination in Germany	Essen
6	Parameters of the railway transport system of Ukraine	
7	Number of cars in the train	56
8	Net weight	3920
9	Parameters of the sea transport systems	
10	Volume of commercial freight of the vessel, thousand tonnes	172.1
11	Parameters of the railway transport system Amsterdam – Essen	
12	Number of cars in the train	45
13	Net weight tonnes	2700
Approximate intensity of freight operations, tonnes per minute:		
14	loading of cars	10
	unloading of cars	20
	loading of the vessel	50
	unloading of the vessel	50
15	Approximate intensity	

Source: developed by the authors

Standard statistical methods provided by the “Statistics” library were employed to collect the necessary statistics. The list of the main agents of the model and their functionality were summarised in Table 1. The simulation model was developed using the AnyLogic Research Edition environment with Java SE because it enabled the integration of discrete-event and agent-based approaches, allowing for their simultaneous use in the simulation.

RESULTS AND DISCUSSION

To simulate dynamic transportation processes and capture the state changes of system elements within each individual agent, process modelling libraries for discrete-event simulation are employed. These libraries enable the modelling of various stages such as train arrival for loading, loading, transportation to the unloading point, unloading, return empty run, and all inter-operational downtime (Fig. 2).

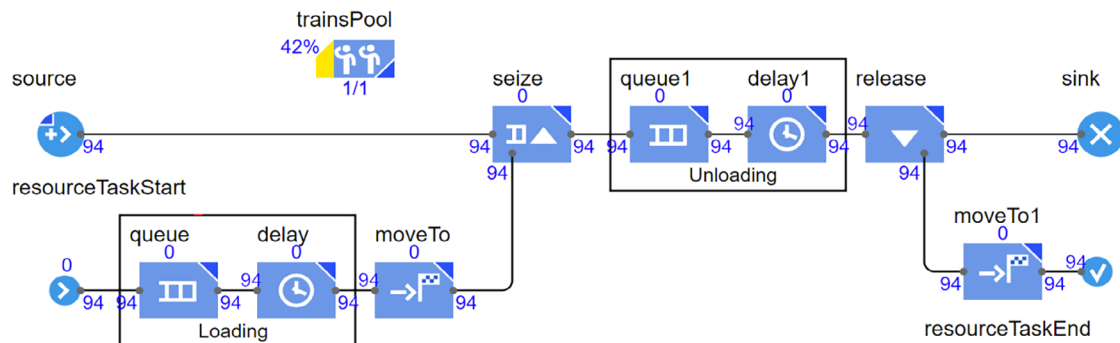


Figure 2. Discrete-event business process of railway line 1 operation (agent railLineOne)

Source: developed by the authors

A new information order is formed as a result of the incoming of the required shipment in the source block.

Further, discretely, the order discretely enters the seize block, where the system captures a free resource (if available) for transportation, specifically, the formed train from the existing fleet, stored within the trainsPool block. In the absence of free resources, the order for transportation is waiting for the released train ready to depart. After capturing the resource (train), it is loaded (queue block – queue formation due to the limited channel of the loading point, and delay block – discrete delay of the train and information order at loading).

Afterwards, the loaded train is simulated to move to the unloading point using the moveTo block. Once again, similar to the loading process, the unloading is discretely simulated within the queue1 and delay1 blocks.

After unloading, the resource (train) is released from the service of the information order (block release) and the block moveTo1 is discretely returned to the block trainsPool. The information order itself is eliminated in the sink block.

According to this principle, the business processes of all three transport and technological subsystems are simulated: railway line 1, sea line, and railway line 2.

The overall interaction among all agents is facilitated by the Main agent, which simulates the comprehensive multimodal process of the freight supply chain starting from the point of freight collection to the final destination terminal of these products (Fig. 3).

The sourceCargoFlow block generates a shipment orders flow, which corresponds to the incoming of finished products at the warehouse of the manufacturer. Each generated order corresponds to one tonne of ready-to-ship

iron ore concentrate and is generated according to the principle of the Poisson distribution.

The process of collecting orders up to the required volume is simulated in the blocks D_railLineOne, D_seaLine, and D_railLineTwo. These blocks replicate the process of gathering the necessary freight volume to match the loading rate of railway line 1, the sea vessel of sea line 1, and the railway fleet of railway line 2, respectively.

The process of collecting a shipment and forming an information order up to the train's departure is performed by Java-code in each corresponding block type Delay (Fig. 3):

```
«waitForTrainCapOne++;
if (waitForTrainCapOne>= trainCapacity){
    waitForTrainCapOne -= trainCapacity;
    railLineOne.source.inject(1);}»;
```

where waitForTrainCapOne is a variable that indicates the available amount of freight ready to form an information order; trainCapacity – rate of loading of a railway rolling stock.

The logic behind this process is that when collecting freight up to the required shipment level, a new information order is generated for transportation by a specific train, represented by the agent railLineOne (Fig. 2).

Once the train arrives at the unloading point and completes the unloading process (in the delay1 block), a Java code is executed, which «skips» the corresponding number of tonnes-orders of freight to the next blocks (D_seaLine and D_railLineTwo) within the main agent:

```
«for (int i = 0; i <main.trainCapacity; i ++){
    main.D_railLineOne.stopDelay
    (main.D_railLineOne.get(i));}»;
```

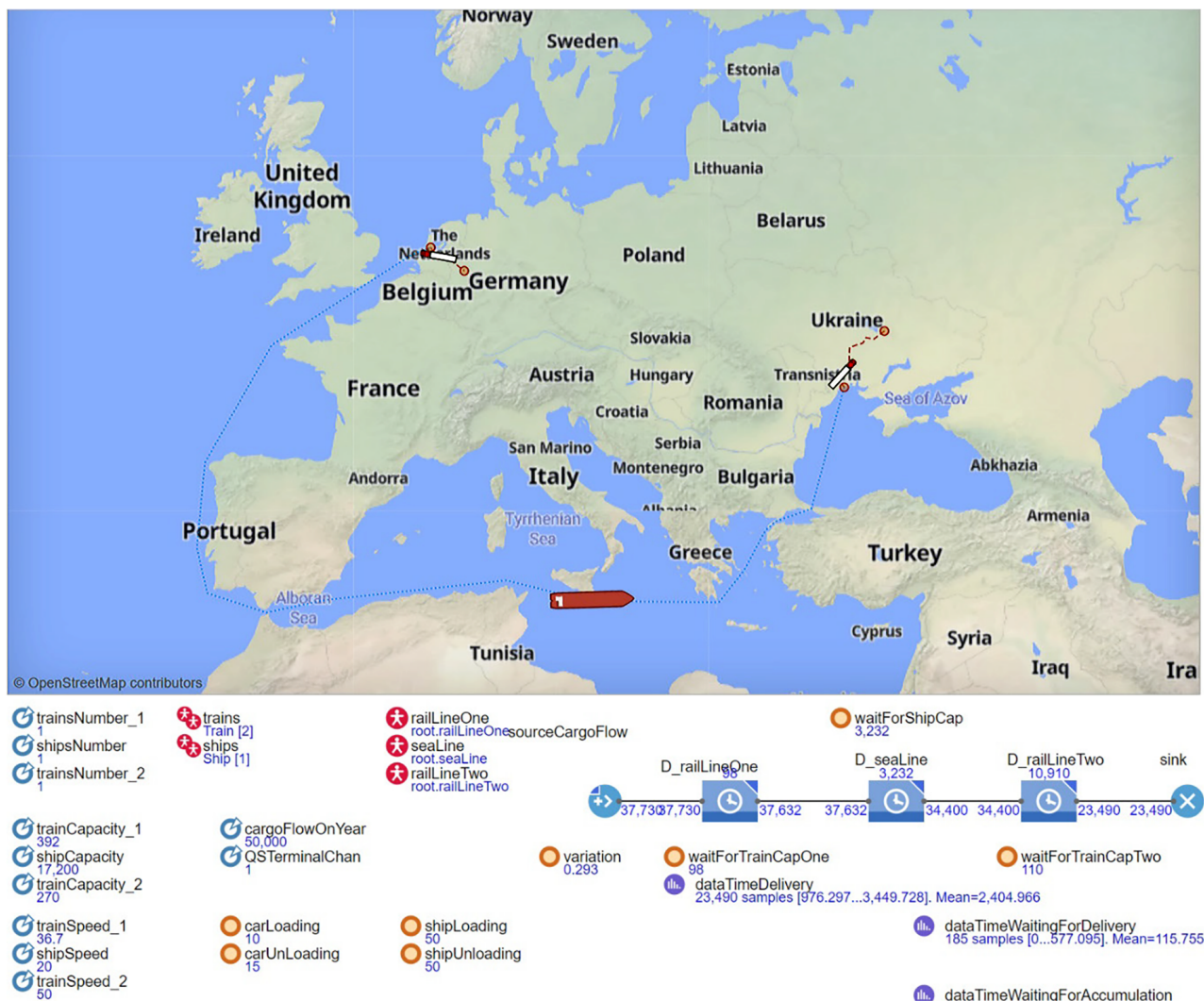


Figure 3. Main Agent window

Implementation of the model.

Based on the simulation of the baseline scenario using the data provided in Table 2, particularly the estimated turnover time of the rolling stock for each line, it can

be determined that one unit of rolling stock for each line would be sufficient for handling 500 thousand tonnes of freight per year. The following results were obtained (Fig. 4-6).

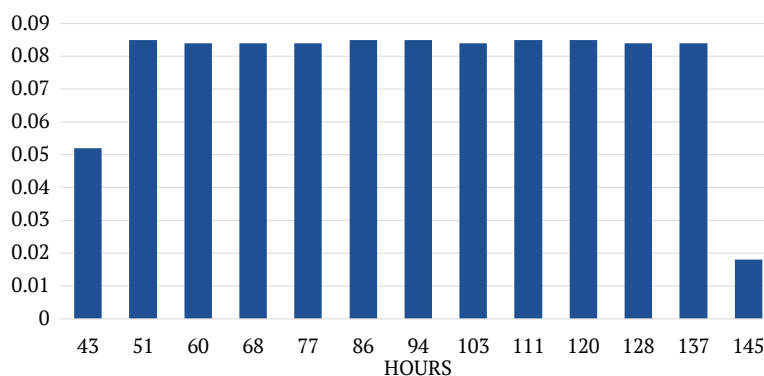


Figure 4. Density of distribution of time of freight delivery

Source: developed by the authors

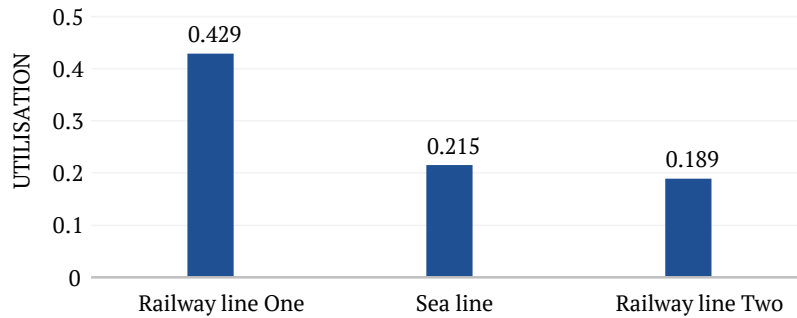


Figure 5. Railway rolling stock and vessels utilization rate

Source: developed by the authors

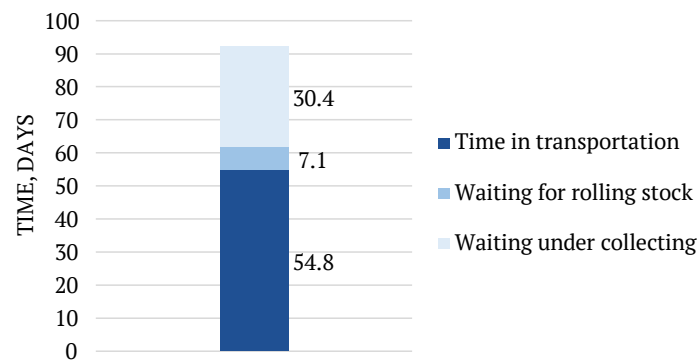


Figure 6. Freight delivery time structure (hours)

Source: developed by the authors

The dependence of the waiting time under collecting on the capacity of the bulk carrier has a clear linear nature, with a coefficient of deviation (determination) $R^2=0.9997$:

$$T_{aver} = 0,0029 P_{bulk} = 134.77, \quad (5)$$

where T_{aver} – average waiting time of a tonne of freight during transportation, hours; P_{bulk} – bulk carrier capacity, tonnes.

The key to the results of this experiment is that even with a significant increase in rolling stock (100 times) from the baseline scenario, the average waiting time at an estimated vessel capacity of 172 000 tonnes will be 638 hours (Fig. 7), which does not differ significantly from the results of baseline scenario with a rational (100 times smaller) fleet of rolling stock.

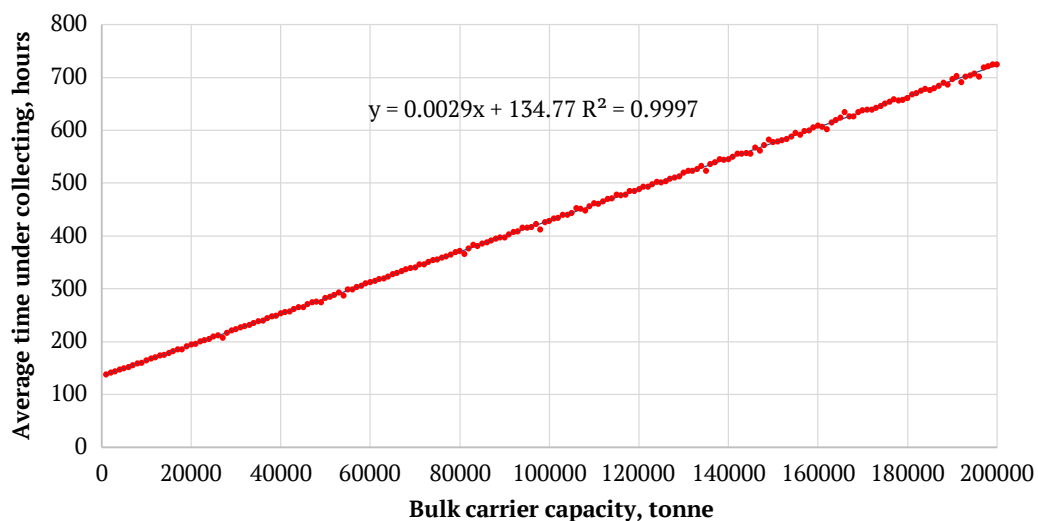


Figure 7. The relation between the average waiting time of the freight under collecting and the rate of commercial capacity of bulk carriers

Source: developed by the authors

Since the duration of direct transportation, which primarily relies on the physical capabilities of transport systems such as the traction characteristics of rolling stock and resistance forces, is a crucial factor, the primary technological criterion for efficient freight delivery organisation is minimising the waiting time of freight at loading and reloading points. Additionally, this total time will encompass both the time taken for freight collection up to the required shipment (based on the commercial capacity of trains and vessels) and the waiting time for an available transport unit (Fig. 6).

The average waiting time for trains depends on the rolling stock, and as can be seen from Figure 6, in the basic simulation, is only 8% of the total delivery time. Delays in delivery often arise from waiting for the rolling stock to be loaded at a slower rate. The efficiency of rolling stock utilisation is greatly impacted by substantial collecting time (Fig. 5), which consistently falls below 50% on all transportation routes. It is considered appropriate to research the interaction of land and sea transportation modes by discrete event simulating (DES) because of the many variables to be analysed together and the necessity of systematic assessment of variables interrelation impact during operational planning, strategic decision-making.

J. Ruiz-Aguilar *et al.* (2016) developed a queuing model network to simulate the container travel time from its departure from the railway terminal to its departure from the seaport using DES. The model was offered as a decision-making tool for intermodal chain planning. H.S. Lopes *et al.* (2017) utilised DES to simulate the overall behaviour of the Brazilian soybean transportation system based on a comprehensive analysis of multiple scenarios.

Agent-based modelling (ABM) has become widely used in transportation, particularly in real-time traffic management and driver behaviour modelling, due to its ability to incorporate detailed information. Variables like travel time reliability, average speeds, and work zone capacity can be effectively analysed using ABM (Abdulsattar *et al.*, 2019; Chargui *et al.*, 2019; C. Wang *et al.*, 2019). Grobarcikova and Sosedova (2016) utilised ABM to investigate the effects of barge location, water level, and transit time on intermodal transportation costs in Danube's container transport.

V. Reis (2019) simulated the decision-making process of individual agents in the administrative and physical layers through a normative stepwise approach using fuzzy set theory and accumulated market knowledge. The model allows assessing the influence of agents' market-related measures and behaviour on their competitiveness and the respective transport chain. M. Le Pira (2018) used ABM to simulate opinion dynamics in stakeholder networks. Individual stakeholders were represented with characteristics like opinion and influence, and they interacted based on simple behavioural rules to observe the convergence of opinions. The author did not mention uncertainty of transportation process. K. Chargui *et al.* (2019) proposed a reactive multi-agent system for simultaneous (re)scheduling of vessel, quay crane, operator, and trucks each hour.

A multi-agent simulation model was developed using the AnyLogic simulation platform to enhance container processing efficiency at the rail yard of the multimodal terminal in Le Havre seaport. The model primarily focused on minimising waiting time and unproductive movements of gantry cranes (Abourraja *et al.*, 2017). Nevertheless, the authors have not represented the vehicles and handling equipment as the agents, which could simplify the understanding of the interaction between agents. R. Elbert *et al.* (2017) developed combined agent-based and discrete event model to investigate the impact of different order release times on the process efficiency of the individual actors (intermodal agency and rail transport company) and the export-oriented container transport chain in Germany in total. However, the authors have not differentiated orders according to their contents. The utility of the AnyLogic simulation platform in addressing facility planning challenges has been demonstrated (Borshchev, 2014), which is particularly effective in multimodal and intermodal transportation, including modelling the receiving and processing of trains (Matsiuk *et al.*, 2019), analysing operational processes in railway stations and marshalling yards (Baugher, 2017; Matsiuk, 2017), and strategically planning intermodal terminals and dry ports (Abourraja *et al.*, 2017).

