Rationale for the design and technological parameters of the extruder for the production of sapropel and grain feed

V V Morozov¹, K A Bogdanov¹, V A Smelik², M S Volkhonov³, V S Kukhar⁴

¹Velikie Luki State Agricultural Academy, Velikie Luki, Russia
²Saint Petersburg State Agrarian University, Petersburg highway 2, Saint Petersburg, Pushkin, 196601, Russia
³Kostroma State Agricultural Academy, Kostroma Region, Kostroma District, Karavaev, 156530, Russia
⁴Ural State Agrarian University, Ekaterinburg, Karla Liebknechta str., 42, Russia

E-mail: kindeib1994@gmail.com

Abstract. It is reasonable to use extruded sapropel feed for increasing the productivity of farm animals. This feed supplements the animal's body with minerals and vitamins as well as has good digestibility. It is well stored and has a low cost. The article shows the scheme of the extruder developed by the authors. It allows to prepare sapropel and grain feed. For the aim of being able to specify the necessary technological parameters of the extruder operation at the design stage, analytical dependences were deduced to determine the processing temperature of the mixture, extruder capacity and the power spent on the extrusion process. The mathematical dependences received theoretically were tested experimentally, and the maximum error does not outweigh 5%, corresponding to the required accuracy of the modelling. The article also determines the most rational modes of extruder operation.

1. Introduction

Researchers are facing the task of improving the efficiency of concentrated feed production for farm animals by increasing their quality and downgrading their production costs. This food must be well digestible, have a low cost, and supplement the animal's body with useful minerals and vitamins [1]. It is possible to increase the effectiveness of feed by using sapropel as a feed additive, which will enrich the animal's body with vitamins and minerals [2].

For increasing the digestibility and nutritional value of the feed, it is required to improve its properties before feeding. Nowadays, it is most advisable to use extrusion for this purpose. This technique of feed pretreatment, in addition to raising the nutritional value of the feed, enhances the storage of the feed by destroying harmful microorganisms and evaporating moisture [3-5]. The extruder enables to refuse the whole complex of machines at the expense of performing several operations at once. The following feed preparation operations are carried out on the extruder: mixing, grinding, pressure and temperature treatment, sterilization and granulation [6-8].

In order to produce high-quality feed, it is required to improve the units for the preparation and processing of feed material with the addition of sapropel.
2. Target setting
The extruders on the market are intended for the production of feed without the addition of sapropel. The impact of the physical and mechanical properties of the sapropel and grain mixture on the structural elements of the working elements of the extruder has not been considered. For improvement of the machine meant for sapropel and grain feed production, it is available on the market to use an extruder as a basis. Moreover, it is essential to change some of the design parameters of the machine, since the feed processing modes differ from the processing modes of the proposed mixture. Consequently, for sapropel and grain feed production, it is required to improve the design of the working element of the extruder and to offer methods for its calculation.

3. Materials and methods
The design of the working element of the extruder for processing grain with sapropel with the reasoning of the construction and technological parameters is advanced by the authors. The machine is equipped with a double spiral vane drum, which allows for an additional ridge to increase the processing temperature and pressure in comparison with a single spiral vane drum with an equal length. Moreover, the machine is supplied with tapered compression rings, which, in contrast to the cylindrical ones, downgrade the extruder's contamination rate and reduce energy consumption. Working elements construction of the machine is presented in the figure 1. The working part of the machine consists of parts rotating from the electric motor: 1 - extruder shaft; 5 - intake auger; 6 - tapered compression rings; 7-heating zone auger; 8-pressing zone auger. Stationary components: 2-feeding zone housing; 3-die nut; 4-extrusion zone housing. The following approach is used for feed processing: the mixture is fed from the tanker of the machine to the intake auger (5), from where it is transported to the first compression ring (6). Owing to the frictional forces, the feed is heated, grinded, and compacted in the process of movement. The compression ring in this design ensures a narrowing of the gap between the rotating and stationary elements of the working part of the extruder, which enhances the pressure applied to the processed mixture, improving its processing. Likewise, the processed material passes through the second compression ring (6), the auger (7) and (8). Then the mixture goes to the die (3), from where the variable gap leaves the machine through the gap. By adjusting the gap between the die (3) and the auger (8), we can change the pressure applied to the mixture inside the machine.

4. Results and discussion
In the developed design of the extruder, it is required to deduce analytical dependences for determining the design and technological parameters (temperature of the mixture processing, extruder capacity, and the power spent on the extrusion process).

