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Physico-Mathematical Apparatus for Numerical Modelling of Feed Expander

Abstract. The productivity of the feed preparation line and its technical and economic efficiency are affected by the design and technological parameters of the equipment. The geometry of the expander screw and its operating modes are no exception. To reduce the specific energy consumption of the expander, it is necessary to establish its rational design and operating parameters. This can be done using analytical calculation methods that consider the mechanisms of movement and destruction of solid substances. Modelling using the discrete element method is becoming increasingly common to describe the movement of solid components in granulators, extruders, or expanders. The purpose of the study is to improve the physical and mathematical apparatus of movement of solid feed components in the screw channel of the feed expander and develop a method for its numerical modelling. Numerical modelling was performed using a model of the movement of a multiphase Euler mixture with a split flow in three-dimensional space. In this case, the motion was subject to an admissible two-layer k-ε model of turbulence and the multiphase equation of state. The physical and mathematical apparatus for the movement of solid feed components in the screw channel of the feed expander was improved, which is the basis for the numerical modelling technique in the Star-CCM+ software suite, based on the fact that the conglomerate of feed components is represented as a package of spherical particles. In this case, the pressure force must be compensated by the total force of contact interaction of particles with each other and the wall. Preliminary numerical modelling of the process of expanded feed preparation was performed in the Star-CCM+ software suite. The practical significance lies in the fact that the improved physical and mathematical apparatus and the developed method of numerical modelling of the feed expander operation process allow substantiating its design and regime parameters to ensure low specific energy consumption without losing the quality of the technological process

Keywords: feed expansion, simulation, discrete element method, Star-CCM+, pressure, velocity vector field, density

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INTRODUCTION

The choice of the technological mode of feed preparation, as a rule, is based on conducting comprehensive studies that identify the nature of changes in the structure and properties of both individual components of raw materials and the feed value of the processed material.

The science of animal feeding has accumulated a large amount of experimental data on the effects of various nutrients, essential amino acids, vitamins, macro- and microelements, antibiotics, hormones, enzymes, and other components on the metabolism and efficiency of feed use. These data serve to further improve the theory and practice of animal feeding in agriculture. They ensure the realisation of the genetic potential of animal productivity. The more efficient the level of feeding, the higher the productivity of animals and the lower the feed consumption per unit of production [1; 2].

With conventional animal feeding, most of the feed is produced on farms. The use of feed in unprocessed form leads to low digestibility. It is known that animals convert only 20-25% of feed energy into products. The task of feed preparation is to reduce these losses by increasing the digestibility of feed [3; 4].

This problem can be solved by subjecting the feed to complex processing in one machine, to carry it out quickly and continuously (to make compositions of several

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components, mix, compress, heat, cook, sterilise, almost simultaneously), which, in the end, affects production cost.

To date, mixed feed and feed additives must meet the requirements of veterinary and sanitary standards [5]. The microflora of manufactured products is determined not only by the quality of raw materials used, but also by the way the production process is conducted, the level of its automation. The main reason for the deterioration of feed quality indicators is microorganisms. They contribute to the development of various unfavourable processes – self-heating, the appearance of a sharp smell, and colour changes [6]. The development of microorganisms can lead to a complete loss of the original properties of mixed feed and make it unsuitable for feeding to farm animals and poultry. The solution of these tasks is possible in machines for deep feed processing: extruders or expanders. The use of expansion technology improves the quality and digestibility of feed, eliminates harmful components for nutrition, and reduces the energy intensity of feed production.

Processing and preparation of feed involve a certain set of influences of the working bodies of technical means on the environment, which is a variety of feed materials with significantly different properties. Therefore, the real performance indicators of machines can be considered only in connection with the physical and mechanical properties and quality of feed.

The geometry of the expander screw has a great influence on the capacity of the extended feed preparation line, and on their quality, and, therefore, is crucial for technical and economic efficiency [7]. To save specific energy costs, there are various analytical calculation methods that consider the mechanisms of movement and destruction of solid substances, so there is no need to conduct long-term experiments by trial and error. There are many assumptions and simplifications that need to be made to obtain an analytical solution; for example, the assumption that feed components form a solid layer that flows at a uniform rate [8]. Modelling using the discrete element method (DEM) is becoming increasingly common for describing solids moving in granulators, extruders, or expanders, since relative displacements between particles are possible [9-11]. The DEM simulation model is used for the virtual design of experiments and allows getting a large database for evaluating the effectiveness of the technological process.

