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DEVELOPMENT OF FEED EXPANDER

Elchyn ALIIEV[1] Volodymyr DUDIN[1]
Oleksandr KOBETS[1] Mykola LINKO[1]

Abstract: *The development's objective is to increase productivity and reduce energy consumption in the execution of the technological process of expanded feed preparation while ensuring the necessary quality and safety of the expandates. The rationale for the construction and technological scheme of the feed expander with an improved shaping nozzle has been provided. This nozzle differs in that it consists of a narrowed area of the cylinder, a concave cone, and a crown nut. When heated plasticized mass is moved into the narrowed area of the shaping nozzle, there is an increase in pressure, followed by a sharp decrease after it passes through. This is achieved by increasing the working volume due to the shape of the concave cone. As a result, the plasticized mass expands and exits through the crown nut, forming expandates. Through numerical modelling, the dynamics and distribution of feed mixture components in the cavity between the cylinder of the shaping nozzle and the cone have been determined based on the force of pressure and the force of contact interaction between feed components. This dependence on the radius of narrowing of the cylinder of the shaping nozzle, the radius of the concave cone, and the distance between the cone and the cylinder have been established. Regression equations for the density of the plasticized feed mixture components at the outlet of the shaping nozzle and the maximum pressure required to extrude the plasticized feed components through the shaping nozzle along their movement direction from the specified research factors have been derived. As a result of experimental studies of the compact feed expander, dependencies of the changes in expander productivity, power consumption, specific energy consumption of the expansion process, and the density of obtained expandates have been established with respect to the moisture content of the compound feed, the gap between the cone and the nut, and the screw rotation speed.*

Key words: *pressing, feeds, auger, forming nozzle, modelling, parameters, adaptive.*

[1] Dnipro State Agrarian and Economic University, Serhiia Yefremova street, no. 25, Dnipropetrovs’ka Oblast 4900, Dnipro, Ukraine;
Correspondence: Elchyn Aliiev; email: aliev@meta.ua.

1. Introduction

Extrusion and expansion processing are gaining increasing popularity in the global agri-food industry, especially in the food and feed sectors [3]. These technologies are used to produce so-called 'engineered' food products and specialized feeds [8]. According to comprehensive studies [10, 16], extrusion and expansion of plant materials involve the formation of finely ground material under barothermal conditions. With the aid of shear energy provided by a rotating screw and additional heating, the food material is heated to its melting or plasticization temperature [17]. In this altered rheological state, the food material is transported under high pressure through a die or a series of dies, and the product expands to its final form. These result in distinct physical and chemical properties of extrudates as compared to the properties of the raw material used.

Extruders and expanders belong to the family of HTST (high-temperature short-time) equipment capable of preparing food products and feeds under high pressure. Since the influence of high temperatures occurs only for a short time, the undesirable denaturation of proteins, amino acids, vitamins, starch, and enzymes is limited. Physico-technological aspects such as heat transfer, mass transfer, impulse transmission, and temperature duration have a significant impact on the properties of food products and feeds during extrusion and expansion processing and can significantly affect the quality of the final product [14].

Extruders and expanders are technological reactors [14], where conditions are created with the presence of specific screw configurations, the use of mixing elements, appropriate gap sizes, motor power, and heating blocks. Proper utilization of these factors allows for the stimulation of transformations in processed materials through the heating process, such as protein denaturation in the presence of water and starch breakdown influenced by the combined effects of heat, friction, and deformation [4].

It is worth noting that there are many similarities between the processes that occur in an expander and an extruder since their essence lies in barothermal treatment. The significant difference between extrusion and expansion is that the latter is less energy-intensive, and at the outlet of the equipment, the die is replaced by a conical discharge valve (the most common solution). The expansion process can be applied directly to a food product or a separate ingredient, and sometimes it is even used as part of a more complex system in which the raw material expands after preparation [4, 5].

A well-known expander produced by A. Kahl GmbH [5] consists of a base, an asynchronous electric motor, a gearbox, a feeder, a hopper, a steam inlet, a cylinder, a screw, a heating element, and a forming nozzle. The forming nozzle is a cylinder with a narrowing cross-section, inside of which there is a rounded cone. Due to the sharp reduction in volume between the narrowed section and the rounded cone, an increase in pressure is observed, leading to increased power consumption at the required density of the expandates and process productivity.

An extruder for producing animal feed from grain agricultural products [22] consists of a working chamber, a shaft with screws, pressing rings, and a pressing cone. The pressing cone is manufactured as a separate component and has channels on its outer surface for the passage of grain mixture to the die orifice. The conical surface of the pressing cone and the conical surface of the die, due to different angles of inclination, create a working chamber, the shape of which allows for the smooth adjustment of the extrusion process by changing its volume. A drawback of this extruder is the periodic clogging of the die and working chamber, causing interruptions in the feed preparation process for cleaning. This, in turn, reduces the productivity of the feed preparation process in the form of extrudates.

The development's objective is to increase productivity and reduce energy consumption in the execution of the technological process of expanded feed preparation while ensuring the necessary quality and safety of the expandates.