Figure1. Working part of the extruder.
For consideration of the material heating in the extruder, we will introduce the auger coiling in the form of two parallel plates (fig. 2a). Material flow is made from left to right by the action of the pressure coil on the side of the ridge.

Friction work can be shown by the expression:

\[ A_1 = \int_0^l F_{ff} \, dx \]  

where \( F_{ff} \) – the friction force between sapropel and grain mixture and the extruder auger. Friction force can be expressed in terms of pressure and square

\[ F_{ff} = P_x \mu S. \]  

where \( \mu \) – friction ratio.

The pressure changes over the channel length according to the dependence:

\[ P_x = \frac{(P_{ae}-P_0)l}{l_1}, \]  

where \( l \) – length from the beginning of the channel to the elementary section \( dx \); \( P_a \) – pressure at the auger end; \( P_0 \) – pressure at the auger beginning.

Contact area of the mixture with the shaft is defined by the formula:

\[ S = 2h_{ar}x + l_c x, \]  

where \( h_{ar} \) – auger ridge; \( x \) – the route from the beginning of the channel to the elementary section \( dx \); \( l_{ac} \) – distance between adjacent coils.

Using figure 1 we will express \( x \) and \( dx \):

\[ x = \frac{l}{\sin \alpha}; \quad dx = \frac{dl}{\tan \alpha}, \]  

where \( \alpha \) – the angle of the auger feed.

Putting equations 2-5 in expression 1, we will get:

\[ A = \int_0^{l_1} \frac{(P_{ae}-P_0)l}{l_1} \frac{lu(2h_{ar}+l_{ac})}{\sin \alpha \tan \alpha} \, dl. \]  

Integrating expression 6, we get a formula for calculating the friction work for the first section of the auger.

\[ A = \frac{l_1^2 \mu (2h_{ar}+l_{ac})(2P_{f1v1}+P_0)}{6\sin \alpha \tan \alpha} \]  

where \( P_{f1v1} \) – pressure before the first compression valve.

Dividing the friction work by the mass of the mixture entering the zone to get a formula for calculating the temperature change of the mixture:

\[ \Delta Q = \frac{A}{M \cdot c}, \]  

where \( M \) – mass of the mixture placed in the auger coils; \( c \) – specific thermal capacity.

Mixture mass in the auger coils is calculated using the formula:

\[ M = \rho v z \]  

where \( \rho \) – mixture density; \( v \) – mixture volume in a coil; \( z \) – coils number in the shaft.

For determining the mixture volume in one coil, look at the diagram in Figure 2b. Using this scheme, we draw a formula for calculating the volume in the inter-turn space for a double spiral vane drum:

\[ v = T \pi (r_{ext}^2 - r_{ag}^2) - 2\delta_c (r_{ext} - r_{ag}) T \sqrt{1 + \cot^2 \alpha}, \]
where \( r_{\text{ext}} \) – external radius of the auger lug; \( r_{\text{ag}} \) – radius of the auger groove; \( T \) – coil lead; \( \delta_c \) – coil width.

\[
\begin{align*}
\text{Figure 2. Extruder auger}
\end{align*}
\]

For the calculation of the power spent on heating, we divide the work by the time the mixture passes through the auger:

\[
N = A\omega / 2\pi z, \tag{11}
\]

where \( \omega \) – angular velocity of rotation of the extruder auger.

The extruder capacity is a very significant indicator of operation. For the evaluation of this test, we consider the first section of the screw of the extruder. Capacity is determined as the mass of the mixture in one coil multiplied by the time of one rotation:

\[
Q_t = m \frac{\omega}{2\pi}, \tag{12}
\]

where \( m \) – mixture mass in one coil; \( Q_t \) – theoretical capacity of the auger.

Mixture mass in one coil is calculated by the formula:

\[
m = \rho v. \tag{13}
\]

Replacing the expressions 13 and 10 in formula 12, we get the equation for calculating the theoretical capacity of the extruder:

\[
Q_{th} = \rho \left( T\pi \left( r_{\text{ext}}^2 - r_{\text{ag}}^2 \right) - 2\delta_c \left( r_{\text{ext}} - r_{\text{ag}} \right) T \sqrt{1 + ctg^2 \alpha} \right) \frac{\omega}{2\pi} \tag{14}
\]

In the extruder operation, there is a material counterflow. Let us write down the equation for calculating the capacity of the extruder considered.

\[
Q_s = Q_t \left( 1 - \frac{P_{\text{tor}}}{P_{\text{max}}} \right), \tag{15}
\]

where \( P_{\text{max}} \) – maximum pressure produced by the auger when there is no axial material movement and when the extruder head is closed.

\[
P_{\text{max}} = \frac{\pi r_{\text{ext}}^2 \omega \eta}{2(2\gamma / r_{\text{ext}} - r_{\text{ag}}) H}, \tag{16}
\]

where \( \eta \) – effective viscosity of the product.