LITERATURE REVIEW

For a better understanding and discussion of the presented problem, some analysis of the theoretical prerequisites for the movement of solids in single-screw granulators, extruders, and expanders is given.

Many approaches to describe the motion of solids in a single-screw granulator, extruder, or expander that have been known so far can be reduced to the concept of the model by W.H. Darnell and E.A.J. Mol [12]. In this model, it is assumed that the pellets behave like a solid block and flow through the helical channel as a solid layer in the block flow. Various pressure and friction forces act on this solid layer, which allow calculating the direction of movement based on the balance of forces and moments. Since then, modelling, especially forces, has been discussed in detail and adapted in many scientific studies.

The above analytical model for describing the motion of solids based on physical and mathematical considerations temporarily ceased in the early 2000s, as numerical modelling based on the discrete element method (DEM) appeared. This was made possible primarily by improving the performance of a personal computer. DEM developed by P.A Cundall and O.D.J. Strack [13] was originally developed for modelling molecular dynamics and has since found wide application in technological processes, mechanical engineering, and geotechnics.

The main advantage of DEM modelling is that it is necessary to make fewer preliminary assumptions about the behaviour of bulk material particles. The basis of DEM is the representation of particles as spheres or particles consisting of several spheres. To calculate the interaction of these particles with other particles or geometries, they are not connected, but virtual overlap is used. Depending on this overlap and boundary conditions, contact models calculate contact forces in the normal and tangential directions. These forces are then used to solve conservation-of-momentum equations and calculate new quantities of motion. When these motion values are integrated at the modelling stage, new particle positions appear, and thus new virtual overlaps appear, and the calculation cycle begins again [14; 15].

Due to the good suitability of DEM for describing the movement of solids in granulators, extruders, or expanders, this method is used to evaluate existing analytical calculation approaches. The main weak point of analytical models is that they never deviate from the assumption of block flow. Moreover, for this reason, the calculation of structural and technological parameters of a screw of complex design may be inaccurate.

The purpose of the study is to improve the physical and mathematical apparatus of movement of solid feed components in the screw channel of the feed expander and develop a method for its numerical modelling.

MATERIALS AND METHODS

The analysis of the movement of solid feed components in the screw channel of the expander is based on the dynamics of movement of solid particle systems by the discrete element method (DEM). Solid feed components, as discrete elements, are fed into the screw channel through the hopper. The flow in the hopper is usually carried out by gravity, although in certain circumstances it is necessary to create additional effort. This study does not address this issue. After the feed components enter the screw channel of the expander, they begin to move along a horizontal line in a spiral. Due to the reduced geometric dimensions of the screw channel, the feed components are compacted to form a solid layer or conglomerate, which is then transported to the forming nozzle.

To consider the physical and mathematical apparatus of movement of solid feed components in the screw channel of the expander, a corresponding calculation scheme is drawn up (Fig. 1). Fig. 1 shows the following geometric parameters of the expander: cylinder diameter D_b, screw shaft diameter D_s, screw channel depth h, screw pitch t, screw-cylinder gap δ, screw channel width b, screw spiral angle φ, and screw winding width *e*.

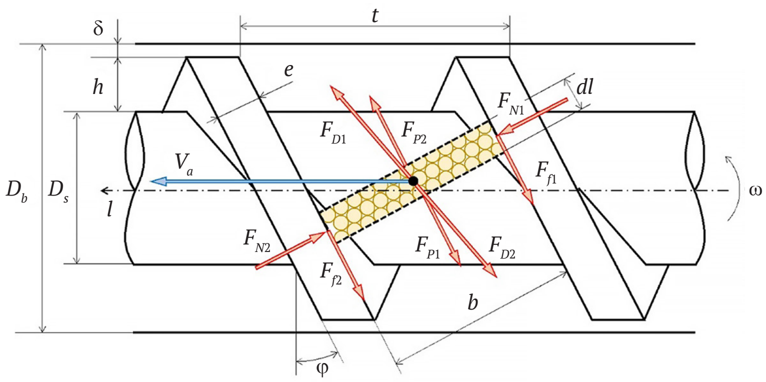


Figure 1. Design scheme of movement of solid feed components in the screw channel of the expander
Source: developed by the authors based on [16-18]