2. Designing an Expander for Animal Feed Production

The set task is achieved by developing an expander for feed preparation, comprising a base, an asynchronous electric motor, a gearbox, a feeder, a hopper, a steam inlet, a cylinder, a screw, a heating element, guides, and a forming nozzle. It differs in that the forming nozzle consists of a crown nut screwed onto the external thread of the cylinder, a narrowed area of the cylinder, inside of which a concave cone is installed with a rigidly fixed nut screwed into a supporting plate attached to the guides (Figure 1).

The use of the developed expander for feed preparation allows for the execution of the technological process of expanded feed preparation with higher productivity and reduced energy consumption while ensuring the necessary quality and safety of the expandate. This is achieved by creating a smooth change in the volume of the working area of the forming nozzle, leading to a decrease in pressure and consequently reducing power consumption at the required process productivity, quality, and safety of the obtained expandates.

The geometry of the expander screw has a significant impact on the throughput capacity of the expanded feed production line as well as its quality, making it crucial for technical and economic efficiency [8]. To save specific energy consumption, various analytical calculation methods exist, taking into account the mechanisms of motion and disintegration of solid materials, thus eliminating the need for time-consuming trial-and-error experiments. Many assumptions and simplifications are required to obtain an analytical solution; for example, assuming that feed components form a solid layer flowing uniformly [23]. Modeling using the Discrete Element Method (DEM) is becoming increasingly popular for describing the movement of solid bodies in granulators, extruders, or expanders, as it allows for relative displacements between particles to be defined [13, 18, 19]. Thus, the DEM simulation model is used for virtual experiment design and provides a large database for evaluating the efficiency of the technological process.

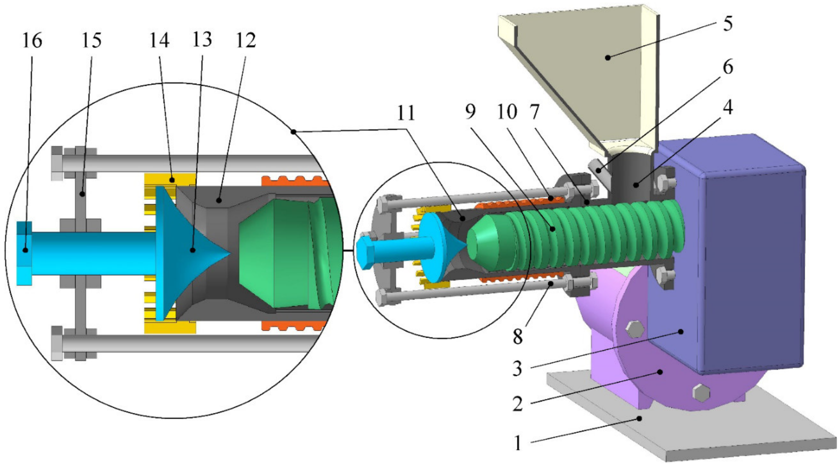


Fig. 1. *Structural and technological diagram of the compound feed expander: 1 – base; 2 – asynchronous electric motor; 3 – gearbox; 4 – feeder; 5 – hopper; 6 – steam inlet; 7 – cylinder; 8 – guide; 9 – screw; 10 – heating element; 11 – forming nozzle; 12 – narrowed area; 13 – concave cone; 14 – crown nut; 15 – supporting plate; 16 – nut*

Due to its suitability for describing the movement of solid materials in granulators, extruders, or expanders, the DEM is used to assess existing analytical calculation approaches [1, 2, 21].

The analysis of the movement of solid feed components in the screw channel of the expander is based on the dynamics of particle movement using the Discrete Element Method (DEM). Solid feed components, as discrete elements, are introduced into the screw channel through a hopper. Flow in the hopper typically occurs by gravity, although under certain circumstances, additional efforts may be required, but this aspect will not be discussed in these studies. Once the feed components enter the screw channel of the expander, they start moving along a horizontal spiral path. As the geometric dimensions of the screw channel decrease, the feed components compact, forming a solid layer or conglomerate, which is then transported to the forming nozzle.

3. Materials and Methods

3.1. Numerical Methods

The first stage of the research involves numerical modeling of the forming nozzle of the feed expander using the CAE system STAR-CCM+.

The forming nozzle of the feed expander consists of a cylinder, a crown nut, and a cone (Figure 2). The cone has a concave shape. The crown nut consists of 20 grooves through which the formed expandates move. The cylinder of the forming nozzle has a slight narrowing in the middle, which is necessary to increase pressure.

The schematic representation of the numerical modeling of the forming nozzle is shown in Figure 2. Initially, a total of 12000 particles of feed components were placed in the cylinder cavity. Then, the piston begins to move at a speed of 0.01 m/s towards the cone, compressing the feed components and moving them to the openings between the cone and the grooves of the crown nut.

For modeling, the following continuum models were adopted: the Discrete Element Method (DEM), Lagrangian multiphase, DEM boundary forces, non-stationary implicit solver, interpolation solution model, and gravity force. The feed mixture components are represented as solid spherical DEM particles with constant density. Particle interactions with each other and with the wall are governed by Hertz-Mindlin models with rolling resistance and linear coupling.

According to previous laboratory research and literature sources [6, 11, 15, 20], the physico-mechanical properties of the feed mixture components are as follows: density – 700 kg/m^3, static friction coefficient – 0.61, normal restitution coefficient – 0.5, tangential restitution coefficient – 0.5; average particle diameter of the mixture D_μ – 0.5 mm; Young's modulus E_p – 22.3 MPa; Poisson's ratio μ_p – 0.31; adhesion work per unit area W_p – 0.49 N/m.