For pressure determination at the beginning and end of the auger in Formula 3, let us consider the movement of the extruded material in the forming extruder head and compression valves.
Let us consider the material movement in the forming extruder head (fig. 3 a). Using this scheme in Figure 3, we will set up a differential equation of equilibrium relative to the horizontal X-axis. Solving this equation, we got the equation for finding the extrusion pressure:

\[ P_{\text{ext}} = \frac{P_0}{e^{-\frac{\xi f \cos \alpha}{S}}} \]  

(17)

where \( \xi = \mu / (1 + \mu) \) – lateral pressure coefficient; \( \mu \) – Poisson’s ratio; \( P_0 \) – pressure output from the hole; \( l \) – hole length, m; \( \alpha \) – angulation of the cone generator, gon; \( f \) – friction ratio; \( S \) – gap between the die and the shaft.

For extrusion pressure determination before compression valve of \( P_{\text{gap}} \) sapropel and gain mixture, let us draw a scheme of a material passing through a conical space (fig. 3 b).

\[ P_{\text{ext}} = \frac{P_{\text{com}}}{(r_1 + l t g \alpha)^2 \cdot \sin \left( \frac{r_1^2 - r_0^2}{r_1 - r_0} \right)} \]  

(18)

where \( r_0 \) – radius of the extruder cylinder; \( \alpha \) – angle of the compression ring cone; \( r_1 \) – initial ring radius; \( l \) – compression ring length; \( P_{\text{com}} \) – pressure after compression ring.

Accounting that the auger equally creates the necessary pressure let us present the equation for calculating the pressure after the compression valves \( P_{\text{com}2} \) и \( P_{\text{com}1} \). Figure 4 presents a pressure change diagram in the extruder.

**Figure 3.** Material movement in the forming head and compression valve of the extruder

Using this scheme, let us set up the differential equation of equilibrium relative to the horizontal X-axis. Solving this equation, we get the equation for determining the extrusion pressure:

**Figure 4.** Pressure changes in a auger extruder with conical compression rings
\[ P_{\text{ext}2} = \frac{P_{\text{ext}(l_1+l_2)}}{l_1+l_2+l_3} \]  
\[ P_{\text{com}1} = \frac{P_{\text{com}2l_1}}{l_1+l_2} \]  

where \( P_{\text{ext}} \) – extrusion pressure before the die; \( P_{\text{ext}2} \) – extrusion pressure before the second compression ring; \( l_1; l_2; l_3 \) – length of the 1st, 2nd and 3rd auger sections, respectively.

For testing the theoretical dependences, a multi-factor experiment was performed to identify the influence of the rotation speed of the extruder shaft, the length of the compression rings and the step of the moving zone on the mixture processing temperature, capacity and power consumption.

A multivariate regression analysis has revealed the temperature dependence \( T, ^\circ \text{C} \) from the rotation speed of the extruder shaft \( n, \text{min}^{-1} \) (b₁); length of the compression rings \( l, \text{mm} \) (b₂); moving area auger step \( T, \text{mm.} \) (b₃):

\[ T = 13,3029 + 0,370419*b_1 + 3,5071*b_2 - 3,96923*b_3 - 0,000875*b_1*b_2 + 0,00784314*b_1*b_3 - 0,0492647*b_2*b_3 - 0,000255*b_1^2 + 0,0257813*b_2^2 + 0,0715625*b_3^2 \]  

An increase in the compression ring length has been determined to enhance the temperature. Increasing the auger step decreases the temperature. The rotation speed of the extruder shaft makes almost no impact on the mixture processing temperature.

Also, the capacity dependence \( Q, \text{kg/h} \) on the design and technological parameters of the extruder is defined:

\[ Q = -75,4461 - 0,38547*b_1 + 13,742*b_2 + 14,7984*b_3 + 0,00025*b_1*b_2 + 0,0189902*b_1*b_3 - 0,693382*b_2*b_3 + 0,000135*b_1^2 - 0,164844*b_2^2 - 0,406667*b_3^2 \]  

Length increase of the compression ring is determined to reduce the extruder capacity. Auger step and shaft speed increases result in enhanced capacity.