As noted above, its geometric parameters change along the length of the expander screw. According to studies [16-18], to "ensure the quadratic (or, as a special case, linear) nature of changes in the parameters of the screw, namely, the cross-sectional area of the screw channel, the area and volume of the channel along the length of the screw, it is sufficient to provide a linear change in two geometric parameters of the screw, namely, the width of the screw channel (screw pitch) and its depth", that is

$$\begin{cases} t = t_0 + k_b dl, \\ h = h_0 + k_h dl. \end{cases} \quad (1)$$

where t – current screw pitch, m; t_0 – initial screw pitch, m; h – current screw channel depth, m; h_0 – initial screw channel depth, m; k_b – "coefficient of change of screw pitch by its length" [16]; k_h – "coefficient of change of the screw channel depth by its length" 16]; *dl* – minimum pitch along the length of the screw channel, m.

Next, the study considers all the forces acting on a conglomerate of feed components during its transportation and compaction (Fig. 1). These forces are considered at the macro level (excluding DEM) under the assumption that the conglomerate of feed components is continuous and homogeneous. Thus, according to Fig. 1, the following forces act on a conglomerate of feed components:

– normal reaction forces between the conglomerate of feed components and the side walls of the screw F_{N1}, F_{N2};

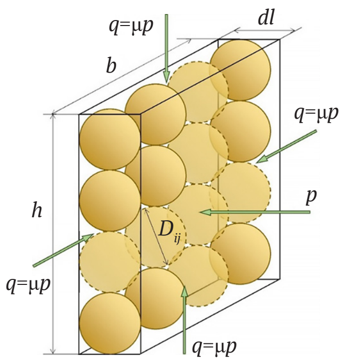
– friction forces between the conglomerate of feed components and the side walls of the expander screw F_{f1}, F_{f2};

– friction force between the conglomerate of feed components and the screw F_{D1};

– friction force between the conglomerate of feed components and the cylinder F_{D2};

– normal force from pressure F_{P1}, F_{P2}.

In studies [16-18], the differential equilibrium equation of the conglomerate element of feed components was solved and the dependence of pressure changes along the length of their movement along the expander channel was obtained. The dependence of the pressure created on the element of the conglomerate of feed components obtained by V.V. Bratishko [16-18] does not consider its structure. Considering a conglomerate of feed components as a dense package of spherical DEM particles (Fig. 2), the pressure force must be compensated by the total force of contact interaction of particles with each other and the wall.



q – lateral pressure, Pa;
p – pressure in the granulator channel, Pa;
h – current screw channel depth, m;
b – screw channel width, m;
μ – lateral pressure coefficient;
dl – minimum pitch along the length of the screw channel, m;
D_{ij} – ij particle diameter

Figure 2. Dense packing of spherical particles of solid feed components in the screw channel of the expander
Source: compiled by the authors

Pressure force F_p is calculated from the geometric parameters of the screw and the number of particles N in the force field in the elementary volume of an element of a conglomerate of feed components:

$$F_p = \frac{q\pi\left(D_b^2 - D_s^2\right)}{4N}, \tag{2}$$

where q – lateral pressure, Pa; D_b – cylinder diameter, M; D_s – screw shaft diameter, m; N – number of particles.

Number of particles N in the unit volume of an element, a conglomerate of components can be calculated as follows

$$N = N_b N_h = \left\lfloor \frac{b}{\langle D_{ij} \rangle} \right\rfloor \left\lfloor \frac{h}{\langle D_{ij} \rangle} \right\rfloor, \tag{3}$$

where N_b – number of particles along the channel width; N_h – number of particles along the channel depth; D_{ij} – ij particle diameter; $\langle\,\rangle$ – average value function; $\lfloor\,\rfloor$ – function for determining the largest integer that is less than or equal to the number in parentheses.