V. Matsiuk *et al.* (2019) utilised the AnyLogic platform to develop discrete-event models that focused on effectively organising transmitting trains according to a "tight schedule" and efficiently collecting trains based on the loading rate. The implemented model was specifically designed to handle container traffic between the dry port Odesa-Lisky and Odesa-port in Ukraine. To conclude, the novelty of this study compared to previous ones lies in the application of ABS to optimise technical parameters in the multimodal supply chain, while also providing detailed analysis of each component.

In contrast to other studies, the given one conducted an experiment to assess the sensitivity of parameter changes to determine the root cause of considerable delays in freight delivery during the collection process for the required shipment. The essence of this experiment is to identify the parameter of transportation, which with all other constant parameters has the greatest impact on the efficiency of transportation. In this case, the efficiency criterion is defined by the total average time it takes for the freight to be collected at the required rate. To minimise the impact of other parameters on the specified efficiency criteria, the rolling stock in the simulation was increased 100 times. Among the experiments, the greatest influence is exerted by the ratio of capacity between trains and vessels. That is, the closer, in absolute terms, the useful capacity of the vessel to the capacity of the train, the more efficient this process is.

CONCLUSIONS

The developed simulation model combines discrete-event and agent-based principles, simulates a supply chain with three transport and technological lines: rail 1, sea, and rail 2, considers various technical and operational parameters such as planned annual freight flows, transport unit loading

rates, delivery speeds along the routes, the number of service channels, and productivity during freight reloading at the junction. The model also accounts for the random nature of freight arrivals at the point of departure, as well as the required fleet size of transport units.

Experimentally, the following has been found:

1. In the basic simulation, approximately 40% of the delivery time is spent waiting for the transport unit to load (8%) and freight being collected up to the loading rate into the transport unit (33%).

2. The sensitivity experiment of the model determined that of all the variable technological parameters of the basic model, the difference in the ratio between the rate of loading of the railway train and the sea vessel has the greatest influence on the average time of freight delivery.

3. The relationship between the capacity of the vessel (with a constant rate of mass shipment into the railway train) and the average time of shipment collection to the loading rate into the vessel, in the event of accidental arrival of freight by rail at the transshipment terminal, shows a highly approximate linear dependence. In further studies, it is necessary to explore other ways of delivering goods. For example, using road transport. Especially for the transportation of other types of goods, such as grain or food.

None.

None.

CONFLICT OF INTEREST

ACKNOWLEDGEMENTS

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**Розробка агентної імітаційної моделі
мультимодальних перевезень залізничного концентрату**

Анотація. Більшість глобальних логістичних ланцюгів реалізуються за допомогою різних видів транспорту. Особливо це стосується генеральних вантажів, таких як залізна руда, нафта, зерно. Зі зростанням кількості учасників у транспортному процесі збільшуються ризики затримок, збоїв у роботі та невиконання термінів доставках. Тому покращення мультимодальних маршрутів постачання вантажів залишається актуальною науково-прикладною проблемою. Метою дослідження було вивчити техніко-експлуатаційних параметрів мультимодального ланцюга постачання вантажів (на прикладі перевезення залізничного концентрату). Для цього була розроблена агентна імітаційна модель. Імітаційна модель реалізована у середовищі Any Logic University Researcher з використанням компілятора Java SE, оскільки цей інструментарій дозволяє одночасно поєднувати дискретно-подієвий та агентний підходи. В результаті експерименту з імітаційною моделлю було встановлено, що: 1) приблизно 40 % часу доставки припадає на очікування вантажем транспортних одиниць для

завантаження (8 %) та перебування вантажу під накопиченням до норми завантаження транспортної одиниці (33 %); 2) експеримент чутливості моделі визначив, що з усіх змінних технологічних параметрів базової моделі найбільший вплив на середній час доставки вантажів має різниця у співвідношенні між нормою завантаження залізничного маршруту та морського судна; 3) залежність між місткістю судна (при рівномірному надходженні вантажу у пункт навантаження) і середнім часом накопичення партії вантажу до норми навантаження у судно, апроксимується лінійною залежністю. Результати дослідження можуть бути використані для вдосконалення технологій транспортування залізничного концентрату з України в інші країни

Ключові слова: технологічна система; оптимізація роботи терміналів; Java-код; залізнично-морський ланцюг постачання; системний аналіз

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Logical-probabilistic model for assessing the reliability of means for preparing and distributing feed

Abstract. In the modern stage of development of animal husbandry, the means used for the preparation and supply of feed mixtures are becoming increasingly common. These facilities combine the operations of loading, grinding, mixing, transporting, and dosed feed distribution. The purpose of this study was to assess and ensure the reliability of the operation of the means for preparing and distributing feed using logic-probabilistic modelling of failures of the feed mixture unloading mechanism as a subsystem of the “Man-Machine-Environment” technical system. In the study, logical-probabilistic modelling of the means for preparing and distributing feed was used as complex technical systems depending on the influence of the components “man-operator”, “machine”, “environment”. The shortest paths of failures and the minimum cross-sections of their prevention for the research objects were analysed. It was proved that to prevent the failure of the “man-operator” component of the system, it is necessary to ensure sufficient qualification of the personnel, foresee the possible occurrence of errors and ensure their timely elimination. It was confirmed that to prevent failures of the feed mixture unloading mechanism, it is necessary to timely control and adjust the condition of parts during operation and when restoring performance. Furthermore, it was established that the probability of failure of the mechanism will be less important under the condition that the probability of elimination of failures in case of insufficient qualification of the operator and in the case of failure of drive parts will be 0.2. It was found that an increase in the probability of failure of the operator under the condition of insufficient qualification, from 0.5 to 0.9, will lead to an increase in the probability of failure as a result of changes in conveyor tension and the impossibility of adjusting conveyor tension, while at 0.9, the probability of failure of the mechanism will be 0.046. The practical significance of the results lies in the possibility of investigating the probability of failure of the feed mixture unloading mechanism based on the reliability of the components of the means for preparing and distributing feed, including drive parts, conveyor belts

Keywords: reliability of machines; a complex technical system; feed mixture unloading mechanism; human operator; environment

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INTRODUCTION

One of the key factors influencing the productivity and health of animals is the feeding process. Countries with a developed agricultural sector of the economy use modern achievements of Industry 4.0 and IT technologies in precision animal husbandry, including global positioning technologies, geographic information systems, technologies for assessing animal productivity and others, which received the greatest development in 2010-2020 (Morrone *et al.*, 2022). T. Norton *et al.* (2019), U. Moallem & L. Lifshitz (2020) note that the efficiency of the livestock industry depends on the features of the technology of preparing and distributing balanced feed mixtures for diverse groups of animals and poultry. Thanks to these implementations, it was possible to use the most innovative systems to improve livestock management approaches. O. Zagurskiy *et al.* (2022) noted that innovative measures can also include a set of ecological principles that are recommended to be implemented in the production activities of livestock enterprises. This will enable scientifically sound decisions in the implementation of social and ecological measures in animal husbandry.

According to K.D. Astanakulov *et al.* (2020) at the current stage of animal husbandry development, both in global practice and in Ukraine, to prepare feed mixtures, machines and equipment for the preparation and distribution of feed, which combine the operations of loading, grinding, mixing, transportation, dosing, and distribution are becoming increasingly common. The world practices of the development of the livestock industry show that in recent decades, the main equipment for preparing and distributing feed is equipment consisting of a frame with a running part, a hopper, a loading mechanism, a grinding-mixing mechanism, and a mechanism for distributing the fodder mixture (Loveikin *et al.*, 2022).

According to T. Fuyang *et al.* (2020), in recent decades in the agrarian sphere, a considerable renewal of machinery and equipment for animal husbandry, including means for preparing and distributing feed, can be observed. Machines and equipment are being updated not only as a result of the commissioning of modern foreign and domestic models of means for preparing and distributing feed, but also as a result of replacing machines with horizontal augers of the grinding-mixing mechanism with corresponding means with vertical augers.

The practices of using and ensuring the performance of means for preparing and distributing feed with vertical screws indicate that foreign samples of these machines have improved technical characteristics, including fairly high operational reliability (Khmelovskiy *et al.*, 2020; Ruzhylo *et al.*, 2022). Therewith, the practice of using machines and equipment in animal husbandry indicates that the intensity of their operation is increasing, most of them have completed their depreciation period, and their operating modes and storage conditions require special attention and constant control of engineering and technical workers, machine operators, maintenance repairmen, service workers.

In recent years, scientific works have emphasized the importance of using technological equipment for the preparation of feed mixtures for cattle on livestock farms specializing in the production of dairy products and beef. A special place in the research of the constructions of feed mixers is occupied by systems of automated control and control of the component composition of feed included in feed mixtures, the data processing method for determining the parameters of work modes was substantiated. The purpose of this study was to ensure the reliability and efficiency of the functioning of means for preparing and distributing feed employing logical and probabilistic modelling of the occurrence of failures of mechanisms as complex technical systems "Human-Machine-Environment".

LITERATURE REVIEW

V. Bulgakov *et al.* (2019) pointed out that the problem of ensuring the efficient and reliable operation of mobile agricultural machinery, including means for preparing and distributing feed, is becoming increasingly urgent, since the speed of its ageing considerably exceeds the pace of their improvement and technical re-equipment of agricultural enterprises of Ukraine. Therefore, to predict the failure of means for preparing and distributing feed, as well as to prevent emergencies on a livestock farm, the issue arises of assessing reliability indicators, determining their residual resource, and establishing the probability of failure-free operation (Banniy *et al.*, 2022). Along with determining the degree of efficiency and reliability of the machine, it is also important to determine the impact of the human operator or other workers on its operation. But according to research results (Najafi *et al.*, 2015; Novitskiy *et al.*, 2016), the efficiency of agricultural machinery operation depends not only on the specific features of the work process, the efficiency of maintenance, and the reliability of the component mechanisms, but on the qualifications and experience of the service personnel.

Analysis by A. Novitskiy *et al.* (2016) shows that as the complexity of agricultural machines increases, the consequences of failures continue to increase, they become more critical. This is especially inherent in the complex "Human-Machine" and "Human-Machine-Environment" technical systems. Therefore, to identify bottlenecks in the "Human-Machine" and "Human-Machine-Environment" systems and establish the influence of the main components or subsystems on the probability of failures, an analysis of their reliability is necessary. It is also important to pick a suitable method of collecting and processing information for quantitative analysis of the reliability of complex technical systems.

In previous studies, Z. Ruzhylo *et al.* (2022) note that the means for preparing and distributing feed structurally, from the standpoint of ensuring reliability, can be presented as a block diagram of sequentially connected subsystems: loading, grinding-mixing, unloading of feed mixture, frame with chassis. The presented subsystems are quite

complex and include a considerable number of elements. The study of literary sources and the conducted research on the problem of ensuring the reliability of means for preparing and distributing feed indicate that the specified issue was understudied in terms of the mechanism of discharge of feed mixture, considering the components of the system “human”, “machine”, “environment”. O. Voinalovych *et al.* (2019) substantiated that the main characteristics of a tool for preparing and distributing feed as a complex technical system, used to investigate reliability according to the method of logic-probabilistic modelling are as follows: failure time, recovery time; failure probability; probability of failure-free operation.

Several methods can be used to determine the reliability indicators of complex “Human-Machine-Environment” technical systems, including:

- ❖ simulation modelling and system analysis (Bulgakov *et al.*, 2017; Amaya-Toral, *et al.*, 2022);
- ❖ logic-probabilistic modelling, failure tree and block diagrams (Leangsuksun *et al.*, 2003; Ruzhylo & Skorokhod, 2005; Li *et al.*, 2013), method of spatial states (Hrinkiv *et al.*, 2020; Ondar *et al.*, 2020);
- ❖ a method of failure analysis based on a survey of experts (Pisarenko *et al.*, 2019; Lo *et al.*, 2019; Aulin *et al.*, 2020).

In modern scientific literature, many studies investigate the construction and analysis of logic-probability models. The study (Novitskiy *et al.*, 2016) presents an analysis of the possibilities of using logic-probabilistic modelling in evaluating the reliability of machines, presents the general principles and features of building models, offers a methodology for development and analysis with their further application on particular systems of feed mixers and feed distributors.

MATERIALS AND METHODS

The results of theoretical and experimental research presented in the study are a continuation of previous studies (Novytskiy & Ruzhylo, 2012; Novitskiy *et al.*, 2016; Ruzhylo *et al.*, 2022) and are aimed at increasing the efficiency of use and ensuring the reliability of livestock machinery and equipment, including means for preparing and distributing feed. To estimate the reliability of the tool for preparing and distributing feed as a complex technical system in operating conditions, statistical data were obtained according to the specified indicators. To solve the purpose and tasks of this study, a logical-probabilistic model was formed for assessing the reliability of the feed mixture unloading mechanism, as a component of the “Human-Machine-Environment” system, using the example of a tool for preparing and distributing feed, the “Profile” shredder-distributor of the “KUNH Ukraine” company (Operator’s manual..., 2018). The logic-probability model was researched and formed at the National University of Life and Environmental Sciences (NULES) of Ukraine. During the study, the reliability of 11 shredder-distributors “Profile 12.2-14.2”, which were operated in the farms of

Khmelnytskyi (“Profile 14.2”), Cherkasy (“Profile 12.2”), and Vinnytsia regions (“Profile 14.2”), was monitored.

The model of formation of failures of the feed mixture unloading mechanism began with the study of the structure, technical characteristics, features of operation, maintenance of serviceability, maintenance of working capacity, establishment of dangerous situations. Dangerous situations were established, which form the sequence of failure and recovery flows. For the logical-probabilistic theory, the analytical description of dangerous situations was performed using logical functions of system failures. The arguments for the failure functions of the means for preparing and distributing feed (system) were initial conditions and initial events. Three components were the starting conditions for the feed mixture unloading mechanism: operator error, failure of mechanism parts; position of the mechanism; unsatisfactory condition of the environment or feed components. Initial conditions were considered for each component. For the first component of the complex technical “human-operator” system, the initial conditions were as follows: insufficient qualification; the occurrence of an error; untimely elimination of the error. Failures of the “machine” component were caused by failure of parts of the unloading conveyor; violation of the position of the conveyor belt; change of conveyor tension; the absence of the ability to adjust the tension of the conveyor. The initial events of the unsatisfactory state of the environment (feed components) were as follows: adverse impact of the environment; unsatisfactory properties of feed components and their contamination; the state of the floor surface in the premises of the livestock farm where the feed mixture is unloaded.

After compiling and testing the sequence of dangerous situations, system failure functions were compiled – the shortest paths of failure of the feed mixture unloading mechanism. Previous studies of means for preparing and distributing feed (Novytskiy & Ruzhylo, 2012) established that the reliability of the feed mixture unloading mechanism is limited by the following elements: hydraulic cylinder; drive details; conveyor belt. From the experience of using the means, it was known that the bearings of the conveyor axle and the hydraulic cylinder of the conveyor were characterized by gradual wear and failure, and emergency ones lost serviceability or performance as a result of failures of shaft bearings and drive chains.

The tool for preparing and distributing feed was controlled and serviced by a human operator, who was a component of the complex technical system “Human-Machine-Environment”. Two important conditions were considered during the formation of the logical-probabilistic model of the occurrence of failures of the feed mixture unloading mechanism:

- ❖ all initial conditions and initial events that could affect the probability of failure were considered;
- ❖ all proposed initial conditions and initial events were accepted by specialists in this field.

When using the mathematical apparatus of logical-probabilistic modelling, the specified conditions were considered and implemented. For the mathematical description of the presented logical-probabilistic model, logical functions of system failures were used, which are presented in the form of an event matrix.

RESULTS AND DISCUSSION

The formation of a logic-simulation model of failures of the mechanism (subsystem) for discharging the feed mixture of the means for preparing and distributing feed includes:

- ❶ establishing a sequence of dangerous situations – subsystem failures;
- ❷ analytical description of the dangerous state of the mechanism using logic functions of system failures;
- ❸ setting arguments of subsystem failure functions, which are initial conditions and initial events;
- ❹ approbation of the sequence of dangerous situations and compilation of subsystem failure functions – the shortest failure paths.

The sequence of formation of failure of the feed mixture unloading mechanism can be presented in the form of a logic-probabilistic model (Fig. 1).