Power spent on the extrusion process \( N, \text{kW} \) is also identified as a function of the extruder parameters:

\[ N = 15,8791 - 0,0365735*b_1 + 0,0821078*b_2 - 0,147034*b_3 + 0,000882353*b_1*b_3 - 0,00269608*b_2*b_3 + 0,000025*b_1^2 + 0,00234375*b_2^2 + 0,001875*b_3^2 \]  

Compression ring length and the rotation speed of the extruder shaft are determined to raise the power consumption. Auger step increase results in power consumption reduction.

The most optimal operating modes of the press-extruder, accounting for the lowest power consumption for the extrusion of 1 kg of feed and the optimal processing temperature, are seen at the following extruder parameters: \( n=785 \text{ min}^{-1}; l=8 \text{ mm}; T=28 \text{ mm}. \) The output parameters match the following values: \( Q=164,4 \text{ kg/h; N}=2,11 \text{ kW; } T=122,6 ^\circ \text{C}. \)

Extruder tests for the extrusion of sapropel and grain mixture have demonstrated the compliance of mathematical models with the processes happening during the extrusion. The maximum error does not outweigh 5%, corresponding to the required accuracy of the simulation.

The proposed working element provides for the production of high-quality feed to have a positive effect on the growth and development of poultry. This article [9] shows findings of the research and economic experience. Extruded sapropel and grain feed produced using an advanced extruder has been identified as contributing to a faster gain of live weight in broiler-type chickens. The working element is designed accounting for the physical and mechanical features of sapropel. At temperatures above 180 0C, sapropel loses its favorable properties for animals. The proposed design and technological features of the working element ensure the temperature conditions of the sapropel and grain mixture in the range of 120-160 0C.

5. Conclusion
The feasibility of extruder development for the production of sapropel and grain feed is substantiated and the operation scheme of this tool is given. The proposed mathematical models for calculating the
extruder enable us to set the technological settings required for sapropel and grain mixture processing at the design phase. Mathematical dependencies are verified by experimental studies. As of the result of experimental studies, the most rational design and technological settings of the extruder operation, ensuring high-quality feed production, have been found.

References
[1] Otarov A I 2019 The influence of heat treatment of grain of various forage crops on the growth and development of fattening gobies of kalmyk breed Veterinary Medicine, Animal Science and Biotechnology 9 pp 74-80
[2] Ignatenkov V G, Bogdanov K A, Ivanov E A, Ivanov A I, Aleksandrov D A 2020 Research of the drum cellular percentage feeder working of a vitamin-fodder additive of multi-purpose grinding and mixing machine based on a sapropel Bulletin of Kurgan State Agricultural Academy 2 pp 62-65
[3] Fattakhova Z F, Shakirov S K, Krupin E O, Bikchantaev I T, Shayakhmetova L N, Askarova A A 2020 The chemical composition, nutrition and fractional composition of winter rye grain proteins after various methods of exposure Carpathian journal of food science and technology 1 pp 71-79
[4] Pietsch V L, Werner R, Karbstein H P, Emin M A 2019 High moisture extrusion of wheat gluten: relationship between process parameters, protein polymerization, and final product characteristics Journal of food engineering 259 pp 3-11
[5] Tangjaidee P, Xiang J, Yin H, Wen X, Quex S Y 2019 Selenium, fibre, and protein enrichment of rice product: extrusion variables and product properties Food quality and safety 1 pp 40-51
[6] Priporov I E, Shepelev A B, Yagyaev E R 2020 Improvement of extruders for preparing protein feed from sunflower seeds Bulletin of Orenburg State Agrarian University 2 pp145-148
[7] Pakhomov V I, Braginets S V, Bakhchevnikov O N, Alferov A S, Rudoy D V 2020 Extrusion technologies of feed and food including biomass of insects (review) Agricultural Science of the Euro-North-East 3 pp 233-244
[8] Pakhomov V I, Braginets S V, Bakhchevnikov O N, Alferov A S, Rukhlyada A I, Babajanyan A S 2020 The results of experimental studies of extrusion of feed containing wheat grain and black soldier fly larvae biomass Agricultural Science of the Euro-North-East 1 pp 28-42
[9] Vasileva M I, Bychkova K V, Arzhanka Yu V, Ignatenkov V G 2020 Live weight of broiler chickens when added to the diet of extruded wheat separately and mixed with sapropel Izvestia of Velikie Luki State Agricultural Academy 1 pp 2 – 8