To determine forces of contact interaction of feed components with each other, a suitable scheme for calculations is drawn up (Fig. 3)

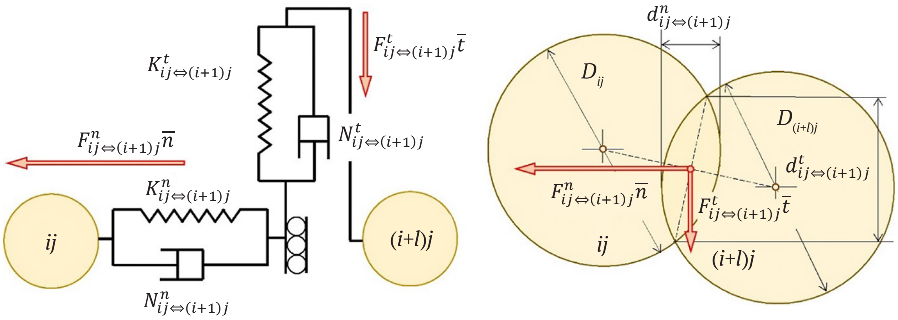


Figure 3. Design scheme of forces of contact interaction of feed components with each other
Source: compiled by the authors

According to the Hertz-Mindlin spring-damper contact Model [19], the total force of contact interaction of feed components with each other is determined as follows

$$\overline{F}^c_{ij\Leftrightarrow(i+1)j} = F^n_{ij\Leftrightarrow(i+1)j}\bar{n} + F^t_{ij\Leftrightarrow(i+1)j}\bar{t}, \tag{4}$$

where $\overline{F}^c_{ij\Leftrightarrow(i+1)j}$ – force of interaction between particles ij and $(i+1)j$, N; $F^n_{ij\Leftrightarrow(i+1)j}$ – normal component of the force between particles ij and $(i+1)j$, N; $F^t_{ij\Leftrightarrow(i+1)j}$ – tangential component of the force between particles ij and $(i+1)j$, N; $\bar{n}, \bar{t}$ – unit vectors of normal and tangential direction, respectively.

The normal component of the force is determined by the following equation:

$$F^n_{ij\Leftrightarrow(i+1)j} = -K^n_{ij\Leftrightarrow(i+1)j} d^n_{ij\Leftrightarrow(i+1)j} - N^n_{ij\Leftrightarrow(i+1)j} V^n_{ij\Leftrightarrow(i+1)j}, \tag{5}$$

where $K^n_{ij\Leftrightarrow(i+1)j}$ – normal coefficient of stiffness of the elastic component, kg/s²;

$$K^n_{ij\Leftrightarrow(i+1)j} = \frac{4}{3} E_{ij\Leftrightarrow(i+1)j} \sqrt{d^n_{ij\Leftrightarrow(i+1)j} R_{ij\Leftrightarrow(i+1)j}}; \tag{6}$$

$N^n_{ij\Leftrightarrow(i+1)j}$ - normal damping coefficient of the damping component, kg/s;

$$N^n_{ij\Leftrightarrow(i+1)j} = \sqrt{\left(5K^n_{ij\Leftrightarrow(i+1)j} M_{ij\Leftrightarrow(i+1)j}\right)} N_{n\ \ damp}. \tag{7}$$

According to research [18], the tangential component of a force is defined as

$$F^t_{ij\Leftrightarrow(i+1)j} = -K^t_{ij\Leftrightarrow(i+1)j} d^t_{ij\Leftrightarrow(i+1)j} - N^t_{ij\Leftrightarrow(i+1)j} V^t_{ij\Leftrightarrow(i+1)j} \tag{8}$$

if $\left|K^t_{ij\Leftrightarrow(i+1)j} d^t_{ij\Leftrightarrow(i+1)j}\right| < \left|K^n_{ij\Leftrightarrow(i+1)j} d^n_{ij\Leftrightarrow(i+1)j}\right| C_{fs}$, where C_{fs} – statistical coefficient of friction between feed component particles. Otherwise, the tangential component of the force is determined by the following equation:

$$F^t_{ij\Leftrightarrow(i+1)j} = \frac{\left|K^n_{ij\Leftrightarrow(i+1)j} d^n_{ij\Leftrightarrow(i+1)j}\right| C_{fs} d^t_{ij\Leftrightarrow(i+1)j}}{\left|d^t_{ij\Leftrightarrow(i+1)j}\right|}; \tag{9}$$

where $K^t_{ij\Leftrightarrow(i+1)j}$ – tangential stiffness coefficient of the elastic component, kg/s²;

$$K^t_{ij\Leftrightarrow(i+1)j} = 8G_{ij\Leftrightarrow(i+1)j} \sqrt{d^t_{ij\Leftrightarrow(i+1)j} R_{ij\Leftrightarrow(i+1)j}}; \tag{10}$$

$N^t_{ij\Leftrightarrow(i+1)j}$ - tangential attenuation coefficient of the damper component, kg/s;

$$N^t_{ij\Leftrightarrow(i+1)j} = \sqrt{\left(5K^t_{ij\Leftrightarrow(i+1)j} M_{ij\Leftrightarrow(i+1)j}\right)} N_{t\ \ damp}; \tag{11}$$

N_{ndamp}, N_{tdamp} – normal and tangential attenuation coefficients, respectively

$$N_{ndamp} = \frac{-\ln(C_{nrest})}{\sqrt{\pi^2 + \ln(C_{nrest})^2}}; \tag{12}$$

$$N_{tdamp} = \frac{-\ln(C_{trest})}{\sqrt{\pi^2 + \ln(C_{trest})^2}}; \tag{13}$$

$R_{ij\Leftrightarrow(i+1)j}$ - equivalent radius of two particles ij and $(i+1)j$, m;

$$R_{ij\Leftrightarrow(i+1)j} = \frac{1}{\dfrac{2}{D_{ij}} + \dfrac{2}{D_{(i+1)j}}}; \tag{14}$$

$M_{ij\Leftrightarrow(i+1)j}$ - equivalent mass of two particles ij and $(i+1)j$, kg;

$$M_{ij\Leftrightarrow(i+1)j}=\frac{1}{\frac{1}{M_{ij}}+\frac{1}{M_{(i+1)j}}}; \tag{15}$$

$E_{ij\Leftrightarrow(i+1)j}$ - equivalent Young's modulus of two particles ij and $(i+1)j$, Pa;

$$E_{ij\Leftrightarrow(i+1)j}=\frac{1}{\frac{(1-\nu_{ij}^2)}{E_{ij}}+\frac{(1-\nu_{(i+1)j}^2)}{E_{(i+1)j}}}; \tag{16}$$

$G_{ij\Leftrightarrow(i+1)j}$ - equivalent shear modulus of two particles ij and $(i+1)j$, Pa;

$$G_{ij\Leftrightarrow(i+1)j}= =\frac{1}{\frac{2(2-\nu_{ij})(1+\nu_{ij})}{E_{ij}}+\frac{2(2-\nu_{(i+1)j})(1+\nu_{(i+1)j})}{E_{(i+1)j}}}; \tag{17}$$

M_{ij}, $M_{(i+1)j}$ – masses of particles ij and $(i+1)j$, kg; $d^n_{ij\Leftrightarrow(i+1)j}$, $d^t_{ij\Leftrightarrow(i+1)j}$ – virtual overlap of particles ij and $(i+1)j$ in normal and tangential directions, m [19]; D_{ij}, $D_{(i+1)j}$ – effective diameters of particles ij and $(i+1)j$, m; E_{ij}, $E_{(i+1)j}$ – Young's modules of particles ij and $(i+1)j$, Pa; ν_{ij}, $\nu_{(i+1)j}$ – Poisson coefficients of particles ij and $(i+1)j$; $V^n_{ij\Leftrightarrow(i+1)j}$, $V^t_{ij\Leftrightarrow(i+1)j}$ – normal and tangential components of the relative velocity of the particle surface at the contact point, m/s.