Time step – 0.01 s. Number of iterations per time step – 5. Exposure time – 4 s. Piston velocity – 0.01 m/s.

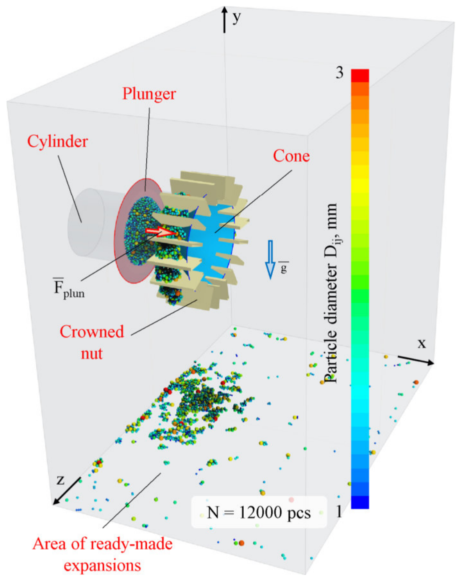


Fig. 2. *Schematic representation of the numerical modeling of the forming nozzle of the expander*

As research factors, we consider the following structural parameters of the forming nozzle with a concave cone (Figure 3): the radius of the cylinder's narrowing in the forming nozzle, R_r (10 – 20 mm), the radius of the concave cone, R_c (30 – 100 mm), and the distance between the cone and the cylinder, δ_c (3 – 9). Modeling was carried out using a full factorial experiment with a total of 3^3 = 27 simulations.

As the energy criterion of the research, the total piston pressure P_Σ has been chosen, which is required to compress the feed components through the forming nozzle. Density ρ_Σ of the plasticized feed component mass at the outlet of the forming nozzle is selected as the quality criterion.

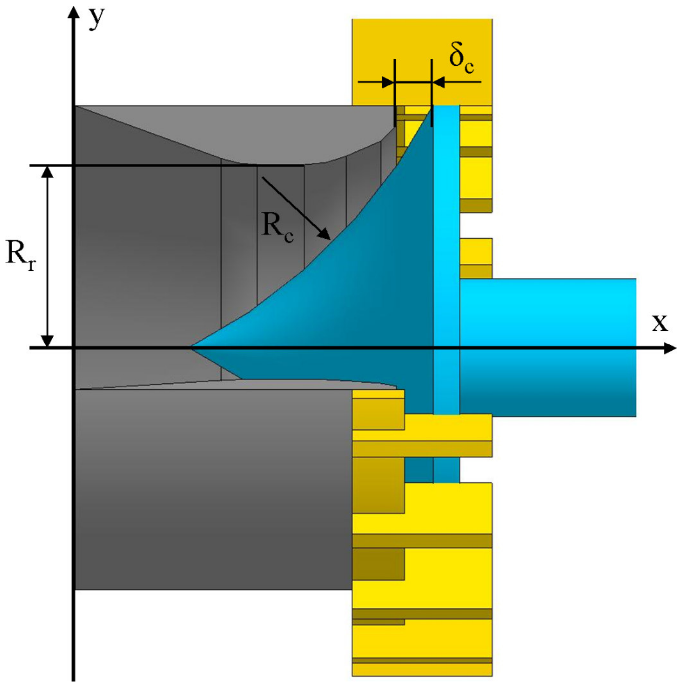


Fig. 3. *Diagram of factors in the numerical modeling of the compression process of feed mixture components in the forming nozzle with a concave cone*

3.2. Methodology of Experimental Research

At the beginning of the research, samples of compound feed with the appropriate particle size distribution, ranging from 1.2 to 2.4 mm particle size, were prepared. The compound feed consisted of wheat, barley, corn, and sunflower meal, in a ratio of 25 : 25 : 25 : 25%, which were ground using a disc grinder to achieve a higher (approximately 92%) homogeneity of grinding compared to a hammer mill. The preparation of the compound feed was carried out using a laboratory spiral-screw mixer for bulk materials, which allowed obtaining mixtures with a homogeneity of 94 – 98%. The initial moisture content of the obtained samples was determined using the thermogravimetric method according to ISO 712:2015. The control method (ISO 712:2009, IDT) was performed using a SESh-3M drying cabinet. The initial moisture content (10 ± 2%) of the compound feed samples was adjusted by adding the corresponding amount of water (Equation (1)).

$$m_w = m_0 \cdot \left(\frac{100 - W_0}{100 - W_1} - 1 \right) \qquad (1)$$

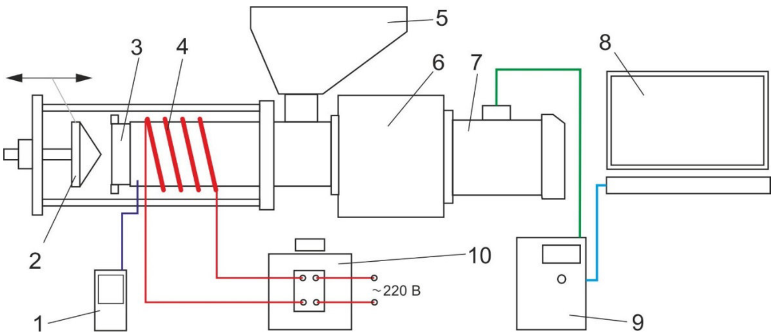
where:

m_w and m_z are the mass of water and the mass of the compound feed sample, respectively [kg];

W_0 and W_1 – the initial moisture content and the desired moisture content, expressed as a percentage [%].