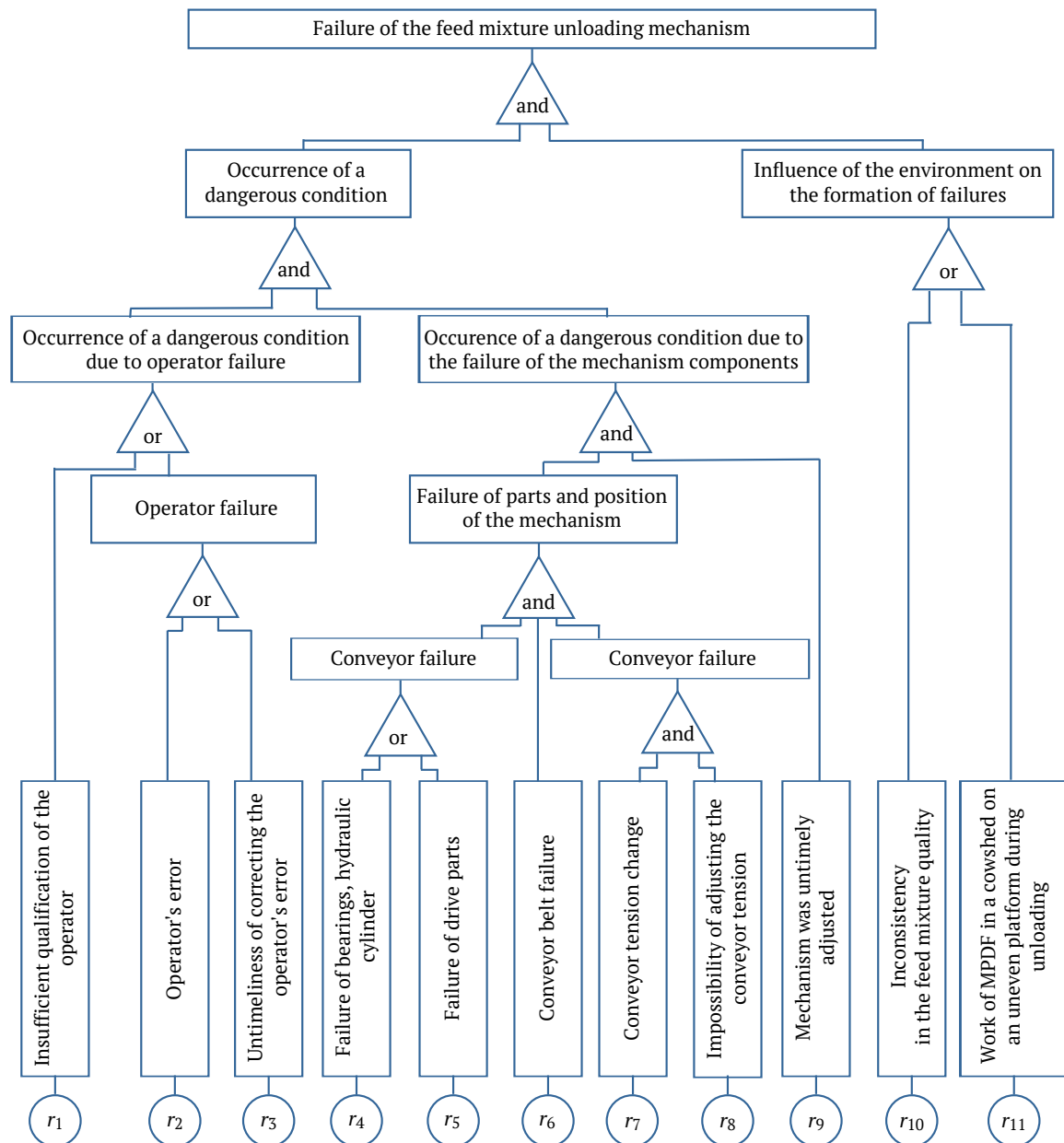


Figure 1. A model of formation of failure of the feed mixture unloading mechanism

Source: developed by the authors based on (Novytskyi & Ruzhylo, 2012)

Failures of mechanism parts, the inability to timely adjust individual components, personnel errors and an

unsatisfactory state of the environment, i.e., events describing the causes of the dangerous situation of the

subsystem, have only two states – “there is an event” (failure of an element, operator error, state of the environment) or “no event”, but they form a complete group of events. The set of causes of failure functions of the subsystem was denoted by r_i , where i is the serial number of the logical variable. Based on the obtained logic-probability model, the subsystem of the means for preparing and distributing fodder will fail, i.e., the event “failure of the feed mixture unloading mechanism” will occur, if the following initial conditions are fulfilled: failure of the operator (r_1-r_3); failure of mechanism components, including mechanism details and positions (r_4-r_9); the influence of the environment or the condition of the feed mixture on the formation of failure (r_{10} and r_{11}). One of the limitations that is considered when creating a logical-probabilistic model is the consideration of all initial events and conditions that lead to the failure of the mechanism as a whole. For the mathematical description of the presented model, it is appropriate to use the logical functions of mechanism failures, which were written in the form of a logical matrix of initial conditions r_i (Novytskiy & Ruzhylo, 2012):

$$y_c(r_1, \dots, r_{11}) = \begin{vmatrix} r_1 \\ r_2 \\ r_3 \end{vmatrix} = \begin{vmatrix} r_4 \\ r_5 \\ r_7 r_8 \end{vmatrix} = |r_9| = \begin{vmatrix} r_{10} \\ r_{11} \end{vmatrix}. \quad (1)$$

The function (1), obtained from the results of the simulation of the failure of the feed mixture unloading mechanism (Fig. 1), is monotonous and repetitive, since the replacement of any element that failed with a serviceable one, or the reservation of an event that affects the formation of the failure, will not lead to subsystem failure. When opening the parentheses, the logical functions of subsystem failures were obtained in the form of a disjunction of the 24 shortest failure paths (2).

$$y_c(r_1, \dots, r_{11}) = \begin{vmatrix} r_1 r_7 r_8 r_9 r_{10} \\ r_1 r_7 r_8 r_9 r_{11} \\ r_1 r_6 r_9 r_{10} \\ r_1 r_6 r_9 r_{11} \\ r_1 r_4 r_9 r_{10} \\ r_1 r_4 r_9 r_{11} \\ r_1 r_4 r_7 r_{10} \\ r_1 r_4 r_7 r_{11} \\ r_2 r_4 r_9 r_{10} \\ r_2 r_4 r_9 r_{11} \\ r_2 r_5 r_9 r_{10} \\ r_2 r_5 r_9 r_{11} \\ r_2 r_6 r_9 r_{10} \\ r_2 r_6 r_9 r_{11} \\ r_2 r_7 r_8 r_9 r_{10} \\ r_2 r_7 r_8 r_9 r_{11} \\ r_3 r_4 r_9 r_{10} \\ r_3 r_4 r_9 r_{11} \\ r_3 r_5 r_9 r_{10} \\ r_3 r_5 r_9 r_{11} \\ r_3 r_6 r_9 r_{10} \\ r_3 r_6 r_9 r_{11} \\ r_3 r_7 r_8 r_9 r_{10} \\ r_3 r_7 r_8 r_9 r_{11} \end{vmatrix}. \quad (2)$$

The study and detailed analysis of the failure formation model of the feed mixture loading mechanism (Fig. 1) and matrix (2) helps assert that the risk of failure is associated with one of 12 different failure formation methods. By transforming formula (2), one can obtain the logical functions of system failures in the form of a disjunction of 5 minimum sections of failure prevention:

$$y_c(r_1, \dots, r_{11}) = \begin{vmatrix} & r'_9 & \\ r'_1 & r'_2 & r'_3 \\ r'_4 & r'_5 & r'_6 & r'_7 \\ r'_4 & r'_5 & r'_6 & r'_8 \\ & r'_{10} & r'_{11} \end{vmatrix}. \quad (3)$$

Analysing the obtained matrices (2) – the shortest failure paths and (3) – minimum failure prevention sections, it can be concluded that to prevent failures of the feed mixture unloading mechanism, it is necessary to timely control and adjust the condition of the parts of the mechanism itself (i.e., r_9 and r'_9). The generation of sequences presented in matrices (2) and (3) helps analyse and synthesize the causes of mechanism failures, and accordingly, the need to formulate tasks to strengthen the requirements for the components of the means for preparing and distributing feed as a complex technical system:

$$P_{MUFM} = P \left\{ \begin{vmatrix} r_1 \\ r_2 \\ r_3 \end{vmatrix} = \begin{vmatrix} r_4 \\ r_5 \\ r_6 \\ r_7 r_8 \end{vmatrix} = |r_9| = \begin{vmatrix} r_{10} \\ r_{11} \end{vmatrix} = 1 \right\} = \\ = P_7 \cdot [1 - G_1 \cdot G_2 \cdot G_3] \cdot \\ \cdot [1 - G_4 \cdot G_5 \cdot G_6] \cdot [1 - G_8 \cdot G_9], \quad (4)$$

where G_i is the probability of failure-free operation, P_i is the failure probability.

The analysis of the shortest failure paths and the minimum cross-sections of their prevention indicate that timely control and adjustment of the mechanism (i.e. r_9 and r'_9). Based on the analysis of the logic functions of subsystem failures, which are presented in matrices (2) and (3), it is possible to prevent the loss of efficiency of the feed mixture unloading mechanism and thus reduce the risk of failure of the means for preparing and distributing feed.

It was investigated the influence of the components “Man”, “Machine”, “Environment” of a complex technical system on the means for preparing and distributing feed and emphasize the impact of components P_1 (insufficient qualification of the operator), P_5 (failure of mechanism drive parts) and P_9 (mechanism untimely adjusted). For the formation model of the failure of the feed mixture discharge mechanism, the influence of components P_1 , P_5 , and P_9 was studied for the following two cases:

a – probability of eliminating mechanism failures in the case of insufficient qualification of the operator and in the case of failure of drive parts, which are 0.1 in value; the mechanism is untimely adjusted with a probability of 0.5;

b – probability of eliminating mechanism failures in case of insufficient qualification of the operator and in the

case of failure of the drive parts, which are 0.2 in terms of values; the mechanism is untimely adjusted with a probability of 0.99.

The results of the study of the reliability of the feed mixture unloading mechanism are presented, respectively, in Figure 2a and Figure 2b.

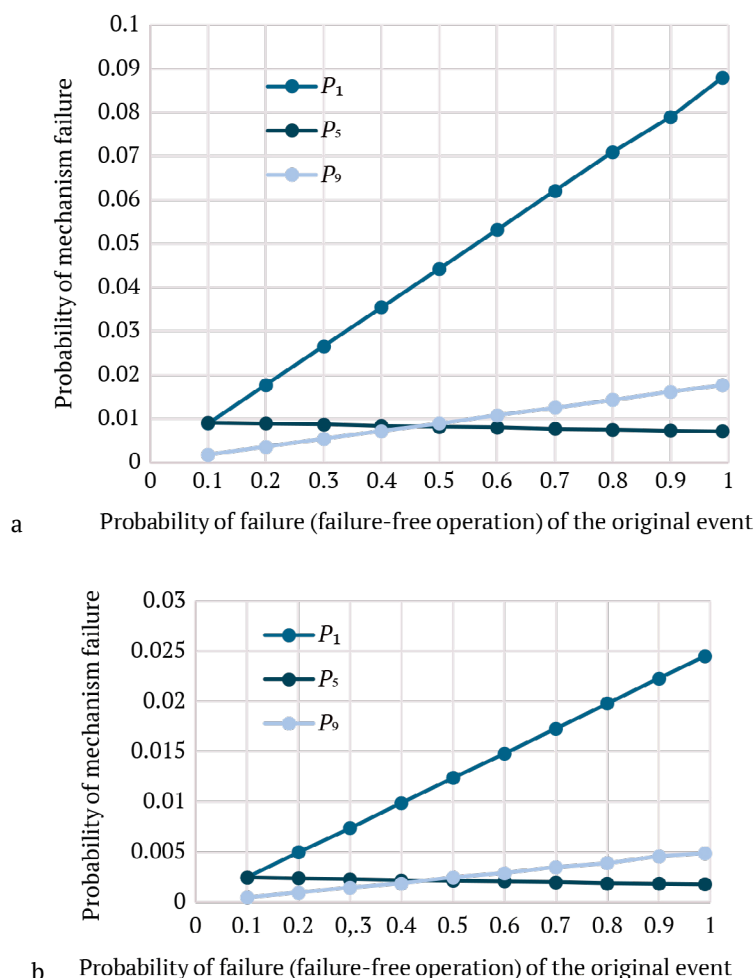


Figure 2. Dependence graph of the probability of failure of the feed mixture unloading mechanism of the means for preparing and distributing feed on the state of components P_1 , P_5 , and P_9

Source: developed by the authors

The analysis of graphical dependencies presented in Figures 2a and 2b showed that the “human-operator” component has a predominant influence on the possibility of failure of the feed mixture unloading mechanism compared to the influence of the “machine” and “environment” components. The probability of failure of the mechanism is less important under the condition that the probability of eliminating the failure of the mechanism in case of insufficient qualification of the operator and in the case of failure of drive parts is 0.2. Therewith, the probability that the mechanism is untimely adjusted is 0.99.

The analysis of the obtained graphical dependencies (Fig. 2a) suggests that an increase in the probability of failure of the operator’s work in case of insufficient qualification, which is 0.1, leads to a decrease in the probability of failure of drive parts, and the probability of failure due to untimely adjustment within 0.5 to 0.99 will increase by 50%, and will be 0.009. The analysis of the obtained

graphical dependencies (Fig. 2b) suggests that an increase in the probability of failure of the operator’s work in case of insufficient qualification, which is 0.2, leads to a decrease in the probability of failure of drive parts, and the probability of failure as a result of untimely adjustment within 0.5 to 0.99 will increase by 50% but will be 0.005.

For the formation model of the failure of the feed mixture unloading mechanism, we will investigate the influence of components P_1 (insufficient qualification of the operator), P_{7-8} (change in conveyor tension and impossibility of adjusting conveyor tension) and P_9 (mechanism untimely adjusted) for two cases: the probability of P_1 (insufficient qualification of the operator) is 0.5 (Fig. 3a) and 0.99 (Fig. 3b), respectively.

Figure 3 shows graphical dependencies of the probability of failure of the feed mixture unloading mechanism in case of insufficient qualification of the operator, failure due to a change in the conveyor tension and the

impossibility of adjusting the conveyor tension, untimely adjustment of the mechanism. The logical variable

corresponding to the insufficient qualification of the operator is denoted by r_1 .

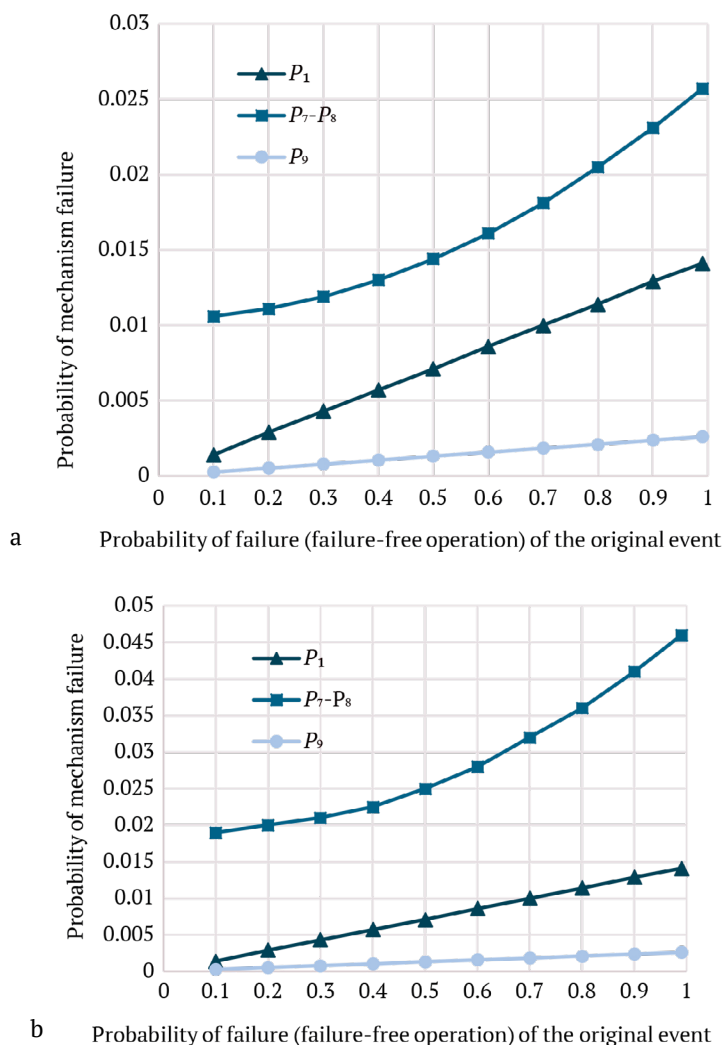


Figure 3. Dependence graph of the probability of failure of the feed mixture unloading mechanism of the means for preparing and distributing feed on the state of components P_1 , P_{7-8} , and P_9

Source: developed by the authors

Figures 3a and 3b present a study of the influence of the logical variable r_1 of the operator under the condition that the probabilities of occurrence of events are 0.5 and 0.9, respectively. Therewith, the probability of failure of the feed mixture unloading mechanism can take different values if the above-mentioned events are undetected or detected. The analysis of the obtained graphical dependencies (Figs. 3a and 3b) suggests that an increase in the probability of failure of the operator's work under the condition of insufficient qualification from 0.5 to 0.9 leads to an increase in the probability of failure due to a change in conveyor tension and the impossibility of tension adjustment transporter. Therewith, the probability of failure of P_{7-8} within 0.5 to 0.99 will increase intensively and will reach its maximum value with insufficient qualification: for a value of 0.5, the probability of failure will be 0.026;

for 0.9, the probability of failure will be 0.046. The analysis of the shortest paths of occurrence of failures and the minimum cross-sections of their prevention indicate that to prevent failures of the feed mixture unloading mechanism, timely control and adjustment of the mechanism is necessary. Based on the analysis of the logical functions of failures of the feed mixture unloading subsystem, it is possible to prevent the loss of efficiency of the mechanism and reduce the risk of failure of the research object as a whole.

The analysis of theoretical and experimental studies of machines for preparation and distribution of feed suggests that most authors conducted research to establish the operational, structural, and functional parameters of mechanisms for loading feed components and grinding-mixing. To improve the dynamic characteristics and reduce the wear of the unit's elements, V. Khmelovskiy *et al.* (2020),

V. Loveikin *et al.* (2022) propose reducing the amount of rotor imbalance by installing an auger in the form of a two-way conical screw. However, their studies did not assess the influence on the dynamic characteristics of the quantity and scheme of installing knives on the turns of the screw. It is unclear how these recommendations will affect the operation of the feed mixture unloading mechanism.

Design and technological parameters of self-propelled mixers are presented in the study by T. Fuyang *et al.* (2020), where the authors recommend improving the parameters of the loading milling mechanism and the vertical auger of the grinding-mixing mechanism. The article states that to ensure the uniformity and quality of the feed mixture, the rotation speed of the auger should be within 22...26 min⁻¹, and the mixing time of the feed components should be 6...8 min. It would be useful to know how improvements in the loading and grinding-mixing mechanisms will influence the operation of the unloading mechanism and the machine as a whole. Issues of ensuring the reliability of self-propelled mixer mechanisms are still relevant.

V. Bulgakov *et al.* (2017) presented theoretical studies of the parameters of screw working bodies, considered the movement of a particle of material by the working body of an agricultural machine in the form of a vertical screw limited by a coaxial fixed cylinder. S.F. Pylypaka & M. Klendii (2022) obtained the dependences of the change in the speed of transporting a material particle under the influence of the coefficient of friction of the particle on the surface of the screw and the coefficient of friction of the particle on the surface of the limiting vertical cylinder, which can be used when substantiating the parameters of feed mixers and feed distributors. V.M. Baranovsky *et al.* (2018) analysed the technological operations associated with the transportation of agricultural materials in closed, immovable enclosures, which are carried out by screw conveyors and help obtain high efficiency of loading and unloading operations.