When feed component particles interact with equipment walls, equations (14)-(15) are valid with the following assumption $D_{wall}=\infty$ and $M_{wall}=\infty$. Substituting, (14)-(15) turn into

$$R_{ij\Leftrightarrow wall}=\frac{D_{ij}}{2},\ M_{ij\Leftrightarrow wall}=M_{ij}. \tag{18}$$

According to Fig. 2 and considering expressions (2)-(5), a system of equilibrium equations is obtained:

$$\begin{cases} \mu p\dfrac{\pi(D_b^2-D_s^2)}{4\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}=\displaystyle\sum_{j=1}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}F^n_{1j\Leftrightarrow wall}+\sum_{i=2}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor-1}\sum_{j=1}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}F^n_{ij\Leftrightarrow(i+1)j}+ \\ +\displaystyle\sum_{j=1}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}F^n_{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor j\Leftrightarrow wall}+\sum_{i=1}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor}F^t_{i1\Leftrightarrow wall}+\sum_{i=1}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor}\sum_{j=2}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor-1}F^t_{ij\Leftrightarrow(i+1)j}+\sum_{i=1}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor}F^t_{i\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor\Leftrightarrow wall}, \\ \mu p\dfrac{\pi(D_b^2-D_s^2)}{4\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}=\displaystyle\sum_{i=1}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor}F^n_{i1\Leftrightarrow wall}+\sum_{i=1}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor}\sum_{j=2}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor-1}F^n_{ij\Leftrightarrow(i+1)j}+ \\ +\displaystyle\sum_{i=1}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor}F^n_{i\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor\Leftrightarrow wall}+\sum_{j=1}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}F^t_{1j\Leftrightarrow wall}+\sum_{i=2}^{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor-1}\sum_{j=1}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}F^t_{ij\Leftrightarrow(i+1)j}+\sum_{j=1}^{\left\lfloor\frac{h}{\langle D_{ij}\rangle}\right\rfloor}F^t_{\left\lfloor\frac{b}{\langle D_{ij}\rangle}\right\rfloor j\Leftrightarrow wall}. \end{cases} \tag{19}$$

The system of equations (21) together with the dependences (1)-(20) and the dependence of V.V. Bratishko [16-18] of the pressure distribution in the helical channel is very difficult to solve analytically due to the presence of a large number of variables that change over time. Therefore, having put this system as a physical and mathematical apparatus in the Star-CCM+ software suite, the study proceeds to consider the numerical modelling method. The study used the software "Simcenter STAR-CCM+ Academic Pack", the license holder of which is Dnipro State Agrarian and Economic University.

RESULTS AND DISCUSSION

Before performing numerical modelling, a 3D expander grid model was constructed using a surface grid generator, polyhedral cells, and a cell extruder.

Geometric dimensions and the generated grid with a base cell size of 0.005 m are shown in Fig. 4. The geometric dimensions of the expander elements are selected from a righteous analysis of existing structures [20; 21], considering their minimisation for reproducing small-sized laboratory equipment.

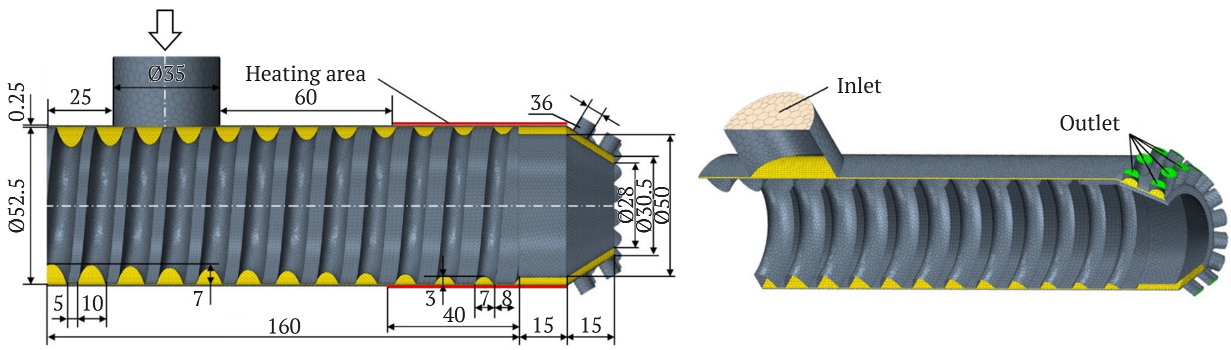


Figure 4. 3D expander model mesh in Star-CCM+

Source: compiled by the authors

The simulation was performed using gradients in 3D space, a model of split flow motion of a multiphase Euler mixture (MMP) using an acceptable two-layer k-ε turbulence model, and a multiphase equation of state. The simulation is non-stationary implicit. Heat-conducting processes followed the multiphase temperature model. The simulation was performed in the field of gravity. The gravity vector is as follows: (0; 0; -9.81) m/s^2.