Based on the results of theoretical and laboratory research, an experimental sample of a compound feed expander was developed and implemented, serving as the basis for the research setup depicted in Figure 4.

The experimental research had the following variables: the gap between the sealing cone and the nut *δc* (1 – 5 mm), screw rotation speed *n* (30 – 60 rpm), and feed moisture content *W* (20 – 30%). The optimization criteria included power consumption *N*, productivity *Q* of the experimental expander, and the volumetric density of the obtained expandates *ρ*.



a.

b.

Fig. 4. *Schematic (a.) and overall view (b.) of the research setup: 1 – digital thermometer with thermocouple FLUS ET-960; 2 – sealing cone; 3 – flow divider nut; 4 – working chamber heater; 5 – loading hopper; 6 – worm gearbox NMRV-63 (1:25); 7 – electric motor AIP/5AI80A4; 8 – personal computer; 9 – frequency converter HYUNDAI N700E; 10 – laboratory autotransformer LATR-1M; 11 – tachometer Benetech GM8905*

Analyzing existing research plans, it was established that, compared to traditional orthogonal and rotatable designs, the Box-Behnken design BB_3 is more economical in terms of the number of experiments and has good statistical indicators, as noted in [7, 12].

The corresponding screw rotation speed was set using the Hyundai N700E frequency converter and monitored with the Benetech GM8905 tachometer. The appropriate gap between the sealing cone and the nut was adjusted by rotating the screw, on which the cone was mounted, and monitored using the depth gauge caliper ShC-150-0.1. The temperature in the working chamber was maintained at 136 ± 2°C using a heater, the heating degree of which was controlled by varying the power supply current with the LATR-1M laboratory autotransformer.

The drive power was recorded using the Hyundai N700E frequency converter, with current readings taken using a personal computer equipped with N700 HIMS software.

The productivity of the expander Q was determined based on the weight obtained over a specific period of time, calculated from the time required to process one batch weighing 1 kg. The elapsed time was measured using a stopwatch. The specific energy consumption q of the process was calculated as the ratio of the consumed power to productivity. The volumetric density of the expandates ρ was determined by measuring the geometric dimensions of individual samples (in a quantity of 10 repetitions) and by weighing them [9]. Geometric measurements were taken using the caliper gauge ШЦ-1-150, and weighing was carried out using JD-2200-2 laboratory scales.

Results Simulation results Figure 5 shows the distribution of feed components in the cavities between the cylinder of the forming nozzle and the cone (at R_r = 15 mm, R_c = 70 mm, δ_c = 6 mm) based on the pressure force F_p and the force of contact interaction between feed components $F^{c}_{ij \Leftrightarrow (i+1)j}$. The dynamics of changes in the values of the total piston pressure P_Σ, the volume of the cavity between the cylinder of the forming nozzle and the cone V_s, the volume V_p, and the density ρ_Σ of the plasticized feed component mass along their movement (axis Ox) are presented in Figure 6.

From Figure 6, it can be observed that the total pressure P_Σ increases along the movement of the plasticized feed component mass until it reaches a maximum value. Subsequently, the pressure stabilizes, indicating a process equilibrium. Therefore, this maximum pressure is sufficient for extruding the plasticized feed component mass. In turn, the density ρ_Σ of the plasticized feed component mass changes non-uniformly along its movement (Figure 6). This is associated with the non-uniformity of the volume of the cavity between the cylinder of the forming nozzle and the cone V_s. However, what matters most for the process is the density of the plasticized feed component mass that forms at the exit from the forming nozzle.

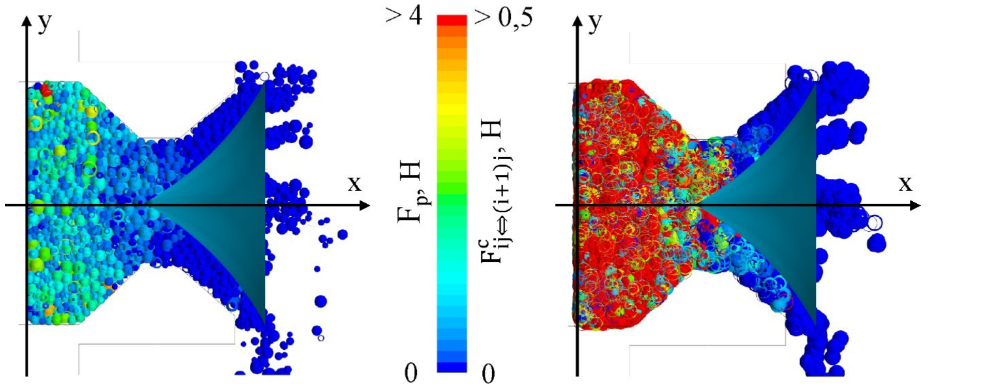


Fig. 5. *Distribution of feed components in the forming nozzle region based on the pressure force Fp and the force of contact interaction between feed components* $F^{c}_{ij\Leftrightarrow(i+1)j}$ *(R_r = 15 mm, R_c = 70 mm, δ_c = 6 mm)*