The characteristic features of the use of screw conveyors for transporting or lifting bulk materials to different distances and heights are considered by V.G. Gorobets *et al.* (2018), B.M. Hevko *et al.* (2018). In these studies, the impact on the performance of the screw conveyor of such parameters as the volume level of filling of loose material and the speed of rotation of the screw was also investigated. The authors of the presented articles analysed the operating conditions of conveyors, provided the results of theoretical and experimental research into the processes of transportation of agricultural materials, which include grain materials, compound feed, bran, and chaff. The obtained research results can be used to improve and ensure the reliability of operation of shredders-distributors.

Of scientific and practical interest are the results of O. Trokhaniak (2022), which highlight the results of substantiated rational constructive, kinematic, and technological parameters of screw conveyors. The technological processes of the movement of agricultural materials in horizontal, inclined directions, and along curves were investigated.

The analysis strongly suggests that the results of the presented research are not yet sufficiently used in the construction of modern tools for preparing and distributing feed (Baranovsky *et al.*, 2018; Pylypaka *et al.*, 2022; Trokhaniak, 2022).

Ensuring reliability in the implementation of the maintenance and repair system is facilitated by equipping modern foreign and Ukrainian means for preparing and distributing feed with built-in electronic devices for functioning and monitoring the technical condition (Gorobets *et al.*, 2018; Fuyang *et al.*, 2020). Equipping the mechanisms of loading, grinding-mixing, and unloading of feed mixture of feed dispensers with diagnostic devices using modern IT technologies will help fulfil their reliability as complex technical systems "Human-Machine-Environment" (As-tanakulov *et al.*, 2020). Therewith, special importance is attached to the "human-operator" as a component of the sociotechnical system.

H.-W. Lo *et al.* (2019) noted that increasing the reliability of machines and reducing possible risks during the production process is crucial for ensuring the operability of research objects. The use of the method of failure analysis and at the same time maintaining the performance of the "human-machine" system is based on the experience of experts, involves the identification of their main types and the establishment of the most critical factors to prevent the risk of their occurrence. The results of the study confirmed the possibility of using logical-probabilistic modelling to analyse failures and ensure the reliability of equipment not only in animal husbandry, but also in mechanical engineering.

During the operation of the device, it was established that a certain number of failures were also caused by the lack of information on the criteria of the limit state of the drive parts in the guidance materials for the use of the device. The practice of using means for preparing and distributing feed has determined that the complex cause of failure of the feed mixture unloading mechanism is untimeliness or violation of the periodicity of control over the condition of parts and regulation of the main parameters of the technical condition. The study presents the results of theoretical and experimental studies of the reliability of means for the preparation and distribution of feed as complex technical systems depending on the influence of the components "human-operator", "machine", "environment" based on logical simulation modelling.

CONCLUSIONS

According to the study results, the distribution of failures of means for preparing and distributing feed as a complex technical system "Human-Machine-Environment" was highlighted, a logic-probabilistic model of failure formation was obtained. The logical-probabilistic model of formation of the failure of the feed mixture unloading mechanism factors in the influence of the components "machine", "person", "environment". Using a logical-probabilistic model and analytical dependencies, the probabilities of

failure of the feed mixture unloading mechanism under several conditions were investigated. The first condition is insufficient qualification of the operator, the second is failure of the drive parts; the third is untimeliness of adjustment of the mechanism. Research has established that the “human-operator” component, i.e., r_1 , has a predominant influence on the probability of failure of the feed mixture unloading mechanism. The probability of failure of the mechanism is less important under the condition that the probability of eliminating the failure of the mechanism due to insufficient qualification of the operator and the failure of the drive parts r_5 is 0.2, and the mechanism is untimely adjusted with a probability of 0.99. An increase in the probability of failure of the operator’s work under the condition of insufficient qualification r_1 , from 0.5 to 0.9 leads to an increase in the probability of failure due to a change in the conveyor tension and the impossibility of adjusting the conveyor tension r_{7-8} . Therewith, the probability of P_{7-8}

failure within 0.5 to 0.99 will increase intensively and will reach a maximum value of 0.046.

In further studies, possible areas for increasing the reliability of the feed mixture unloading mechanism for preparing and distributing feed will be considered: research and formation of measures to reduce the probability of mechanism failures as a result of untimeliness of the error elimination by the operator; research of the logical-probabilistic model of the formation of failures depending on the influence of the external environment; formation of feedback with machine manufacturers regarding the formation and implementation of a reliability program at the design and manufacturing stages.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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None.

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**Логіко-імовірнісна модель оцінки надійності засобів
для приготування і роздавання кормів**

Анотація. У сучасному етапі розвитку тваринництва все більш поширеними стають засоби, які використовуються для приготування і подачі кормових сумішей. Ці засоби поєднують у собі операції завантаження, подрібнення, змішування, транспортування та дозованої роздачі кормів. Метою статті була оцінка і забезпечення надійності експлуатації засобів для приготування і роздавання кормів за рахунок логіко-імовірнісного моделювання виникнення відмов механізму вивантаження кормової суміші як підсистеми технічної системи «Людина-Машина-Середовище». В дослідженні було використано логіко-імовірнісне моделювання засобів для приготування і роздавання кормів як складних технічних систем в залежності від впливу складових «людина-оператор», «машина», «середовище». Проаналізовано найкоротші шляхи виникнення відмов та мінімальні перерізи їх попередження для об'єктів дослідження. Доведено, що для запобігання відмови складової системи «людина-оператор» слід забезпечувати достатню кваліфікацію персоналу, передбачати можливе виникнення помилок та забезпечувати своєчасне їх усунення. Підтверджено, що для запобігання відмов механізму вивантаження кормової суміші необхідно своєчасно проводити контроль та регулювання стану деталей в процесі експлуатації та при відновленні працездатності. Встановлено, що ймовірність виникнення відмови механізму буде мати менше значення при умові, що ймовірності усунення відмов при недостатній кваліфікації оператора та при відмові деталей приводу будуть становити 0,2. Виявлено, що збільшення значення ймовірності відмови роботи оператора за умови недостатньої кваліфікації, з 0,5 до 0,9 призведе до збільшення ймовірності відмови в результаті зміни натягу транспортеру та неможливості регулювання натягу транспортеру, а при 0,9 ймовірність відмови механізму буде становити 0,046. Практичне значення результатів полягає в можливості дослідження ймовірності виникнення відмов механізму вивантаження кормової суміші виходячи з надійності складових засобу для приготування і роздавання кормів, включаючи деталі приводу, полотна транспортера

Ключові слова: надійність машин; складна технічна система; механізм вивантаження кормової суміші; людина-оператор; середовище

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Research of thermal and hydrodynamic flows of heat exchangers for different air-cooling systems in poultry houses

Abstract. Increasing the productivity of poultry farms relates to the need to create an optimal, regulated microclimate in poultry houses. This issue becomes of primary importance due to the decrease in the productivity of poultry farming caused by the imperfection of the existing systems. The purpose of this study was to develop and numerically model a shell-and-tube heat exchanger of an innovative design for cooling supply air as an element of the air conditioning system used in ventilation systems of distinct types in the summer period. CFD modelling using ANSYS Fluent software was used to simulate hydrodynamic processes and heat exchange processes in channels with compactly arranged pipes in a bundle. Two types of ventilation systems were considered, namely tunnel and side. For them, heat exchangers designed to cool incoming air in summer were developed. A total of 80 automatic inlet valves measuring 0.3×0.85 m were installed in the side walls. Furthermore, evaporative cooling systems 5.3×1.1 m were located on the front-end walls. Numerical modelling of hydrodynamics and heat transfer was performed, as well as an analysis of the operation of heat exchangers of two distinctive designs for tunnel and side ventilation. Velocity, temperature, and pressure fields in the channels under study were obtained. The conditions of the hydrodynamic flow in the channels of the heat exchangers were analysed. In the case of the tunnel ventilation system, the pressure drop is 991 Pa, which is 3.3 times less compared to the side ventilation system. The outlet temperature is +23°C, which meets the design requirements. The main disadvantage is the financial costs for the purchase, cutting of pipes and their welding. To ensure standardized conditions of the air environment in the poultry house, considering all aspects of technical and economic analysis, it is proposed to choose a heat exchanger for the tunnel

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ventilation system. In practice, such heat exchange devices can be used not only in microclimate systems of poultry houses, but in the industrial, energy sector, and critical infrastructure facilities

Keywords: automatic inlet valves; Computational Fluid Dynamics; poultry farm; tunnel ventilation; side ventilation

INTRODUCTION

Increasing the productivity of poultry farms is associated with the need to create an optimal microclimate in the air environment in poultry houses. An important task here is the development of innovative approaches and principles for solving the problem of cooling and heating supply air in poultry houses in summer and winter. This issue is relevant due to the decrease in the productivity of poultry farming caused by the imperfection of the existing microclimate systems in the summer at elevated temperatures and humidity of the outdoor air. Current power supply systems in poultry houses require elevated energy consumption and costs to provide a controlled environment in poultry houses.

In the studies by V. Blanes-Vidal *et al.* (2008), E. Bustamante *et al.* (2017) presented modelling of air flows and heat and mass transfer using Computational Fluid Dynamics (CFD) in poultry houses equipped with a side ventilation system. The authors suggest that the method of side mechanical ventilation is more effective compared to other methods and can reduce thermal stress and increase the productivity of poultry keeping in the summer. The results of the mathematical modelling were compared with the data of experimental studies and the difference does not exceed 12%. M. Zajicek & P. Kic (2012) present CFD solutions for various improved enclosures for different flow configurations and broiler room shapes. The effects of transverse and longitudinal ventilation are combined with changes in the directions of incoming air flows, as well as with a different cross-sectional shape obtained using louvers.

According to the calculations presented by E. Bustamante *et al.* (2017), it was concluded that the insufficient speed of air movement, as well as the absence of a cooling system, increase the thermal stress of the poultry, which leads to a decrease in ventilation productivity. This is facilitated by the uneven flow of air in the area where the poultry is located and the area of stagnant air, which worsens the conditions for thermoregulation of the poultry. V.G. Gorobets *et al.* (2018), N. Biçer *et al.* (2020) considered an outdoor air-cooling system using a specially designed heat exchanger using water from artesian wells as a coolant. Mathematical modelling of heat and mass exchange processes during air ventilation in poultry houses with a highly adjusted arrangement of ventilation equipment was performed. As a result of numerical modelling, the fields of velocities, temperatures, and pressures in the poultry house were determined.

When developing new types of heat exchanger designs, such factors as their compact characteristics, efficiency of heat transfer through the surface separating heat carriers, pressure losses in the circuits of each heat carrier and other parameters characterizing heat exchange surfaces are

considered. Another important analysis tool for determining the effectiveness of the developed design of the heat exchanger is detailed mathematical modelling of heat, mass, and energy exchange processes in the heat exchanger (Ambekar *et al.*, 2016; El Maakoul, 2016; Bayram & Sevilgen, 2017). Such modelling allows for the analysis of local hydraulic and thermal characteristics on heat exchange surfaces (Kim *et al.*, 2016; Leoni *et al.*, 2017; Ling *et al.*, 2017), to determine their thermal efficiency coefficient and to estimate the hydraulic losses that determine the power of the pumps, which are used to remove coolants (Pal *et al.*, 2016; Mellal *et al.*, 2017; Shahril *et al.*, 2017).

The most common designs of heat exchangers, which are mainly used in engineering, are recuperative ones. As a rule, shell-and-tube heat exchangers have a chequerboard or corridor arrangement of tube bundles, and the conditions of their hydrodynamic flow and heat exchange have been thoroughly investigated in several scientific works (Thakre & Pachghare, 2017; Abbasi *et al.*, 2020; Bahiraei *et al.*, 2021). However, hydrodynamics and heat transfer in the case of small-diameter tube bundles have been understudied. Z. Yang *et al.* (2020), A.C. Caputo *et al.* (2022) note that the use of such heat exchange surfaces in shell-and-tube heat exchangers allows improving their energy and economic characteristics compared to known designs.

The purpose of this study was to develop modern designs of shell-and-tube heat exchangers, as well as to conduct research on hydrodynamic flows and heat transfer in inter-tube channels to improve systems for maintaining a standardized microclimate of the air environment in poultry farms.

MATERIALS AND METHODS

The study was conducted during 2020–2022 by the National University of Life and Environmental Sciences, Kyiv. The basic enterprise was a poultry farm located in the city of Ladyzhyn (LLC “Vinnytsia Poultry Farm”). In this enterprise, conventional type poultry houses with dimensions of 20×120×5.8 m for 50,000 heads were used for breeding poultry. The microclimate maintenance system used in poultry houses had two types of ventilation systems, namely tunnel and side. It had 18 exhaust fans of the type Munters EM50 1.5 HP (Sweden), which were located on the back-end wall of the poultry house with a total volumetric airflow of 1,036 thousand m³/h. On the side walls of a separate poultry house according to the current technology to keep a normalized microclimate of the ventilation system, there are automatic inlet valves with a total number of 80 pieces measuring 0.3×0.85 m (Fig. 1). Furthermore, evaporative cooling systems of 5.3×1.1 m were located on the front-end walls of the poultry house. Notably, the existing

microclimate maintenance system had several shortcomings, namely, insufficient cooling of heated outdoor air in the summer, high water consumption in evaporative cooling systems and high humidity levels in poultry houses. The study used a new system for cooling external heated air, which was cooled in shell-and-tube heat exchangers,

where water from underground wells was used as a coolant. Therewith, heat exchangers were used instead of the evaporative cooling system and automatic supply valves. For these ventilation systems, a new design of heat exchangers was developed, which were designed to cool the incoming air in summer.

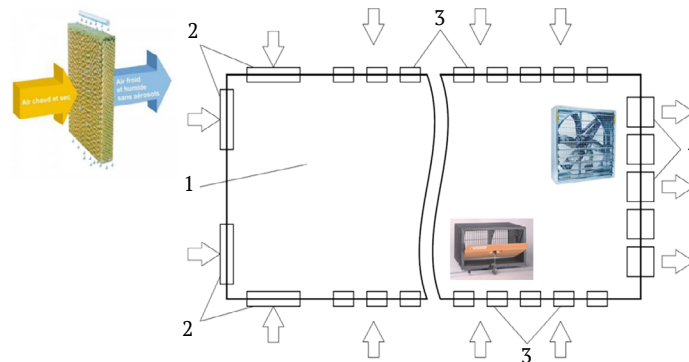


Figure 1. Scheme of the evaporative cooling system and side ventilation inlet valves in the poultry house

Note: 1 – poultry house; 2 – evaporative cooling cassettes; 3 – ventilation supply valves; 4 – exhaust fans

Source: developed by the authors

A heat exchanger with a case of rectangular cross-section with transverse flow around pipes with an inherent geometry of the arrangement of pipes with a diameter of $d=10$ mm was considered (Fig. 2). It differed from conventional chequered and corridor tubular bundles. The heat exchangers, which contain a transverse tube bundle, consisted of rows of tubes, where the adjacent tubes of each

row were tangent to each other, and the adjacent tubes in each row were arranged with a sequential offset relative to the axis of the row. In this study, adjacent tubes were offset by 1 mm from each other. In both types of heat exchangers (HE), the width of the channel between adjacent rows of tubes was equal to 15 mm, the number of tubes along the depth of the channel in one collector was equal to 51 pcs.

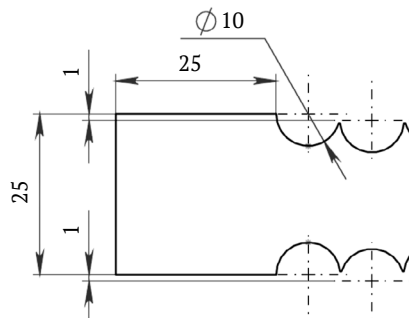


Figure 2. Location of tubes in the HE bundle, (top view)

Source: developed by the authors

All calculations were performed with an air consumption of 1,036 thousand m^3/h . The heat carrier was air $+40^\circ C$ at the entrance, which flows through the heating ducts in summer to cool the air in the poultry house. At the exit from the heat exchanger, the air temperature should have been close to $+20^\circ C$. Groundwater from artesian wells was used as a coolant (Gorobets *et al.*, 2021). In turn, the temperature of cold water at the entrance to the thermal power plant was equal to $+10^\circ C$. Since the problem was solved in 2D projection, to reduce the cost of computer resources, the boundary conditions for the temperature on the inner walls of the pipes were set

differently for each collector. It was assumed that the water temperature in the pipes of each collector will change according to a linear characteristic. Thus, in the HE for the tunnel ventilation system, the average value of the temperature at the first collector was $19.87^\circ C$, while at the second – $13.29^\circ C$, assuming that the water temperature at the outlet was $23.16^\circ C$. With the side ventilation system, the temperature on the first collector is $21.625^\circ C$, on the second and third – $16.975^\circ C$ and $12.325^\circ C$, respectively. The water temperature at the outlet of the thermal power plant is $23.95^\circ C$. Water consumption for all HES is presented in Table 1.

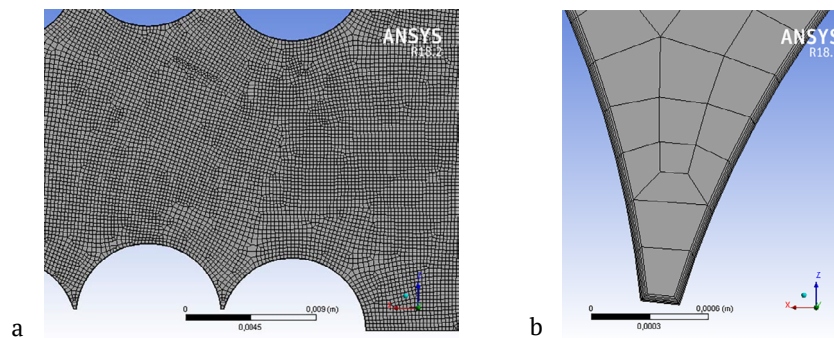
Table 1. Design parameters of HE for distinct types of ventilation systems

Ventilation system	Water consumption for all HEs, m ³ /h	Air consumption for all HEs, m ³ /h	Air consumption for one HE, m ³ /h	Width of HE, m	Height of HE, m	Number of tubes in one HE, pcs	Number of collectors, pcs	Quantity of HE, pcs	Total length of pipes, m
Tunnel	372.0	1,036,704	86,392	2.65	1.0	10,812	2	12	129,744
Side	382.4	1,036,880	12,961	0.85	0.3	5,202	3	80	124,848

Source: developed by the authors

The system of movement of coolants in the channels and in the tubes was crossed. To obtain sufficient cooling of the supply air from +40°C to +20°C, the heat exchangers were designed according to the inlet dimensions of the valves and evaporative cooling cassettes. Due to the need for such a considerable air exchange (1,036 thousand m³/h) and the necessary heat exchange between heat carriers, the number of collectors in heat exchange units for systems with tunnel and side ventilation was different. Table 1 presents the structural data of both designs of heat exchangers for distinct types of ventilation systems.