Physical models for simulating the movement of feed components in the expander in the Star-CCM+ software suite are: a three-dimensional space model, an implicit non-stationary model, a physical model of a single-component gas (air), a real gas (air) model, a model of k-ε turbulence of air flow, an isothermal energy equation, a model of the Navier-Stokes equation averaged over Reynolds, a flow model – separate, boundary and gradient methods, a multiphase Lagrange model of the medium, a multiphase interaction model, discrete elements model (DEM), and the field of gravity.

Feed components are defined as Lagrange phases: density – constant; presence of pressure gradients; particle resistance model; DEM particles – spherical, single-component, and solid.

For example, soybean seeds were chosen as feed components. According to preliminary laboratory studies, soybean seeds have the following physical, mechanical and rheological properties: density – 700 kg/m^3; Young's modulus – 0.2 MPa; Poisson's coefficient – 0.2; normal recovery coefficient – 0.5; resting friction coefficient – 0.58; tangent recovery coefficient – 0.5; rolling resistance coefficient – 0.3; seed diameter – 0.01 m [22]. The Hertz-Mindlin contact interaction model is based on the interaction between the components: normal reduction coefficient – 0.5; rest friction coefficient – 0.58; tangent reduction coefficient – 0.5. The medium in which the components move is air with the following properties: dynamic viscosity – 1.85508·10^{-5} Pa·s; Prandtl's turbulent number – 0.9. Medium temperature – 293 K; medium pressure – 101,325 Pa. Gravity acceleration – 9.8 m/s^2.

The limit parameters selected are as follows. The upper plane of the feed neck (inlet) is represented by a model of the mass flow of feed components, which flows to the screw by gravity under the influence of gravity. The holes of the forming nozzle (outlet) are represented by a free flow of the mixture, the physical parameters of which are formed as a result of modelling.

The screw rotates around its own axis at a constant frequency of 120 rpm.

The solver in Star-CCM+ is selected non-stationary implicit in time increments of 0.01 s. First-order time discretisation. The maximum number of iterations per unit of time is 10, which ensures the necessary convergence of the result. The simulation time is 60 seconds.

As a result of the simulation of the expander operation, the pressure distribution (relative to atmospheric) in the cavity between the screw and the cylinder was obtained (Fig. 5). Fig. 5 clearly shows that the pressure increases along the screw axis in the direction of movement of the multiphase mixture. The increase in pressure is explained by a decrease in the volume of the cavity along the screw axis. At the outlet of the forming nozzle holes, the pressure value is 14.2±0.02·10^5 Pa.

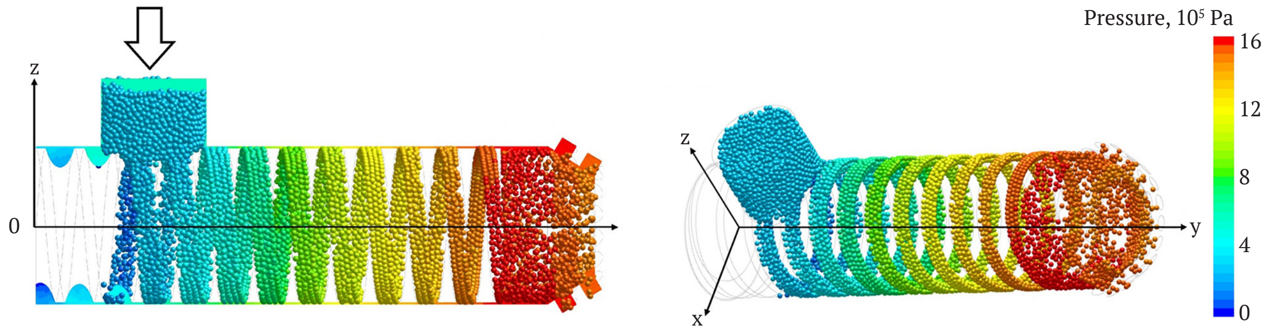


Figure 5. Pressure distribution (relative to atmospheric) in the screw channel of the expander
Source: compiled by the authors