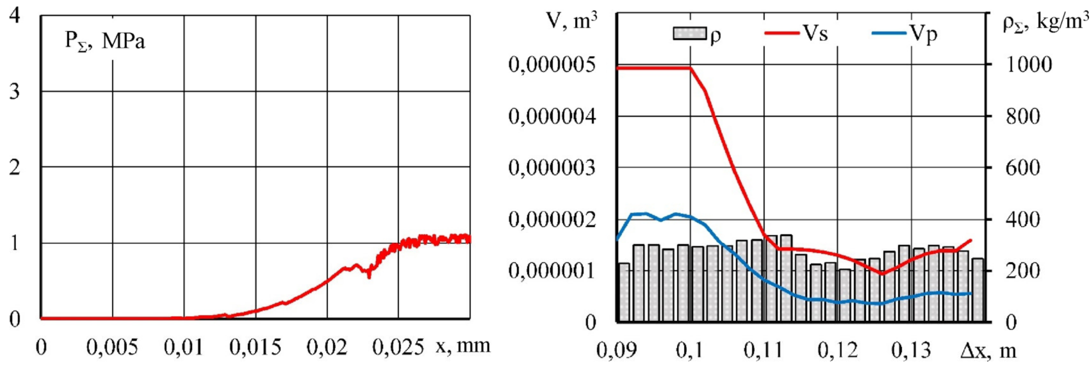


Fig. 6. Dynamics of changes in the values of the total piston pressure P_Σ, the volume of the cavity between the cylinder of the forming nozzle and the cone V_s, the volume V_p, and the density ρ_Σ of the plasticized feed component mass along their movement (R_r = 15 mm, R_c = 70 mm, δ_c = 6 mm)

After processing the data in Wolfram Cloud, a regression equation for the maximum total piston pressure *Pmax*, required to extrude the plasticized feed component mass through the forming nozzle, as a function of the experimental factors was obtained (Figure 7) – Equation (2):

$$P_{max} = 5.62305 - 0.859031 \cdot \delta_c + 0.037993 \cdot \delta_c^2 + 0.00762086 \cdot R_c - 0.18484 \cdot R_r + 0.0141087 \cdot R_c \cdot R_r \quad (2)$$

After processing the data in Wolfram Cloud, a regression equation for the density ρ_{out} of the plasticized feed component mass at the exit from the forming nozzle was obtained (Figure 8) – Equation (3):

$$\rho_{out} = 381.881 - 22.7835 \cdot \delta_c + 1.46774 \cdot R_c - 4.25958 \cdot R_r + 0.661457 \cdot \delta_c \cdot R_r - 0.0568048 \cdot R_c \quad (3)$$

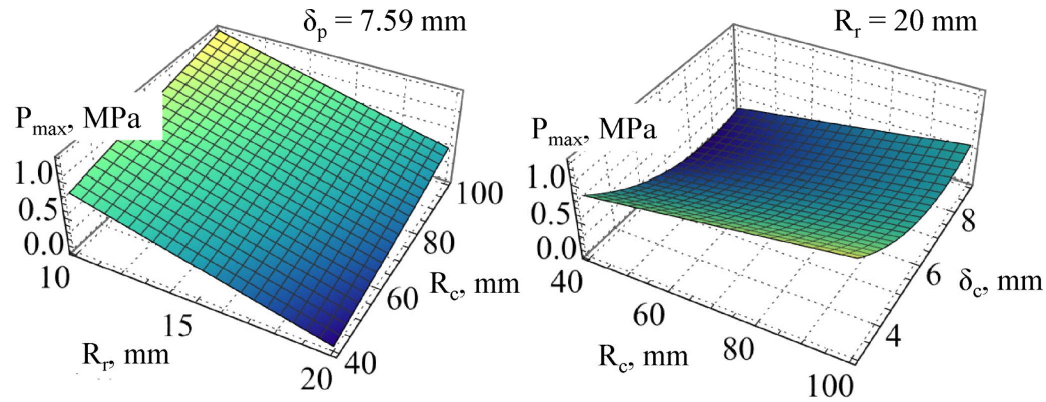


Fig. 7. *Dependence of the maximum total piston pressure P_{max} required for extruding the plasticized feed component mass through the forming nozzle on the radius of the cylinder constriction R_r, the radius of the concave cone R_c, and the distance between the cone and the cylinder δ_c*