CFD modelling of hydrodynamic processes and heat exchange processes in channels with a compact arrangement of pipes in a bundle was carried out using the ANSYS Fluent software package (ANSYS..., 2017). The mathematical model was based on the Navier-Stokes equation (Khmelnik, 2021), the energy conservation equation for convective currents, and the continuity equation. The standard k-ε model of turbulence was used in the calculations. Mesh generation was performed in ANSYS Meshing based on the Workbench platform (Fig. 3).

**Figure 3.** Mesh generated in ANSYS Meshing

Note: a – full channel, b – boundary layer

Source: developed by the authors

When creating the grid for the heat exchanger of all designs, local grid control was used. The minimum associated size was $2.5 \cdot 10^{-4}$ m. The quadriside grid was generated using the construction of the boundary layer with the Total Thickness approach. For the first layer, the thickness was $5 \cdot 10^{-5}$ m, the number of layers was 6. The quality indicator of the grid, i.e., Orthogonal Quality, for both types of heat exchangers was within 0.561–0.564.

RESULTS AND DISCUSSION

Studies indicate that the air velocity in the intertube channels for heat exchangers located in holes with a tunnel ventilation system will be lower compared to heat exchangers with a side ventilation system. Due to the considerably larger dimensions of the heat exchangers for the tunnel ventilation system, 2 collectors are provided for it, and 3 collectors for the second one. Accordingly, the number of pipes included in the collectors was chosen so that the outlet temperature was close to +20 °C. The incoming hot

air enters the heat exchanger from the right side. Figures 4–5 show the variation of temperatures for distinct types of ventilation systems. As air passes through the inter-pipe channels of the bundles of pipes in which water flows from underground wells, the air temperature will decrease. For the tunnel ventilation system, the air approaching at the intersection between collectors 1 and 2 is cooled to a temperature of +30.1°C (Fig. 4). For the side ventilation system, for which the HE was designed for 3 collectors, the temperature between 1 and 2 collectors drops to +32.3°C, and between 2 and 3 – to +26.1°C (Fig. 5). Based on the conducted studies, when using the tunnel ventilation system, the temperature in the HE decreases from +40 to +22.5°C (Fig. 4), and with the side one – from +40 to +19.7°C (Fig. 5). Therewith, the number of pipes and the dimensions of the heat exchanger for the first case will be substantially smaller, which is conditioned upon the lower temperature pressure on the inner part of the pipes for heat exchangers with a tunnel ventilation system.

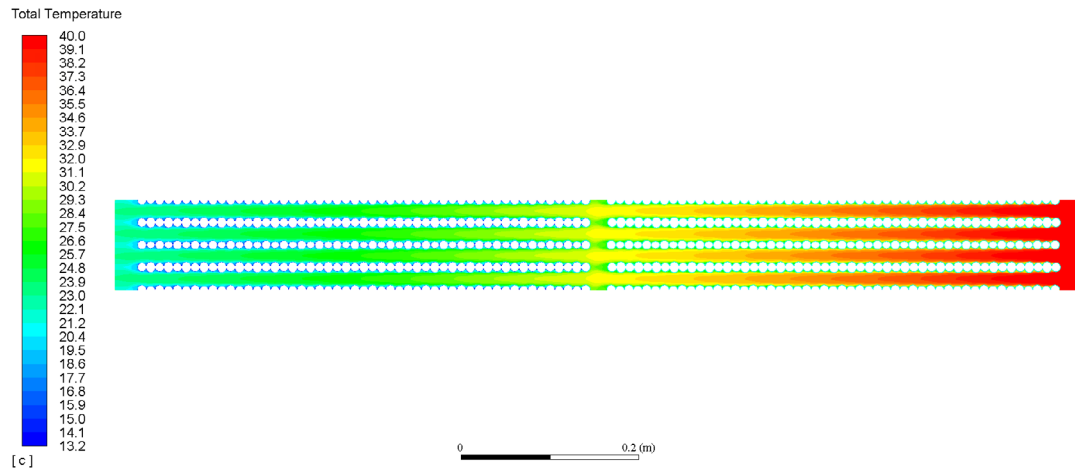


Figure 4. Field of temperatures in HE for the tunnel ventilation system, °C

Source: developed by the authors

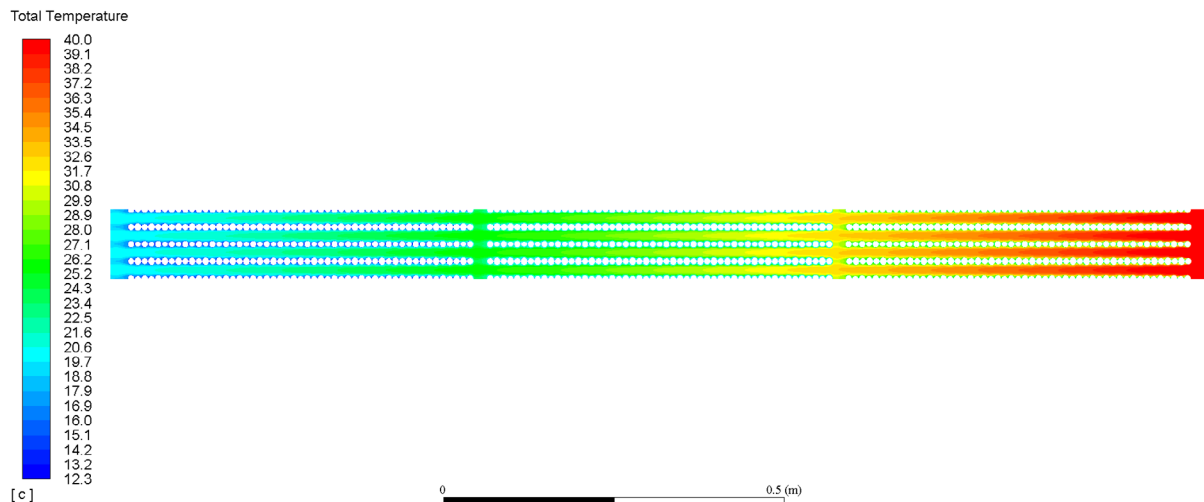


Figure 5. Field of temperatures in TE for the side ventilation system, °C

Source: developed by the authors

On Figure 6 presents the distribution of velocity vectors at the entrance to the HE channel for different types of ventilation systems. The analysis of the velocity field during the flow around the investigated bundle of pipes indicates their complex nature. On the part of the pipe surface adjacent to the flow in the inter-pipe channel, the velocity near the surface is maximum. Accordingly, a boundary layer is formed in these areas and the local values of the heat transfer coefficients will also be maximum. Separation currents are formed in the areas between adjacent pipes, close to the contact lines. The speed of the eddy flows in these areas is substantially lower, which leads to a decrease in the local values of the heat transfer coefficient on the surface of the pipes in the separation zones.

Therewith, the local values of the heat transfer coefficient for different flow zones can differ several times. To increase the areas where the local values of the heat transfer coefficient are maximum, the diameter of the pipes was chosen to be the minimum, since the size of

the separation and stagnation zones increases with the increase in diameter.

In the case of the tunnel ventilation system (Fig. 7), the maximum air speed in individual points is 17.6 m/s, and the average speed in the narrowest passage of the channel is 15.1 m/s. In the case of the lateral ventilation system (Fig. 8), the maximum speed in certain sections of the flow is 27.2 m/s, and the average is 23.5 m/s.

Table 2 provides a more detailed overview of CFD simulation results for different types of ventilation systems. Notably, depending on the location of the heat exchanger in the end zone of the poultry house (tunnel ventilation), the flow rate in the heat exchanger channels increases, i.e., the heat transfer coefficient on the surface of the beam increases. This, in turn, leads to a decrease in the number of pipes in the heat exchanger, a decrease in its weight and manufacturing cost. Differences in local heat exchange characteristics for tunnel and side ventilation systems help pick a better hot air cooling system – in this case, preference is given to tunnel ventilation.

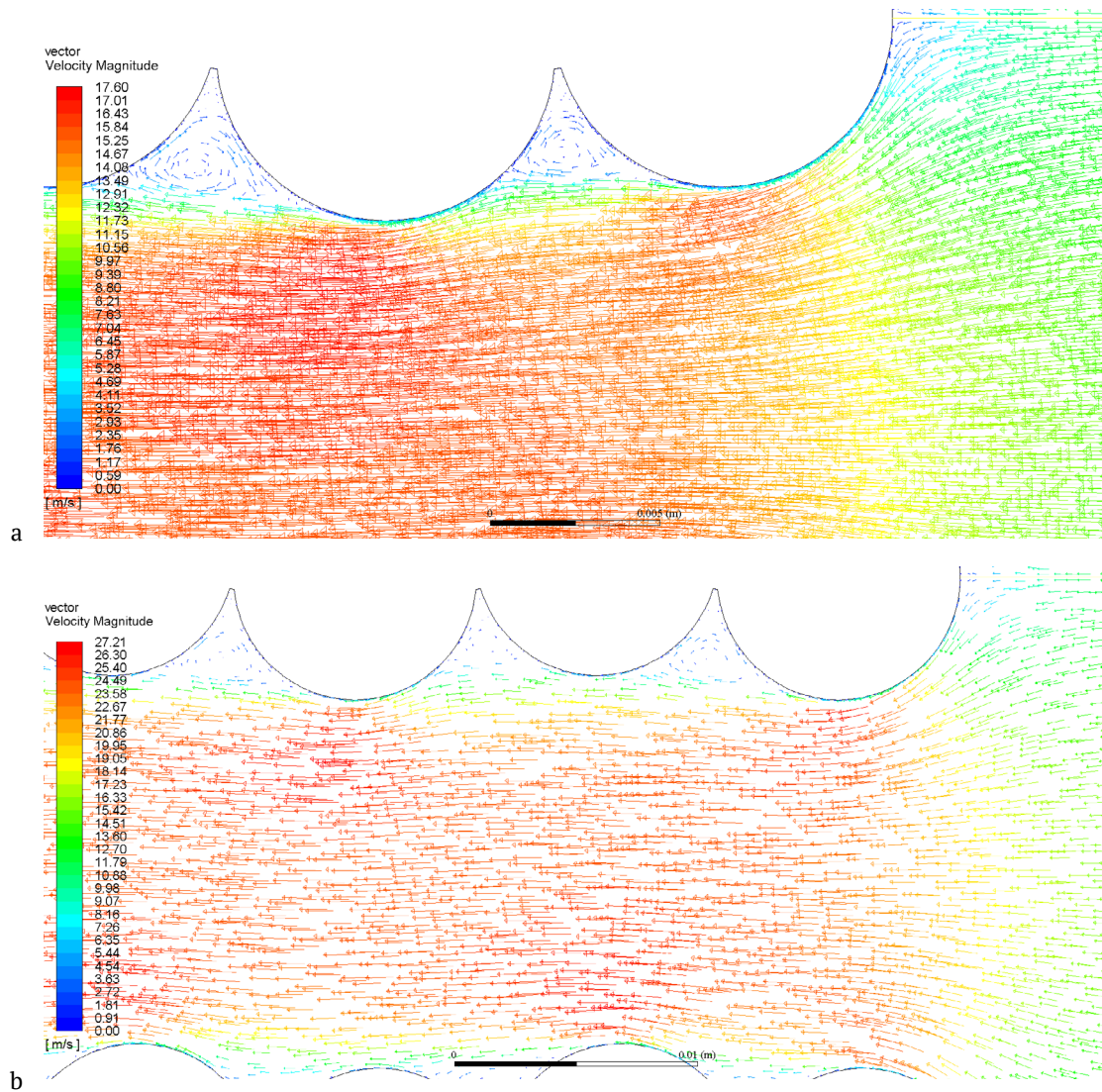


Figure 6. Airflow velocity vector at the entrance to the HE, m/s

Note: a – for the tunnel ventilation system, b – for the side ventilation system

Source: developed by the authors

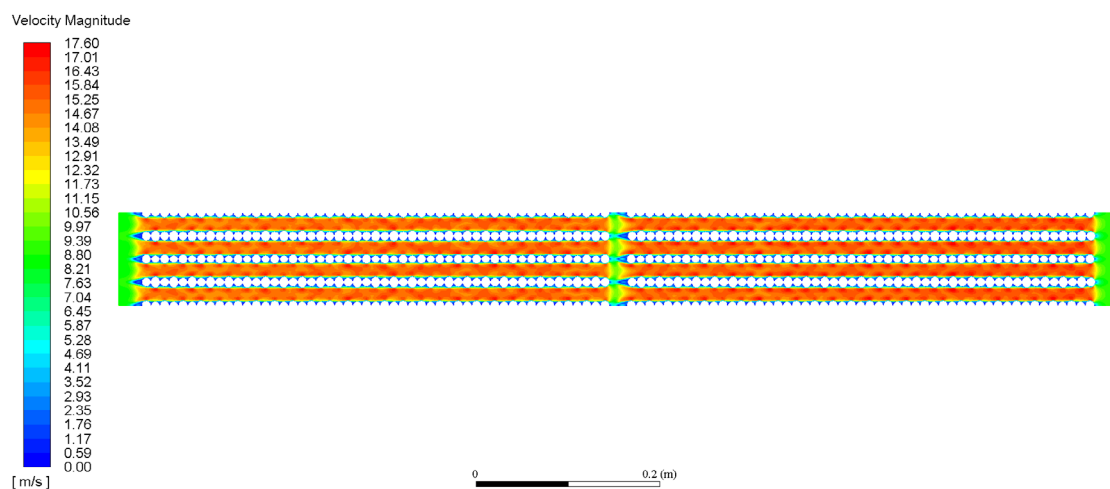


Figure 7. Air speed in the channel for the tunnel ventilation system, m/s

Source: developed by the authors

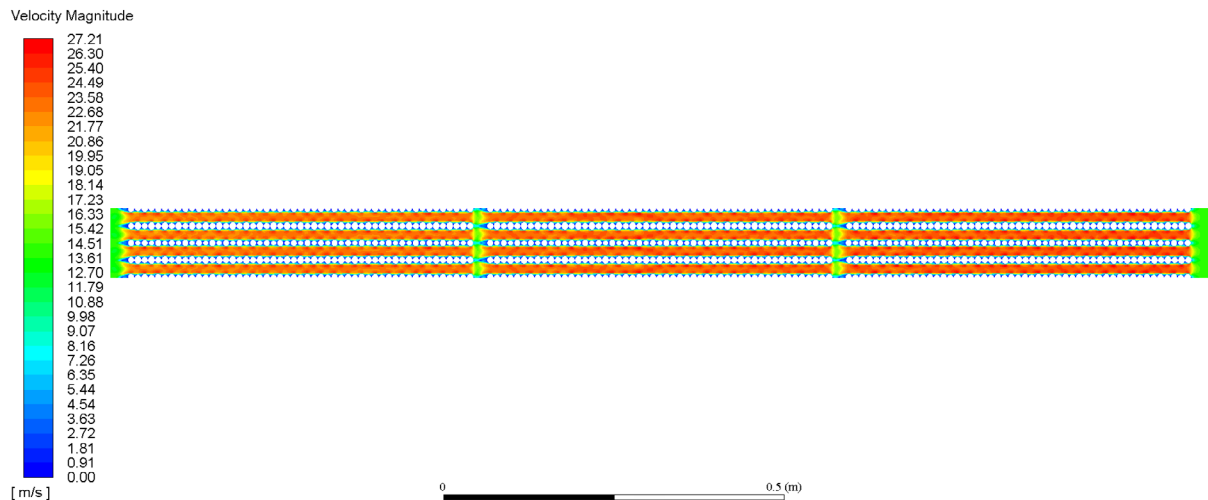


Figure 8. Air speed in the channel for the side ventilation system, m/s

Source: developed by the authors

Table 2. CFD simulation results of HE for different types of ventilation systems

Ventilation systems	Temperature of water at the exit from the HE, °C	Temperature of the air at the outlet of the HE, °C	Pressure drop in the HE channel, Pa	Average air speed in the narrowest section of the HE channel, m/s	Maximum air speed in the HE channel, m/s	Thermal capacity of all HEs, kW	Thermal capacity of one HE, kW
Tunnel	23.16	22.55	991	15.10	17.60	5,696.64	474.72
Side	23.95	19.66	3,286	23.53	27.21	6,204.00	77.550

Source: developed by the authors

From the comparison of heat exchangers according to the pressure drop in the channels (Fig. 9-10), developed for distinct types of systems, it can be observed that they differ by approximately 3.3 times. For the side ventilation system in the HE channels, the pressure drop is 3.3 kPa, the maximum pressure values in individual areas reach

3.44 kPa (Fig. 9). For the tunnel ventilation system, where the pressure drop is 0.99 kPa. At certain points of the channel, the pressure reaches 1.08 kPa (Fig. 7). Prominent pressure drops are accompanied by an increase in the power of exhaust fan motors. Thus, it will be more suitable to pick a HE for the tunnel ventilation system (Table 2).