The presented findings in the form of numerical data and visualisation of the technological process of feed expanding confirm the theoretical studies by R. Guy [7], J.L. White and H. Potente [8], V.V. Bratishko [18]. In turn, the results of experimental studies [13] confirm the nature of the pressure distribution (relative to atmospheric) in the screw channel of the expander. This allows asserting the adequacy of the developed physical and mathematical apparatus for numerical modelling of the feed expander in the Star-CCM+ software suite. That is, in further studies to substantiate the range of rational design and regime parameters of the feed expander, provided that the required pressure is provided at the outlet of the forming nozzle holes, a full-fledged numerical experiment can be carried out using generally accepted experimental planning methods.

CONCLUSIONS

The physical and mathematical apparatus of movement of solid feed components in the screw channel of the expander was further developed, which is the basis for the method of numerical modelling of the feed expansion process in the Star-CCM+ software suite. Preliminary numerical simulation of the process of expanded feed preparation is carried out in the Star-CCM+ software suite, which determines as research criteria: pressure in the cavity between the screw and the expander cylinder, the obtained density, the expander performance, the vector field of feed component velocities in the screw channel. The following factors should be selected as research factors: supply of feed components, screw rotation speed, screw diameter, length, and pitch, and the coefficient of change in screw pitch and depth along its length.

In the future, based on the results of numerical modelling using the method of planning multi-factor experiments, it is necessary to establish regularities in the influence of research factors on criteria in the form of second-order regression equations. Further, as a result of solving the compromise problem according to the research criteria, it is necessary to establish rational design and mode parameters of the feed expander. After that, it is planned to test the obtained theoretical regularities experimentally on an experimental feed expander installation

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Фізико-математичний апарат чисельного моделювання експандера кормів

Анотація. На продуктивність лінії приготування кормів і на її техніко-економічну ефективність впливають конструктивно-технологічні параметри обладнання. Не винятком є геометрія гвинта експандера і режими його роботи. Для зменшення питомих енерговитрат експандера необхідно встановити його раціональні конструктивно-режимні параметри. Це можна зробити використовуючи методи аналітичного розрахунку, які враховують механізми руху і руйнування твердих речовин. Моделювання з використанням методу дискретних елементів набуває все більшого розповсюдження для опису руху твердих компонентів в грануляторах, екструдерах або експандерах. Метою дослідження є удосконалення фізико-математичного апарата руху твердих компонентів корму у гвинтовому каналі експандера кормів і розробка методики його чисельного моделювання. Чисельне моделювання проводилося із застосуванням моделі руху розділеної течії багатофазної ейлерової суміші у тривимірного просторі. При цьому рух підпорядковувався допустимої двошарової k-ε-моделі турбулентності і багатофазного рівняння стану. Було проведено удосконалення фізико-математичного апарата руху твердих компонентів корму у гвинтовому каналі експандера кормів, яке покладено в основу методики чисельного моделювання в програмному пакеті Star CCM+, базувалося на тому, що конгломерат компонентів корму представляється у вигляді упаковки сферичних частинок. При цьому сила тиску повинна компенсуватися сумарною силою контактної взаємодії частинок між собою і стінкою. Проведено попереднє чисельне моделювання процесу експандованого приготування кормів в програмному пакеті Star CCM+. Практична значимість полягає в тому, що удосконалений фізико-математичного апарата і розроблена методика чисельного моделювання процесу роботи експандера кормів дозволяє обґрунтувати його конструктивно-режимні параметри для забезпечення низьких питомих енерговитрат без втрати якості виконання технологічного процесу

Ключові слова: експандування кормів, симуляція, метод дискретних елементів, Star CCM+, тиск, векторне поле швидкостей, щільність

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