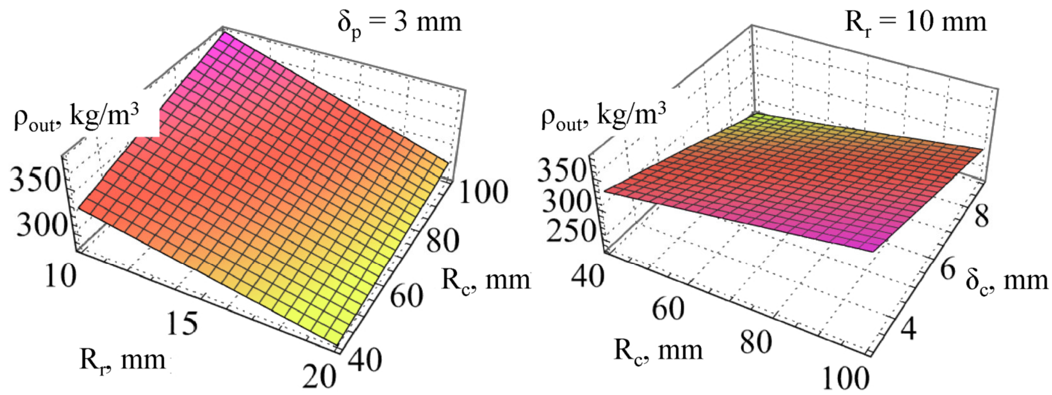


Fig. 8. *Dependence of the density ρ_{out} of the plasticized feed component mass at the exit from the forming nozzle on the radius of the cylinder constriction R_r, the radius of the concave cone R_c, and the distance between the cone and the cylinder δ_c*

As seen from Figures 7 and 8, the optimal values of the criteria differ, so it is necessary to solve a multi-criteria optimization problem. Multi-criteria optimization refers to the process of simultaneously optimizing two or more conflicting objective functions or optimization criteria within a specified domain – Equation (4):

$$\begin{cases} P_{max}\left(R_r, R_c, \delta_c\right) \to \min; \\ \rho_{out}\left(R_r, R_c, \delta_c\right) \to \max. \end{cases} \tag{4}$$

Solving Equation (4) jointly with Equations (2) and (3) in Wolfram Cloud using the "FindMinimum" function, optimal values for the factors were calculated where possible: R_r = 14.2 mm,

R_c = 89.9 mm, δ_c = 3.7 mm. In this case, ρ_{out} = 331.2 kg/m^3, and P_{max} = 1.84 MPa.

4. Experimental Results

In accordance with the provided methodology, multifactorial experimental studies of the operation process of the small-sized feed expander were conducted. The general appearance of samples of the obtained product (expandates) is shown in Figure 9.

W = 25%, δ_c = 1 mm, n = 60 об/хв W = 25%, δ_c = 3 mm, n = 60 об/хв W = 25%, δ_c = 5 mm, n = 60 об/хв

Fig. 9. Samples of the Obtained Product

As a result of processing experimental data, the dependence of the expander's productivity Q on the research factors in coded form was obtained (Figure 10) – Equation (5):

$$Q = 1.78314 + 0.401115 \cdot n + 1.41111 \cdot \delta_c \tag{5}$$

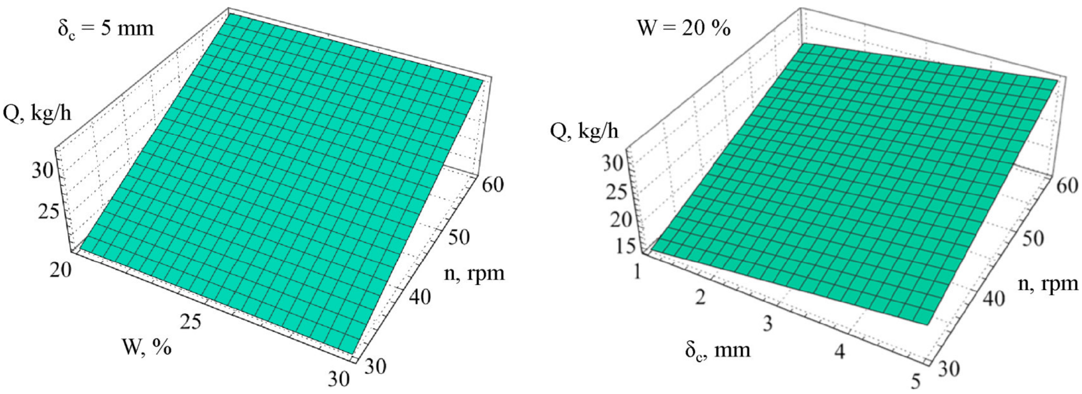


Fig. 10. *The dependence of expander productivity Q on feed moisture W, gap between the cone and nut δ_c, and screw rotation speed n*

The obtained Equation (5) is adequate according to the Fisher criterion F_p = 1.9979 < $F_{0.05}(12;30)$ = 2.09, and the variance is homogeneous according to the Cochran criterion G_p = 0.1082 < $G_{0.05}(2;15)$ = 0.3346.