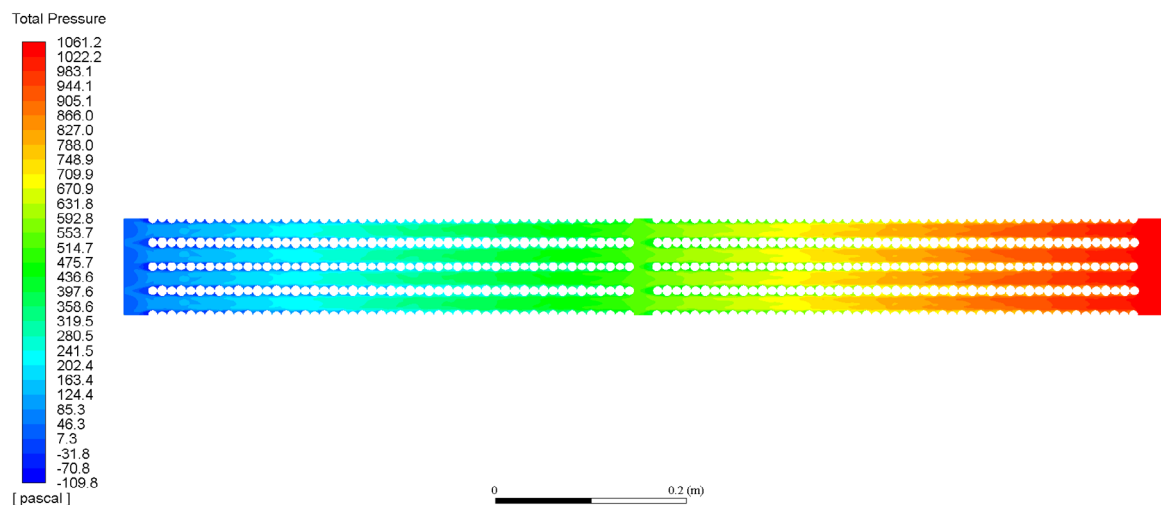


Figure 9. Pressure drop in the HE channel for the tunnel ventilation system, Pa

Source: developed by the authors

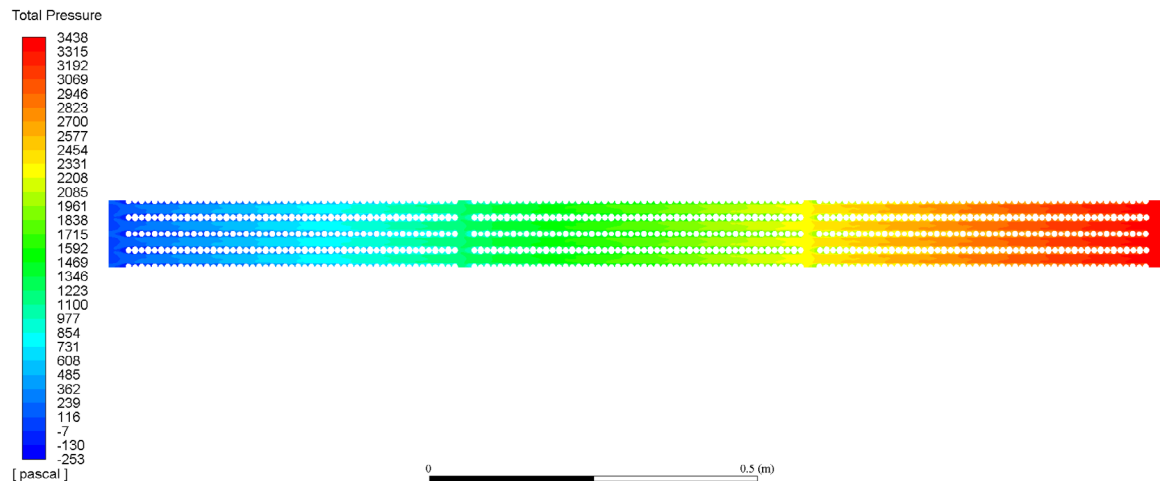


Figure 10. Pressure drop in the HE channel for the side ventilation system, Pa

Source: developed by the authors

When designing and manufacturing a heat exchanger for a microclimate control system in poultry houses, it is necessary to consider numerous parameters. These include the pressure drop in the heat exchanger channels, which affects the power and performance of ventilation systems; the temperature at the outlet of the HE, which enters the poultry house and cools the air in the room, etc. The basis of the project is the development of heating systems for two types of ventilation systems. In the case of the tunnel ventilation system, the pressure drop is 991 Pa, which is 3.3 times less compared to the side ventilation system. The outlet temperature is $+23^{\circ}\text{C}$, which meets the design requirements. But the disadvantage is the financial costs of purchase, pipe cutting, and thermal welding. Both the tunnel and side ventilation systems are quite effective. When choosing a ventilation system, one should consider such factors as pressure losses in heat exchangers, the amount of metal, as well as the material costs required for their manufacture. When the pressure loss increases, the power consumption required to drive the fans increases. The production of many heat exchangers for the side ventilation system increases their mass and, accordingly, the cost of their production compared to tunnel ventilation, for which only two heat exchangers need to be produced. Thus, to ensure normalized conditions of the air environment in the poultry house, considering all aspects of the technical and economic analysis, it is suggested to pick a HE for the tunnel ventilation system. Such costs are justified since the improvement of microclimate parameters helps increase the weight of poultry and increase the productivity of the poultry farm in the summer. However, the reconstruction of the ventilation system requires considerable capital costs, and not all poultry farms can afford the installation and maintenance of the proposed system.

Side ventilation system, according to the studies of V. Blanes-Vidal *et al.* (2008), E. Bustamante *et al.* (2017) is more effective. However, when using HE and judging by the research conducted in this paper, it is necessary to pick

a tunnel ventilation system. The article by N. Biçer *et al.* (2020) proved that the tunnel ventilation system is more effective in the hotter period of the year. The advantage of the tunnel ventilation system is that when the heat exchangers are placed on the end wall of the poultry house, the direction of air movement in the poultry house is straight and directed towards the end wall on which the exhaust fans are located. Therewith, in contrast to the lateral air supply, there is no change in the air direction by 90° , which, as is known, increases pressure losses due to an increase in local resistances. As a result, with the same mass flow of air, it is necessary to increase the power of exhaust fans. The second factor that improves the hydrodynamic pattern of the flow during tunnel ventilation is the smaller number of stagnant zones compared to the side ventilation system, which causes an uneven distribution of temperatures in the volume of the poultry house. The latter factor affects the conditions of the microclimate, under which chickens in some areas of the poultry house will be in worse conditions, which reduces the productivity of the poultry house as a whole.

In the studies of V.G. Gorobets *et al.* (2018), N. Biçer *et al.* (2020) it is assumed that the tunnel ventilation system is effective, compared to the rest of the known ones. The general conclusion of the conducted research is that the use of a cooling system using HE is an effective system for maintaining the microclimate. Notably, the conclusion made is confirmed by studies conducted by V.G. Gorobets *et al.* (2021), where HEs with different geometries of placement of small-diameter pipes in a pipe bundle were investigated. Therein, the displacement of adjacent pipes relative to each other was from 1 to 5 mm. Therewith, the excess pressure in such bundles reached up to 15 kPa. In this regard, in the present study, it is proposed to use a bundle of pipes with minimal displacement of neighbouring pipes. The maximum excess pressure is 3.3 kPa for the lateral ventilation system and up to 1 kPa for the tunnel ventilation system. The selected design solution with a

minimum displacement of the pipes in the bundle reduces the pressure drop by 4.5 times compared to the maximum pressure losses obtained in the study by V.G. Gorobets *et al.* (2021) for individual pipe arrangement geometries, where the displacement between adjacent pipes was large.

In the proposed heat exchangers for cooling external heated air, the design of the selected heat exchanger is substantially different from conventional designs. The difference lies in the choice of compact bundles, where the chequerboard or corridor arrangement of pipes in the bundle changes – in compact bundles of pipes, the step size between adjacent pipes in the flow direction is minimal. With such an arrangement of pipes in bundles, channels for the flow of air coolant are formed, where pressure losses are substantially smaller. This helps reduce the required power of ventilation systems when using heat exchangers of the proposed design.

The second major difference of such heat exchangers is the use of small diameter pipes. When flowing around individual pipes in a bundle, a boundary layer is formed on their surface at the point of attachment of the external flow, which breaks off in the aft part of the pipe. When using small-diameter pipes, the boundary layer formation length is substantially shorter compared to large-diameter pipes. Since the local values of the heat transfer coefficients are maximal at the initial areas of boundary layer formation, the value of the average value of the heat transfer coefficient on the surface of small-diameter pipes will be 1.5-2 times larger. This helps reduce the size of the heat exchangers of the proposed design by 1.5-2 times and reduce their weight by 15-20%.

A specific feature of the proposed design of heat exchangers for cooling supply air is displacement of adjacent pipes relative to each other. The amount of displacement can be 1-5 mm. Therewith, curved channels are formed between adjacent rows of pipes in the bundle, which increases the value of the heat transfer coefficient for the bundle as a whole. However, with an increase in the amount of displacement, pressure losses increase considerably, so it is necessary to choose such a configuration where the increase in the heat transfer coefficient would not lead to significant pressure drops in the heat exchanger channels. In the proposed design of the heat exchanger, the value of the displacement was selected equal to 1 mm. With such a displacement, the pressure loss will not be significant, i.e., the power of the fans for pumping the air coolant in the heat exchangers will be insignificant with an increase in the total heat transfer coefficient. The selected design of the heat exchanger is the best for the developed microclimate maintenance system in poultry houses.

The conducted studies suggest that when developing new systems for cooling supply air in poultry houses using shell-and-tube heat exchangers with compact placement of small-diameter pipes and well water as a coolant, a tun-

nel ventilation system can be recommended. To improve the mass-dimensional characteristics and increase the efficiency of heat exchange equipment, it is necessary to use working surfaces with heat exchange intensifiers.

CONCLUSIONS

A new system for maintaining the microclimate in poultry houses with tunnel and side ventilation is proposed, which is based on the use of water from underground wells to cool the outside air in shell-and-tube heat exchangers. An innovative design of the shell-and-tube heat exchanger with a compact arrangement of small-diameter pipes in pipe bundles for air cooling in the ventilation system has been developed. CFD modelling of hydrodynamics and heat transfer processes in pipe bundles of different geometries with their compact arrangement for various ventilation systems was carried out using the ANSYS Fluent software package. Fields of temperatures, pressures, and velocities in the channels of the HE under study were obtained. In the case of using a tunnel ventilation system, the average speed in the narrowest channel passage of such HEs is 15.1 m/s. The pressure drop is 991 Pa. And with a lateral ventilation system, the average speed of such HEs is 23.5 m/s, while the pressure is 3.3 kPa.

The conditions of hydrodynamics and heat exchange in the channels of the heat exchanger were analysed, and the factors affecting the intensity of heat exchange between the cold and hot coolant on the surface of the tube bundles were determined. The geometry of the pipe bundles and the flow regimes where the parameters of the cooled air meet the regulatory requirements were determined. Ventilation systems with tunnel and side ventilation were compared, and the advantages of tunnel ventilation for maintaining a normalized microclimate in poultry houses were proved. The design of the shell-and-tube heat exchanger, which is the most effective in the operation of ventilation systems, was determined. It was shown that the parameters of the selected heat exchanger using the tunnel ventilation system help reduce the pressure drop by 3.3 times compared to the heat exchanger for the side ventilation system and to reduce the material costs and funds for their manufacture. In the future, to increase the heat transfer coefficient, the authors recommend investigating the energy and mass-dimensional characteristics of the heat exchange equipment.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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**Дослідження теплових та гідродинамічних течій теплообмінників
для різних систем охолодження повітря в пташниках**

Анотація. Підвищення продуктивності птахофабрик пов'язане з необхідністю створення оптимального регульованого мікроклімату в пташниках. Ця проблема набуває першочергового значення у зв'язку зі зниженням продуктивності птахівництва через недосконалість існуючих систем. Метою дослідження була розробка та чисельне моделювання кожухотрубного теплообмінника нової конструкції для охолодження припливного повітря як елемента системи кондиціонування повітря, що використовується в системах вентиляції різних типів у літній період року. Для моделювання гідродинамічних процесів та процесів теплообміну в каналах з компактно розташованими трубами у пучку було застосоване CFD-моделювання з використанням програмного забезпечення ANSYS Fluent. Розглянуто два типи вентиляційних систем, а саме тунельну та бокову. Для них розроблені теплообмінники, призначені для охолодження повітря, що надходить у літню пору року. У бічних стінах були влаштовані автоматичні припливні клапани загальною кількістю 80 штук розміром 0,3×0,85 м. Крім того, на передніх торцевих стінках розташовувалися системи випарного охолодження 5,3×1,1 м. Проведено чисельне моделювання гідродинаміки і теплопереносу, а також аналіз роботи теплообмінників двох різних конструкцій для тунельної та бічної вентиляції. Отримано поля швидкостей, температур і тисків у досліджуваних каналах. Проаналізовано умови гідродинамічної течії в каналах теплообмінників. У випадку з тунельною системою вентиляції перепад тиску дорівнює 991 Па, що в 3,3 рази менше порівняно з системою бічної вентиляції. Температура на виході становить +23 °С, що відповідає вимогам проектування. Основним недоліком є фінансові затрати для придбання, порізки труб і власне, їх зварювання. З метою забезпечення нормованих умов повітряного середовища в пташнику з урахуванням усіх аспектів техніко-економічного аналізу запропоновано вибрати теплообмінник для системи тунельної вентиляції. На практиці такі теплообмінні апарати можуть використовуватись не лише у системах мікроклімату пташників, але також і в промисловій, енергетичній галузі та об'єктах критичної інфраструктури

Ключові слова: автоматичні припливні клапани; Computational Fluid Dynamics; птахоферма, тунельна вентиляція; бокова вентиляція

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Substantiation of the rational parameters of the hinged working bodies of the flexible screw conveyor

Abstract. The relevance of this study lies in the need to improve, develop innovative designs, and determine the best structural and kinematic parameters of the hinged sections of the screw working bodies of the conveyors, to obtain better functional and operational characteristics in transporting bulk and lumpy materials and granular fertilizers. Therefore, the purpose of this study was to improve the performance of flexible screw conveyors by developing and determining the best parameters of hinged flexible screw sectional working bodies for transloading bulk materials along curvilinear transportation branches. The study was conducted using the methods of the theory of mathematical and computer modelling, the method of mathematical planning of the experiment. The paper presents innovative designs of hinged screw working bodies and substantiates their best parameters for ensuring the movement of bulk materials along curvilinear routes. The study found the correlation between the magnitude of the torque that occurs between the loaded screw sections and their spatial arrangement. Analytical dependences were obtained for the stiffness conditions of a separate section with a hinged connection, depending on the load and design parameters of the conveyor. It was found that the angular displacement of the sections according to the state of dependence helps to significantly (up to 4-5 times) reduce the amplitude of the change in the torque of the drive and lowers its maximum value. It was proved that in the pushing mode, energy consumption is 1.06...1.4 times higher than in the pulling mode. The practical significance of the results lies in the ability to choose the optimal structural, kinematic, and technological parameters of the developed sections of the screw working body for transporting bulk or lumpy materials and mineral fertilizers

Keywords: screw conveyors; curvilinear branch of transportation; power parameters; bulk material; transloading gear

INTRODUCTION

The transportation of bulk materials requires compliance with standards related to maximum productivity in the execution of the technological process, minimization of energy consumption and damage to the bulk material. The execution of such technological operations during their movement on curvilinear branches in closed elastic fixed casings, carried out by screw conveyors, allows for high mobility of loading and unloading operations (Bulgakov *et al.*, 2017; Çelik & Güneş, 2017; Baranovsky *et al.*, 2018).

V.G. Gorobets *et al.* (2018), B.M. Hevko *et al.* (2018), V. Kuvachov *et al.* (2021) noted the specific features of

using screw conveyors for transporting or lifting bulk materials over short and medium distances. These studies also analysed the influence of such parameters as the rotating speed of the screw on the performance of the screw conveyor; angle of inclination of the conveyor feeder; volumetric filling level of bulk material. Operating conditions that affect the performance of a screw conveyor are considered by applying the Discrete Element Method (DEM) to simulate a single-stage screw conveyor with periodic boundary conditions. S. Xiaoxia *et al.* (2017), Y. Tian *et al.* (2018) established that the uniformity of the flow depends on the

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design of the screw working body and the hopper, the shape of the particles, and the force of friction against the walls. The results of this study improve the representation of the use of screw conveyors for particular materials.

R.B. Hevko *et al.* (2017), R.B. Hevko *et al.* (2018), V. Kaminskyi *et al.* (2021) proposed mathematical models of the screw conveyor loading process. The use of the proposed models creates conditions for the development of innovative designs of screw conveyor devices with substantiation of their rational parameters. H. Li & W.F. Liu (2012), M.R. Hevko (2013), O.L. Lyashuk *et al.* (2015) demonstrated the operating modes of an inclined screw conveyor that contains a helical working element with constant parameters. The kinematics of the grain load was studied based on the equations of motion in the screw conveyor. The movement of the freight in the established high-speed mode was analysed.

The studies of A.S. Merritt (2008), P.J. Owen & P.W. Cleary (2009), P.J. Owen & P.W. Cleary (2010) showed damage to grains when processing in a screw conveyor and estimated the moisture content of the bulk material (at three levels of 8%, 11%, and 14%), the gap between the working body and the casing (at four levels of 6 mm, 9 mm, 12 mm, and 15 mm) and screw rotation speed (at five levels of 100 rpm, 200 rpm, 300 rpm, 400 rpm, and 500 rpm). J.W. Fernandez *et al.* (2011) proposed a theoretical model of power consumption of a screw conveyor with flexible discreteness of spiral elements. Simulation results suggest

that increasing the spiral angle will increase the particle transport rate. Thus, it is necessary to improve and develop innovative designs of screw working bodies and substantiate the best structural and kinematic parameters of hinged sections of conveyor screws, which can ensure the improvement of functional and operational indicators of transporting bulk and lumpy materials and mineral fertilizers.

The purpose of this study was to improve the functional and operational characteristics of transporting bulk and lumpy materials and mineral fertilizers by improving and developing innovative designs of screw working bodies with a hinged connection of their sections and substantiating the best structural and kinematic parameters of the screws.

The originality lies in the establishment of patterns of changes in the kinematic and power parameters of the hinged screw working bodies of the augers for various load conditions and operating modes, as well as the distribution of stresses and deformations in the screw sections and the influence of the ratio of the parameters of the screw elements and axial plates on the twist angle and, accordingly, the bearing capacity of the section shaft and regularities.

MATERIALS AND METHODS

To improve the performance of screw conveyors, which lie in ensuring the transportation of bulk materials along curved routes, increasing the load-bearing capacity, as well as improving their maintainability, an auger with hinged sections was developed. Its scheme is presented in Figure 1.

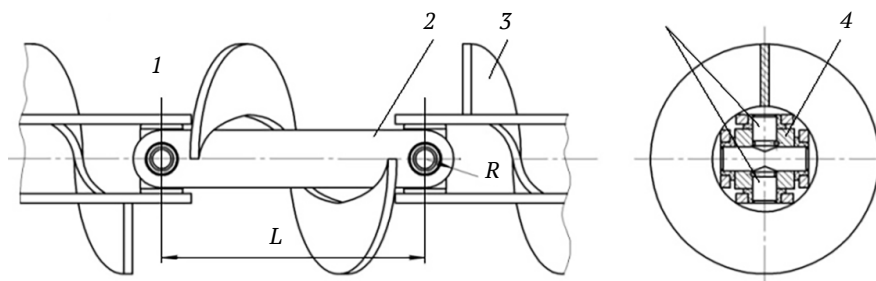


Figure 1. Design scheme of the developed auger with hinged sections

Note: 1 – plate; 2 – spiral rib; 3 – radial trunnion of the finger; 4 – intermediate frame, L – length of the hinged section; R – radius of the side surfaces of the hinged plates

Source: R.B. Hevko *et al.* (2018)

During the rotation of the working element in the elastic fixed casing between the sections, the torque is transmitted using plates 1 with a rib 2, which are rigidly fixed on a pair of radial pins of the finger 3 and the intermediate frame 4. During the operation of the conveyor along curvilinear routes, the radial fingers rotate, which ensures transmission of torque and helps transport bulk material with helical spirals.

The analysis of the technical characteristics of various brands of screw conveyors suggests that for the same structural dimensions (diameter $d=100$ mm and screw pitch $t=70...80$ mm), kinematic parameters (screw rotation speed $n=400...700$ mm) and technological character-

istics (the angle of inclination of the working body to the horizon $\alpha \leq 40^\circ$) the productivity of the conveyor during hopper loading of grain material for its bulk mass of 0.75 t/m³ is 20...25% higher compared to a self-loading nozzle (Roberts, 2015).

To increase the length of the technological branch in the central part of the conveyor, a transloading nozzle is installed, as well as drive nodes of the flexible working bodies of the loading and unloading tracks. This helps substantially reduce the torques on the working bodies at the points of attachment to the drive shaft. To conduct experimental research, a test bench was developed and manufactured, its design scheme is presented in Figure 2.

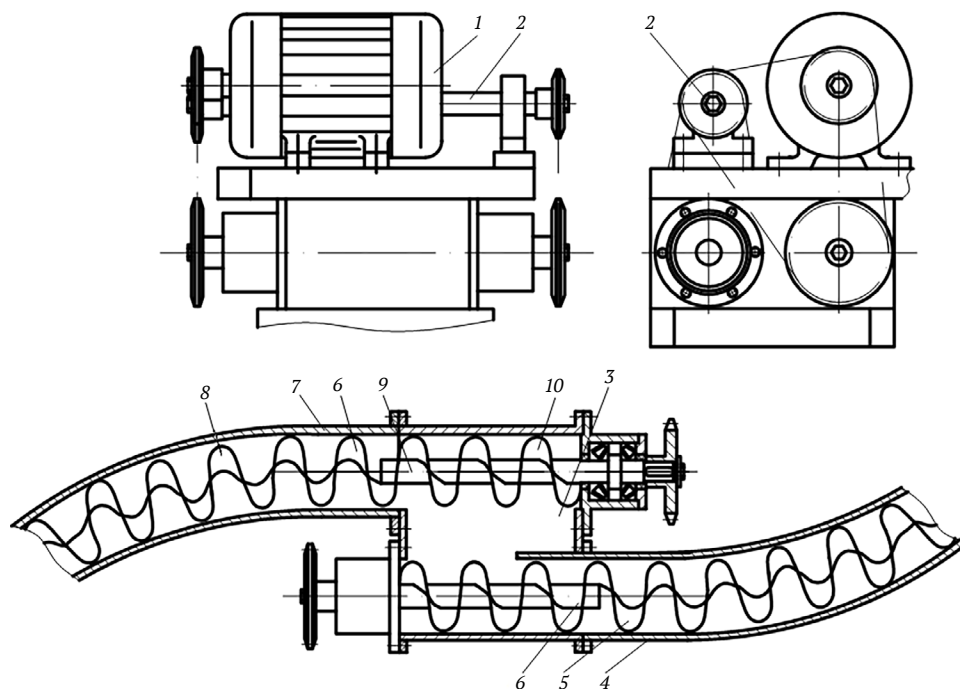


Figure 2. Schematic diagram of the flexible screw conveyor test bench

Source: A.W. Roberts (2015)

The overloading feeder of the test bench of the flexible screw conveyor (Fig. 2) contains the loading and unloading branches, which are designed in the form of casings 7 and 4, and the loading 8 and unloading 5 flexible screw bodies are placed in them in parallel. Screws, respectively, are fixed on the drive shafts 6 and 9, which are located in the overload feeder 3. Therewith, the intermediate shaft 2 is located parallel to the drive shafts and fixed on the overload feeder. The drive and intermediate shafts outside the overload feeder are kinematically connected to the shaft of electric motor 1.

During operation, the drive shafts are kinematically connected, the electric motor shaft and the intermediate shaft allow the working flexible working bodies to rotate. When feeding bulk or lumpy material, auger 8 transports it in a stationary casing towards the overload feeder. Because the drive shafts are located in a horizontal plane, the material to the unloading branch is moved via radial flat plates. The basis of the development of the hinged working bodies of flexible screw conveyors is the principle of the functioning of Hooke's spatial hinges of the polycardan type (Hevko, 2013). The angular displacement of the following after the first section is determined by the equations as follows:

$$\begin{aligned} \varphi_2 &= \arctg[(\cos \alpha_{1,2})^{-1} \operatorname{tg}(\varphi_1 + \psi_1)] - \\ &\quad - \arctg[(\cos \alpha_{1,2})^{-1} \operatorname{tg}(\psi_1)]; \\ \varphi_2 &= \arctg[(\cos \alpha_{2,3})^{-1} \operatorname{tg}(\varphi_2 + \psi_2)] - \\ &\quad - \arctg[(\cos \alpha_{2,3})^{-1} \operatorname{tg}(\psi_2)]; \\ \varphi_{n+1} &= \arctg[(\cos \alpha_{n,n+1})^{-1} \operatorname{tg}(\varphi_n + \psi_n)] - \\ &\quad - \arctg[(\cos \alpha_{n,n+1})^{-1} \operatorname{tg}(\psi_n)]; \end{aligned} \quad (1)$$

where φ_i is the angle of rotation of the section in the selected frame of reference; $\alpha_{i,i+1}$ is the angle between the axes of the sections in the plane that passes through the axes of the sections; i is the section number, $i=1,2,\dots,n$; ψ_i is the phase angle of the section hinge.

The angular velocity and angular acceleration were equal to:

$$\omega_{n+1} = \frac{a c \omega_1}{a^2 \sin^2 \varphi + (b \sin \varphi + c \cos \varphi)^2}, \quad (2)$$

where ω_{n+1} is the angular speed of the next section; ω_1 is the angular speed of the driving section.

In the case when $\omega_1 = \text{const}$, the angular acceleration of the section is determined according to the following expression:

$$\varepsilon_{n+1} = - \frac{a c \omega_1^2 [(a^2 + b^2 - c^2) \sin 2\varphi + 2 b c \cos 2\varphi]}{[a^2 \sin^2 \varphi + (b \sin \varphi + c \cos \varphi)^2]^2}, \quad (3)$$

where a, b, c are parameters of the model, which are determined through quantitative and spatial placement of sectional overcut elements:

$$\begin{aligned} a &= a_1 a_2 \dots a_n; b = a_1 a_2 \dots a_{n-1} b_n + a_1 a_2 \dots a_{n-2} b_n c_{n-1} + \dots \\ &\quad + a_1 b_2 c_3 \dots c_n + b_1 c_2 \dots c_n b; c = c_1 c_2 \dots c_n; a_1 = \cos \alpha_{1,i+1} 1 + \operatorname{tg}^2 \psi_i; \\ c_1 &= \cos \alpha_{i,i+1} + \operatorname{tg}^2 \psi_i. \end{aligned}$$

The considered power parameters during the twisting of the first and, respectively, the second section of the auger (Fig. 3):

The torque applied to the driven section from the driving section M_{21} is determined from the known dependence:

$$M_{21} = M_k \sqrt{1 + \tan^2 \alpha_{1,2} \cos^2 \Phi}, \quad (4) \quad \text{where } M_k \text{ is the torque required to move the freight by one section.}$$

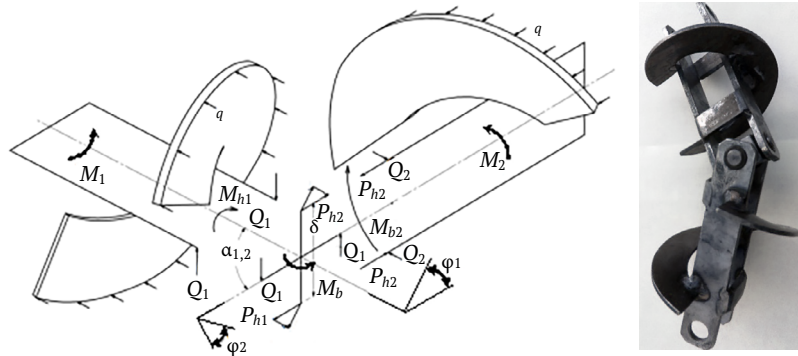


Figure 3. Placement of forces during a static load on the crosspiece

of the interfacial cross-shaped hinged rotary mechanism of the sectional working body

Note: M_1 is the torque of the driving section; M_2 – torque of the driven section; M_b is the bending moment; M_{h1} is the torque of the interfacial flexible rotary mechanism of the driving section; M_{h2} is the torque of the interfacial flexible rotary mechanism of the driven section; M_{b1} is the bending moment that occurs in the plane of the misalignment of the driving section; M_{b2} is the bending moment that occurs in the plane of the misalignment of the driven section; Q_1 is the cutting force of the driving section; Q_2 is the cutting force of the driven section; P_{h1} is the concentrated force of the interfacial flexible rotary mechanism of the driving section; P_{h2} is the concentrated force of the interfacial flexible rotary mechanism of the driven section; q is the distributed load affecting the spiral; $\alpha_{1,2}$ is the angle between the axes of the driving and driven sections in the plane that passes through the axes of the sections; ϕ_1 is the angle of rotation of the driving section; ϕ_2 is the angle of rotation of the driven section; δ is the lever where a pair of forces is applied

Source: M.R. Hevko (2013)

Accordingly, the torque from the drive M_{n1} , applied to the n^{th} (driving) section on the section from the track of constant curvature and, therefore $\alpha_{n+1,n} = \alpha_{n,n-1}$:

$$M_{n1} = M_k \{1 + [\prod_{m=1}^{n-1} \sqrt{1 + \tan^2 \alpha_{1,2} \cos^2 [\Phi - \pi \lambda (m-2)/(n-2)]]\}, \quad (5)$$

where λ is the parameter of the angular displacement of one section relative to another, n is the number of sections.

If the axes of each of the sections are placed parallel to each other, then the maxima of the alternating torque for all sections will coincide, and the drive will have maximum torque values with the maximum amplitude of their oscillations (Liashuk *et al.*, 2015). Figure 4 shows the graphs of the torque applied to a flexible screw, from the angle of its rotation along a curved path with a constant angular displacement between sections $\alpha_{n,n-1} = \pi/6$. The number of moving sections in the auger here is 8. The eighth section is fixedly connected to the drive, accordingly M_{81} is the drive moment. The moment needed to move the freight by one section was assumed to be $M_k = 100$ (units or %). Accordingly, in Figure 4a sections were placed without angular displacement, while in Figure 4b – with an offset $\Delta\phi_{n,n-1} = \pi/6$ in relation to the previous section. We assume that between the first and second sections $\Delta\phi_{2,1} = 0$.

It was found that the rational values of the angular displacements of the sections depend on their number in the transportation screw and is determined by the dependence $\alpha_{n,n-1} = \pi/(n-2)$.

Given that, according to dependencies (2) and (3), the kinematic and dynamic parameters of the sectional screw conveyor change, the costs of transporting freight along curvilinear paths associated with its periodic acceleration increase accordingly. And therefore, the effect of rational angular displacement of sections will be even greater.

The force is calculated according to the following formula:

$$P_{h1} = 0,5 M_{h1} / \delta, \quad (6)$$

where δ is the lever where the pair of forces is applied (Fig. 3).

As a result of the inclination of the axes of the overcut of the sections, there is a bending moment M_{b1} , which is applied in the planes of the skew of the sections, it is found from $M_{b1} = M_1 \tan \alpha_{1,2} \cos \phi$.

The bending moment acting in the overcut of the driven section was determined according to the formula:

$$M_{b2} = M_1 \tan \alpha_{1,2} \sin \phi (1 - \sin^2 \alpha_{1,2} \sin^2 \phi)^{0.5}. \quad (7)$$

In the case when it is necessary to increase the rigidity of the sections of the auger, it is proposed to use a design with rigid fastening of the screw strip to the shaft plates, which forms a kind of frame that enables a considerable increase in the rigidity of the section. The general appearance of the specified section and the model for finding its torsion angle are presented in Figure 5.

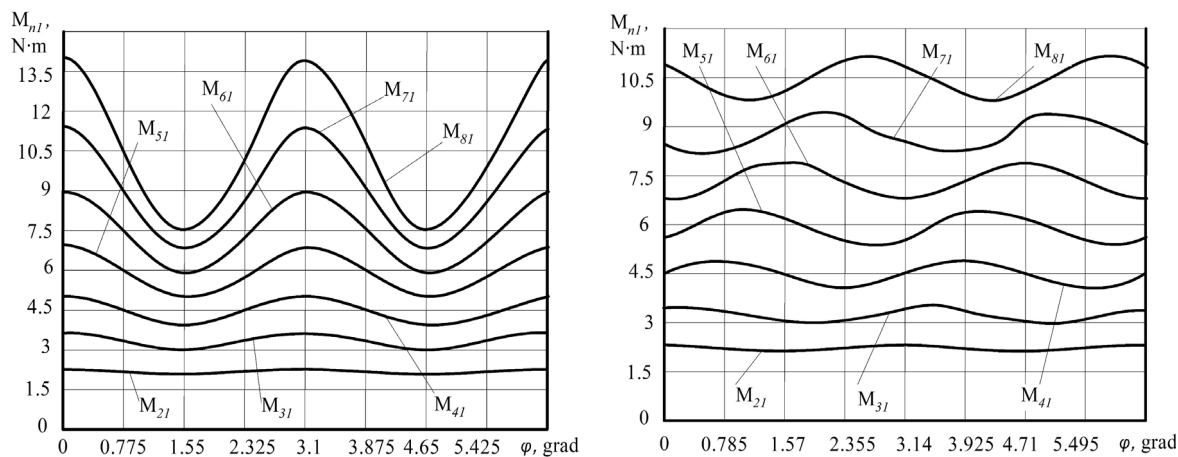


Figure 4. Change in torque on the drive 8 of the sectional shaft of the flexible screw from the angle of rotation of the screw, without angular displacement of sections, and with angular displacement $\alpha_{n,n-1} = \pi/6$

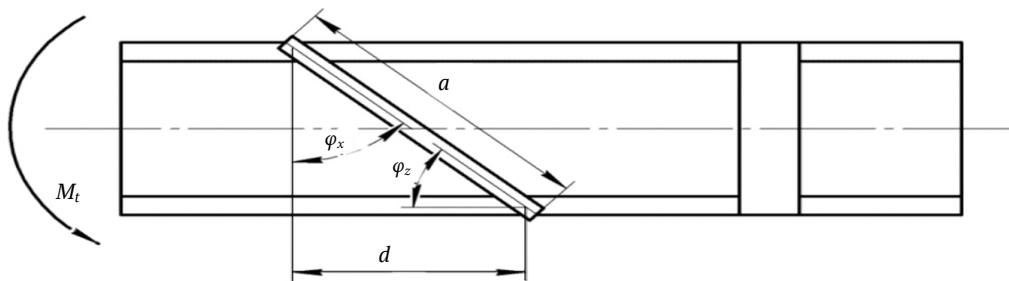


Figure 5. Design model for the determination of its torsion angle

Source: M.R. Hevko (2013)

Section stiffness condition for the permissible torsion angle:

$$\varphi = \frac{M_t l}{G J_d \left(1 + \frac{E F_p (2\omega \cos \varphi_z - e d \cos \varphi_x)^2}{m d G J_d} \right)} \leq [\varphi], \quad (8)$$

where M_t is the applied torque; l is the length of the sectional connection; m is the length of the rod between its attachment points; d is the distance between the points of the

inclined rod; E , G are the elasticity moduli of the first and second kind, respectively; J_d is the moment of inertia of the rod section; F_p is cross-sectional area of an inclined rod; ω is sectoral coordinate of the attachment point, m^2 ; φ_z , φ_x are the angles of inclination of the rod to the base of the section; e is distance from the centre of the bend to the plane.

A test bench was developed for conducting experimental research, the general view of which is presented in Figure 6.

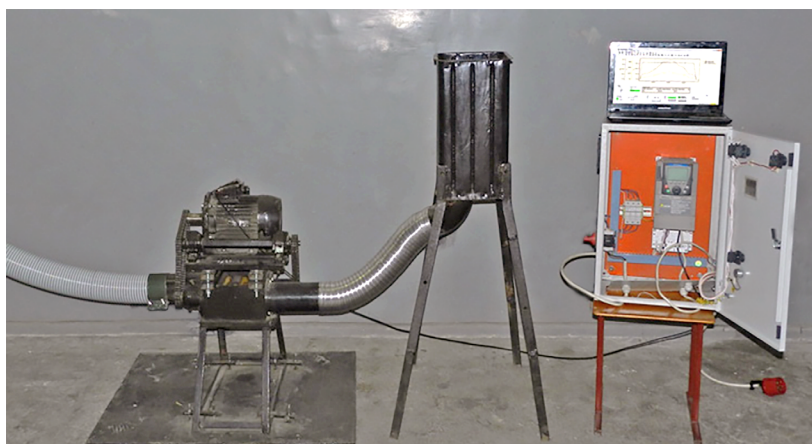


Figure 6. Test bench for conducting research

Source: developed by the author

The work of the test bench was as follows. Grain or bulk material was poured into the hopper and then moved to the unloading area. To start the engine and control its angular velocity, rotation was carried out using the Altivar 71 frequency converter and the Power Suite v.2.5.0 software. After the end of the material overload process, the curves of changes in torque and engine power over time were obtained on the computer display in the Power Suite program window.