As a result of processing experimental data, the dependence of power consumption N on the research factors was obtained (Figure 11) – Equation (6):

$$N = 898.22 + 12.0228 \cdot n - 15.1022 \cdot W - 186.449 \cdot \delta_c + 31.0749 \cdot \delta_c^2 \quad (6)$$

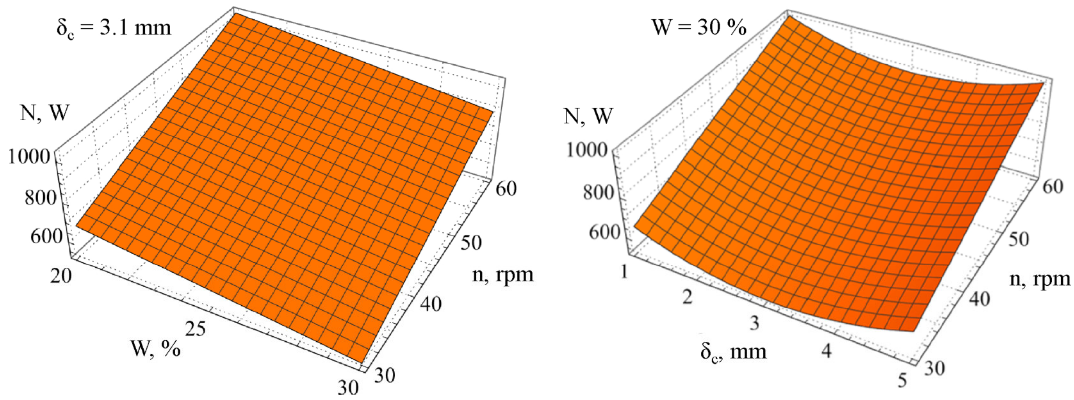


Fig. 11. *The dependence of power consumption N on feed moisture W, gap between the cone and nut δ_c, and screw rotation speed n*

The obtained Equation (6) is adequate according to the Fisher criterion Fp = 0.9848 < F0.05(11;30) = 2.13, and the variance is homogeneous according to the Cochran criterion $G_p = 0.1456 < G_{0.05}(2;15) = 0.3346$.

As a result of processing experimental data, the dependence of the specific energy consumption of the expansion process q on the research factors was obtained (Figure 12) - Equation (7):

$$q = 111.579 - 0.785547 \cdot n + 0.00721513 \cdot n^2 - 2.8468 \cdot W + 0.0524621 \cdot W^2 - 11.2437 \cdot \delta c + 1.51579 \cdot \delta_c^2 \quad (7)$$

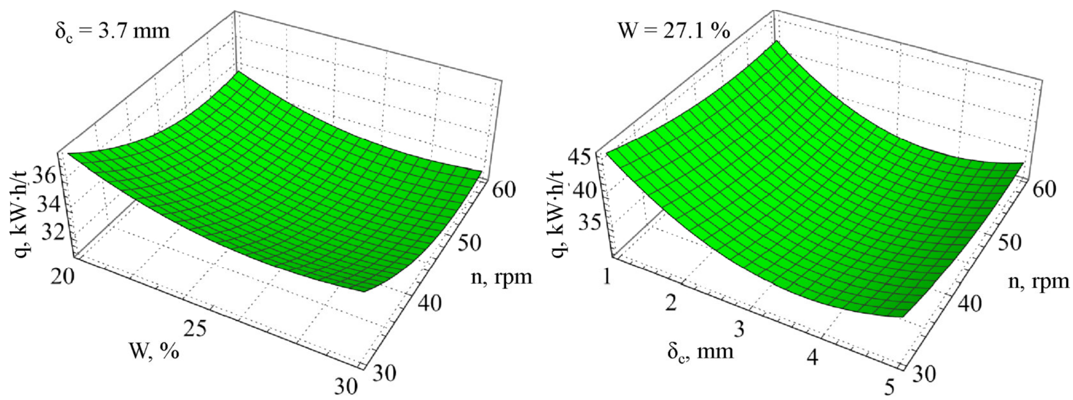


Fig. 12. *The dependence of specific energy consumption q on feed moisture W, gap between the cone and nut δ_c, and screw rotation speed n*

The obtained Equation (7) is adequate according to the Fisher criterion $F_p = 0.8698 < F_{0.05}(8;30) = 2.27$, and the variance is homogeneous according to the Cochran criterion $G_p = 0.841 < G_{0.05}(2;15) = 0.3346$.

By finding the values of the research factors in the Wolfram Cloud software package where the minimum value of the specific energy consumption of the expansion process q = 30.7 kWh/ton was observed, it was determined that W = 27.1%, δ_c = 3.7 mm, and n = 54.4 rpm. In this case, productivity was Q = 28.8 kg/h, and power consumption was N = 879 W.

As a result of processing experimental data, the dependence of the density of expandates ρ on the research factors was obtained (Figure 13) - Equation (8):

$$\rho = 264.289 - 0.825 \cdot n + 12.902 \cdot W - 0.279201 \cdot W^2 - 7.25791 \cdot \delta_c^2 \quad (8)$$

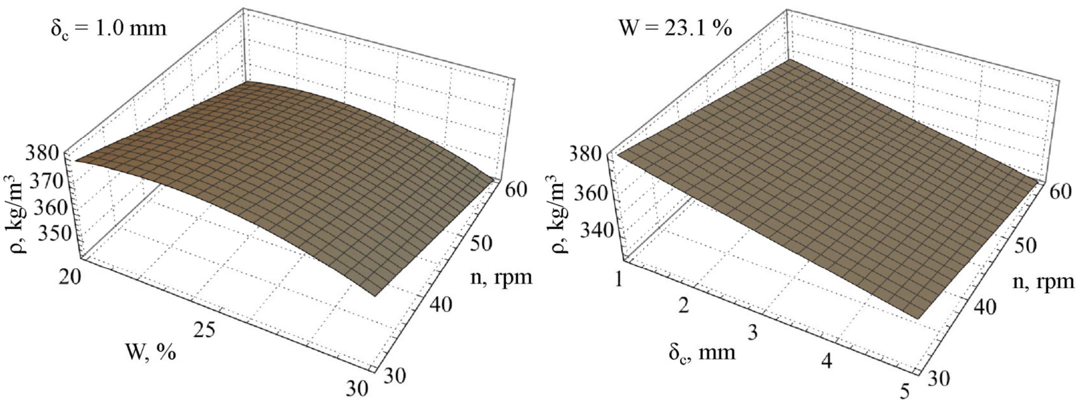


Fig. 13. *The dependence of expandate density ρ on feed moisture W, gap between the cone and nut δ_c, and screw rotation speed n*

The obtained Equation (8) is adequate according to the Fisher criterion $F_p = 2.1118 < F_{0.05}(10;30) = 2.16$, and the variance is homogeneous according to the Cochran criterion $G_p = 0.1414 < G_{0.05}(2;15) = 0.3346$.

Let's compare the results of experimental studies with theoretical models. Theoretical research aimed to determine structural parameters, while experimental research focused on identifying operational and technological parameters. However, the gap parameter between the cone and nut (δ_c) was a studied factor in both theoretical and experimental investigations. Therefore, the comparison will be conducted based on this factor. Corresponding dependency graphs have been constructed for the identified optimal parameters, as shown in Figure 14. The Pearson correlation coefficient is 0.94.

It has also been determined that at rational values of W = 27.1%, δ_c = 3.7 mm, n = 54.4 rpm, at which the specific energy consumption of the expansion process q is minimal, the density of the expandates is ρ = 336 kg/m^3.

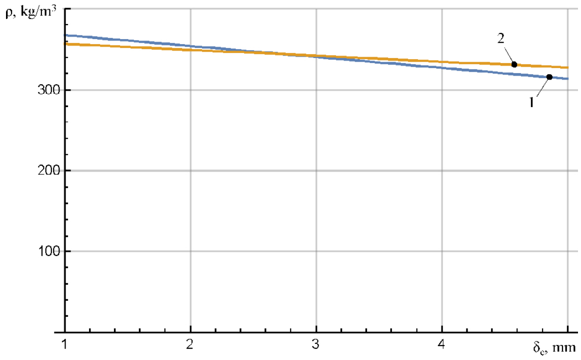


Fig. 14. *Comparison of theoretical (1) and experimental (2) dependencies of expandate density (ρ) on the gap between the cone and nut (δ_c): 1 – theoretical dependency (3) at R_r = 14.2 mm, R_c = 89.9 mm; 2 – experimental dependency (8) at W = 27.1 %, n = 54.4 rpm*

5. Conclusions

The rationale for the construction and technological scheme of the feed expander with an improved shaping nozzle has been provided. This nozzle differs in that it consists of a narrowed area of the cylinder, a concave cone, and a crown nut. When heated plasticized mass is moved into the narrowed area of the shaping nozzle, there is an increase in pressure, followed by a sharp decrease after it passes through. This is achieved by increasing the working volume due to the shape of the concave cone. As a result, the plasticized mass expands and exits through the crown nut, forming expandates.

Through numerical modeling, the dynamics and distribution of feed mixture components in the cavity between the cylinder of the shaping nozzle and the cone have been determined based on the force of pressure (F_p) and the force of contact interaction between feed components $F^{c}_{ij\Leftrightarrow(i+1)j}$. This dependence on the radius of narrowing of the cylinder of the shaping nozzle (R_r), the radius of the concave cone (R_c), and the distance between the cone and the cylinder (δ_c) have been established. Regression equations for the density (ρ_{out}) of the plasticized feed mixture components at the outlet of the shaping nozzle and the maximum pressure (P_{max}) required to extrude the plasticized feed components through the shaping nozzle along their movement direction from the specified research factors have been derived.

As a result of solving the multi-objective optimization task involving research criteria, namely, reducing P_{max} and increasing ρ_{out}, rational design parameters of the shaping nozzle have been determined: R_r = 14.2 mm, R_c = 89.9 mm, δ_c = 3.7 mm. Under these conditions, ρ_{out} = 331.2 kg/m³, and P_{max} = 1.84 MPa.

As a result of experimental studies of the compact feed expander, dependencies of the changes in expander productivity (*Q*), power consumption (*N*), specific energy consumption of the expansion process (*q*), and the density of obtained expandates (*ρ*) have been established with respect to the moisture content of the compound feed (*W*), the gap between the cone and the nut (δ_c), and the screw rotation speed (*n*).

By finding the values of research factors in the Wolfram Cloud software package that correspond to the minimum specific energy consumption of the expansion process (q = 30.7 kW·h/ton), it was determined that W = 27.1%, δ_c = 3.7 mm, and n = 54.4 rpm. Under these conditions, the productivity was Q = 28.8 kg/h, power consumption was N = 879 W, and the density of expandates was ρ = 336 kg/m³.

Since the parameter of the gap between the cone and the nut (δ_c) was a research factor in both theoretical and experimental studies, the comparison was conducted specifically based on this factor. For the determined rational parameters, corresponding dependency graphs were constructed, and the Pearson correlation coefficient was calculated, which amounted to 0.94.

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