The distance between the ends of the adjacent edges of the spiral Δ is adjusted by changing the length of the base of the shaft. It consists of hinged helical sections that have the form of two parallel flat plates, and helical ribs are attached to them. Flat plates, via anti-friction bushings, interact with the hinge element 4, which is made in the form of a square. A number of radial holes are made in mutually perpendicular planes in the hinge element, and the fingers are placed in them, with the fingers also placed on flat plates.

In the case of repositioning the fingers in the radial holes in the hinge element with their subsequent fixation, we can obtain adjustment of the length Δ of the screw pitch.

Thus, the control of the length Δ between the screw pitch can be obtained by using square bases of variable length, on the sides of which mutually perpendicular holes are made.

Parameters of the working element: external diameter of the rib – 96 mm; the inner diameter of the auger rib is 46 mm; rib pitch – 80 mm.

The screw rotation speed was adjusted using the Altivar 71 frequency converter. Tests were performed for three of its sizes: 14 mm, 28 mm, and 42 mm. With an increase in the length Δ of the pitch and the same length of the working body, its mass decreased and was 7.38 kg, 7.04 kg, and 6.64 kg, respectively. Therewith, the distance of overloading of agricultural material was 1.5 m.

RESULTS AND DISCUSSION

According to the research results, the curves of changes in the peak values of the torque T and engine power N depending on the increase in the rotation frequency of the screw n at different values of Δ in the pulling (Fig. 7a) and pushing (Fig. 7b) modes were obtained.

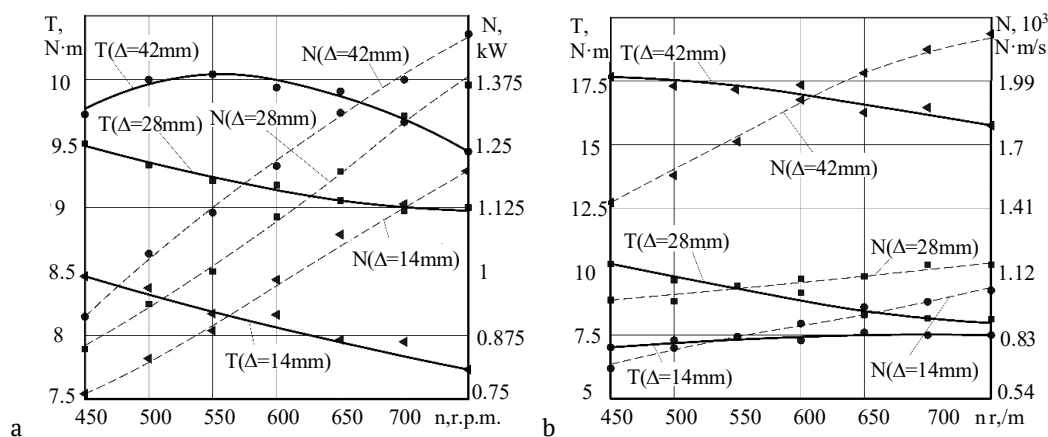


Figure 7. Graphs of changes in power N and torque T as a function of the rotation frequency of the flexible screw n , in steady (a) and pushing (b) modes during grain movement

Source: developed by the author

The analysis of the obtained curves shows that in the case of an increase in the rotation frequency n of the screw in the range from 450 to 750 rpm, the torque T tends to decrease. In the case of consideration of power N , the graphs were obtained with a linear nature of the growth of N as the value of n increases.

In this range of rotation frequency of the working body, bulk or lumpy material passes the length Δ not only due to kinetic energy, which is obtained through the interaction with the screw ribs, but due to the constant supply of material from the intake zone as well. An increase in the distance Δ between the ends of adjacent helical ribs leads to a relative increase in the values of torque T and power N because in transportation, part of the material accumulates between adjacent helical ribs, which adversely affects energy consumption.

Tests were also performed to establish the influence of the radius of curvature of the technological branch R_k and the height of the lifting of bulk material h on the value of the torque T and power N on the drive of the flexible conveyor during the movement of such bulk and granular materials as industrial salt, wheat, and peas.

Since the influence of the value of the rotation frequency of the flexible conveyor screw on the value of the torque had already been determined, the rotation frequency of the flexible screw was not changed, and its value was 450 rpm.

Based on the obtained results of the experimental tests, graphical dependences of the torque on the drive of the flexible auger on the height h of the transportation of agricultural material (Fig. 8) and on the radius of curvature R_k of the technological branch of the transportation (Fig. 9) were constructed.

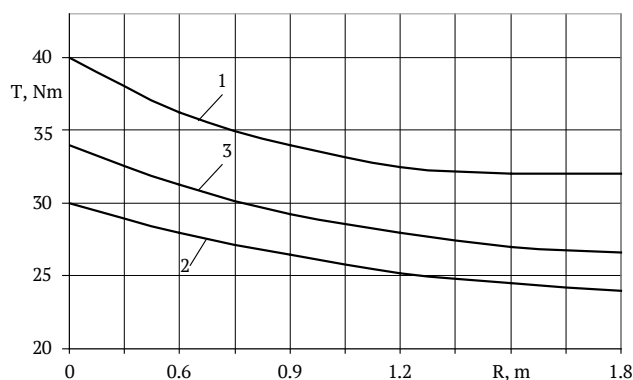


Figure 8. Variation of the torque T on the flexible screw from the radius of curvature of the transloading branch R_k for $n=450$ rpm for varied materials

Note: 1 – industrial salt; 2 – grain; 3 – peas

Source: developed by the author of this study

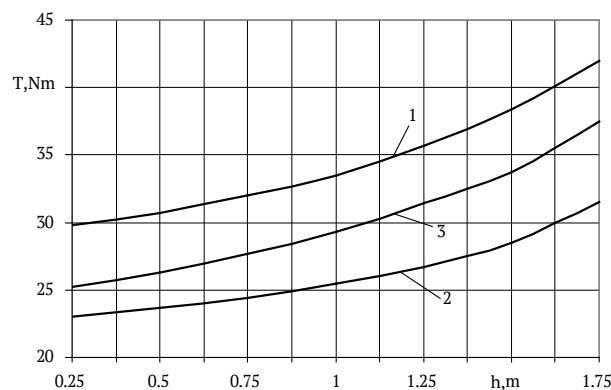


Figure 9. The change in the torque T on the flexible auger from the height of the agricultural material transloading h for $n=450$ rpm

Note: 1 – industrial salt; 2 – grain; 3 – peas

Source: developed by the author of this study

The analysis of the obtained graphs (Fig. 8) suggests that an increase in the curvature radius of the technological branch of transportation R_k in the range of 0.6...1.8 m leads to a decrease in the torque T ; therewith, for wheat $\Delta T=14\%$, for peas – $\Delta T=15\%$, and for technical salt $\Delta T=10.2\%$.

The analysis of the graphs (Fig. 9) suggests that an increase in the height of transportation of agricultural material h within the range of 0.25...1.75 m leads to an increase in the torque T ; therewith, for wheat $\Delta T=24.5\%$, for peas $\Delta T=30\%$, and for technical salt $\Delta T=29\%$.

From the data for conducting a multifactorial experiment, a regression dependence was derived to establish the influence of n , Δ , and h (height of lifting of agricultural material) on the torque T during grain transloading.

$$T = -0,667442 + 0,012691n + 17,064586h + 0,118525\Delta - 0,000005n^2 - 0,005277nh - 0,000438n\Delta - 0,827612h^2 - 0,023019h\Delta + 0,014866\Delta^2 \quad (9)$$

Figure 10 shows the response surfaces of changes in T values due to changes in two factors.

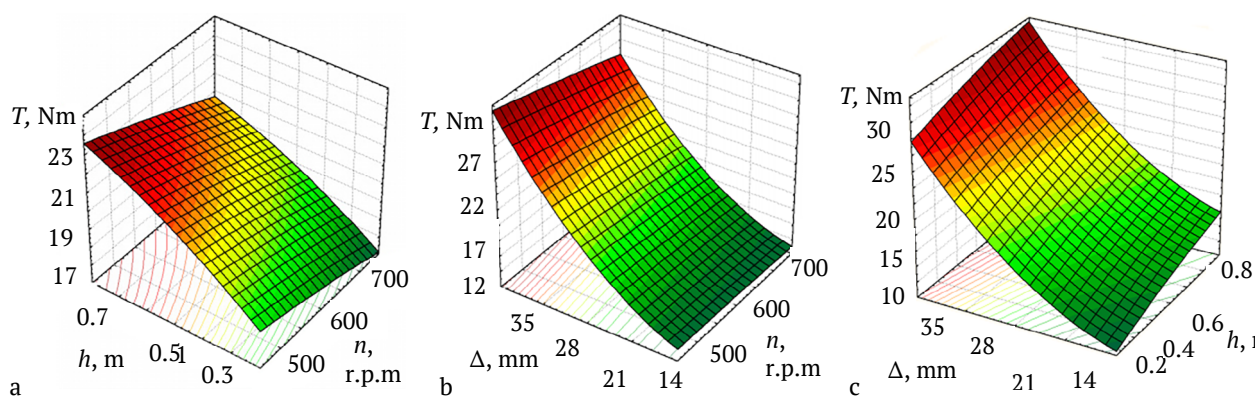


Figure 10. Response surfaces of a drive shaft torque from variable factors

Note: a: $T=f(h,n)$; b: $T=f(\Delta,n)$; c: $T=f(\Delta,h)$

Source: developed by the author of this study

It was determined that the dominant factor affecting the value of the torque T is the value of the gap Δ and n ; however, the height of lifting the load h also has a substantial effect on the value of T .

The factor field was determined by the following range of parameter changes: 400 (rpm) < n < 700 (rpm); 0.2 (m) < h < 1.2 (m); 0.014 (m) < Δ < 0.042 (m).

A test was conducted to determine the efficiency of a screw conveyor with a flexible working element. The parameters of the developed working element were as

follows: $D_k=100$ mm; $D=96$ mm; $d=46$ mm; $p=80$ mm. The research was carried out using bulk materials of the appropriate bulk mass: wheat – 720 kg/m³; peas – 728 kg/m³; compound feed – 555 kg/m³; bran – 252 kg/m³.

It was determined that the maximum efficiency of the conveyor for transporting materials of larger bulk mass (peas, wheat) corresponds to the rotation frequency of the screw working body within 650...670 rpm and their values are similar: (7...7.2 m³/h; 5...5.2 t/h). A further increase in the rotation frequency n of the working element causes a

decrease in the efficiency of the conveyor, which can be explained by a smaller volume of material intake. Having a greater bulk weight, the material reacts more slowly and partially returns to the hopper. In the case of lighter materials (combined feed, bran) in this range of changes in the frequency of rotation of the working element, an increase in efficiency factor is observed and their nature is linear.

The analysis of theoretical studies of the working bodies of flexible screw conveyors (I. Çelik & E.C. Güneş (2017), V. Kuvacov *et al.* (2021)) suggests that most authors derived analytical dependencies to establish operational, structural, and functional parameters of flexible screws. H. Li & W.F. Liu (2012), O.L. Lyashuk *et al.* (2015) proposed mathematical models of the vertical screw conveyor loading process. An algorithm for solving differential equations with partial derivatives of the movement of a fluid medium in a screw channel has been developed. The use of the proposed model helps develop innovative designs of intake devices of screw conveyors with substantiation of their rational parameters.

Therewith, the issues regarding the substantiation of the parameters of the working bodies, which ensure their high operational functional and characteristics at the minimum permissible weight of the auger structure, are not resolved. Solving these problems will help significantly reduce energy costs for the process of moving, the degree of damage to bulk and lumpy agricultural material.

Studies presented in the studies by M.R. Hevko (2013), V.M. Baranovsky *et al.* (2018), and the proposed type of screw working body are characterized by 8-12 times lower energy consumption for the transportation of bulk materials.

Comparing the performance of a rigid (horizontal, inclined, and vertical) screw working body of the conveyor, the study of which is described in the articles of A.S. Merriitt (2008), S. Xiaoxia *et al.* (2017), Y. Tian *et al.* (2018), it can be stated that the proposed design of the working body is different in that it helps transport materials along curvilinear tracks, which considerably increases the productivity of the flexible screw conveyor. H. Li & W.F. Liu (2012), M.R. Hevko (2013), O.L. Lyashuk *et al.* (2015) proposed the use of a flexible tubular screw conveyor to extend the range of self-loading. The main shaft and outer tube are made of rubber, and the propeller blade is made of continuously rigid plastic. The conveyor is commonly used in a wide range for flexibility. A method of reducing the wear of the screw conveyor is proposed. Furthermore, the change in energy consumption of the conveyor transmission under the influence of the design parameters of the screw was analysed.

In the study of D. Mondal (2018), the filling factor of the screw conveyor is a key point for the transmission efficiency. It is proposed to determine it using a ribbon helix with different screw speeds. Design parameters and rotation speed are optimized using EDEM simulation software. The theoretical results are then verified experimentally.

İ. Çelik & E.C. Güneş (2017) suggested a flexible discrete screw conveyor with spiral blades. The parameters of energy consumption when using a flexible helical blade

structure were investigated employing theoretical analysis and simulation experiments.

The study results presented in this paper relate to helical spirals without the use of a flexible shaft. However, based on the practical observations of S. Xiaoxia *et al.* (2017), P.J. Owen & P.W. Cleary (2010), during the transportation of material along a curvilinear route (especially with small radii of curvature equal to about 1.5 m) due to the presence of cyclic deformations caused by the presence of different signs during the screw rotation, destruction occurs, which significantly limits the use of such screws due to non-performance operational requirements. Whereas the proposed working body can work at a minimum radius of curvature in the technological line of about 0.5 m, which considerably increases the mobility of the flexible screw conveyor. Therefore, to increase the reliability of the technological process during the development and research of working bodies, it is necessary to use a sectional method of manufacturing flexible screws, which will help eliminate sign-changing cyclic loads; to increase the contact area between the torque transmission nodes, which allows reducing the internal stresses and forces in the friction pairs due to the increase in the torque transmission arm.

Based on the obtained analytical dependencies, for the selection of rational design parameters of flexible sectional screw conveyor working bodies, the interrelationship of power characteristics was established, proceeding from the conditions of its operation, the laws of influence of structural nature and force. The dynamic and technological parameters of the developed flexible sectional screw working bodies were established according to the functional and performance indicators of the flexible screw conveyor process.

CONCLUSIONS

To improve the performance of screw conveyors, namely, to ensure the transportation of bulk materials along curvilinear routes, to increase the load capacity, as well as to increase their maintainability, a hinged screw working element was developed. The performed theoretical calculations of the structural and kinematic characteristics of the hinged sections of the screw helped determine the relationship between the magnitude of the torque that occurs between the loaded screw sections and their spatial location. Analytical equalities of the condition of stiffness of a separate section and elements of the hinged connection depending on the forces and structural dimensions of the working body were derived.

It was found that the angular displacement of the sections according to the dependence obtained in the study allows reducing both the amplitude of the change of the drive torque (up to 4...5 times) and its maximum value. A study was conducted using the developed test bench and a hinge-screw working body to determine the torque T and the power N . Based on the conducted multifactorial experiment, a regression relationship was obtained to determine the effect of the rotation frequency of the working body n , the value Δ and the height of the material lift h on the value

of the torque moment T during grain material transportation. Its analysis strongly suggests that the dominant factor affecting the value of T is the setting of the clearance Δ , followed by the value of n and the height of the material lift h .

Based on the conducted set of theoretical and experimental studies, a competitive sectional screw working body was created, which allows improving the functional and performance characteristics of screw conveyors for transporting bulk and lumpy agricultural materials. The use of the proposed sectional screw working bodies in the constructions of conveyors, considering the recommended parameters, will allow transporting agricultural materials efficiently along curvilinear tracks.

In the future, it is necessary to perform calculations and analyse the change in the efficiency factor of the hinged mechanism depending on the main design parameters. To establish the feasibility of using long conveyor screws with a significant number of elements, to determine the limits of increasing the bending radius of the screw in this case to improve the overall efficiency factor of the entire conveyor.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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None.

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Обґрунтування раціональних параметрів шарнірно з'єднаних робочих органів гнучкого гвинтового конвеєра

Анотація. Актуальність дослідження полягає в необхідності вдосконалювати, розробляти нові конструкції та визначати оптимальні конструктивні та кінематичні параметри шарнірно з'єднаних між собою секцій шнекових робочих органів конвеєрів, з метою отримання кращих функціональних й експлуатаційних характеристик процесу транспортування сипких та кускових матеріалів і гранульованих добрив. Тому метою проведеного дослідження було покращення експлуатаційних показників гнучких шнекових конвеєрів шляхом розроблення й визначення оптимальних параметрів шарнірно з'єднаних між собою гнучких гвинтових секційних робочих органів для перевантаження сипучих матеріалів по криволінійних гілках транспортування. Дослідження виконано із використанням методів теорії математичного та комп'ютерного моделювання, методу математичного планування експерименту. У статті представлено нові конструкції шарнірних гвинтових робочих органів та обґрунтовано їхні оптимальні параметри для забезпечення переміщення сипких матеріалів по криволінійних трасах. Визначено взаємозв'язок між величиною крутного моменту, який виникає між навантаженими гвинтовими секціями та їх просторового розміщення. Отримано аналітичні залежності для умов жорсткості окремої секції із шарнірним з'єднанням в залежності від навантаження та конструктивних параметрів транспортера. Встановлено, що кутові зміщення секцій згідно встановленої в статі залежності, дозволяє суттєво (до 4-5 раз) зменшити амплітуду зміни крутного моменту приводу, а також понизжує його максимальне значення. Було доведено, що при штовхаючому режимі енерговитрати є більшими у порівнянні з тягнучим у 1,06...1,4 рази. Практичне значення результатів полягає в можливості обрати оптимальні конструктивні, кінематичні та технологічні параметри розроблених секцій гвинтового робочого органу для транспортування сипких чи кускових матеріалів і мінеральних добрив

Ключові слова: шнекові механізми; криволінійна гілка транспортування; силові параметри; сипкий матеріал; перевантажувальні механізми

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