Theoretical justification of the feed preparation technology by the gear pelletizer

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Abstract. In order to provide the livestock industry in the Russian agro-industrial complex with a feed of the right quantity and quality, it is necessary to conduct research on the design and creation of a set of technical tools, applicable to large, medium and small farms. Scientific researches and development on the design and creation of models of such tools are carried out at the Department of Mechanization of animal husbandry and life safety of FSBEI HE Kuban SAU. In particular, the design of the gear-type pelletizer with the main working body consisting of a matrix with pressing channels and gears, engaged in the complex motion when rolling the matrix, was developed. The working process of pressing the material consisting of crushed grain fractions, by the pelletizer, was described. As a result of theoretical substantiation the significant formulas of channel outlet pressure and pelletizer’s performance were derived by the end of the article.

1. Introduction

Animal husbandry enterprises of small forms of management are insufficiently provided with the equipment that would make it possible to prepare feed with high quality indicators in the form and quantity without violating rational feeding regimes, keeping and breeding of animals. A high percentage of equipment used in farms is produced by countries of Europe and Asia and is more than 90%. In Russia, factories for the production of technological equipment for livestock farms are closed or are about to start producing high-performance equipment mainly for large farms, while small farms need low-volume equipment to use [1].

Extensive fodder production is developed in regions where more than 10 hectares of all types of forage land fall on one head with a small proportion of arable land in the fodder area.

At present, the unsatisfactory state of technical equipment of feed production is one of the main reasons for the untimely and poor quality of technological operations in meadow cultivation, field cultivation and fodder harvesting, which leads to losses of 25-30% and more of the grown crop and almost half of its feed value. Provision of farms with grass-land equipment is 10-30% of the need. The level of mechanical operations on fodder harvesting averages 50-70%, including grass mowing, silage harvesting 84-96%, and loading and unloading 25-50% [2].

Studies of the feed pressing process were carried out by a number of scientists: I.A. Dolgov, S.M. Dotsenko, L.P. Kartashov, I.T. Kovrikov, V.S. Kokoshko, G.M. Kukta, S.V. Melnikov, V.I. Osobov,
G.Ya. Farbman, V.Y. Frolov, V.I. Shcherbina and others, and are fundamental in the study of improving the technological process of feed pressing and granulating.

To study the issue of qualitative improvement of the feed pressing process, a constructive-technological scheme of a gear pelletizer was developed, and a scientific hypothesis was proposed: improving the quality of the granules preparation, reducing the crumbling coefficient and increasing the strength characteristics of the finished product (pellets) is possible due to the development of a constructive-technological scheme of a gear-type pelletizer with a rolling head engaged with a matrix and analytical justification of the operating and design parameters that will enable to optimize the basic structural and technological components of the gear-type pelletizer at the design stage.

2. Materials and methods
The constructive-technological scheme of a gear pelletizer was developed (figure 1), including a support 2, rolling heads 6 engaged with a matrix 7 having a central hole, conical channels 8 and a rotary drive, and it differs in that it has hoppers located in one another, one of which is external 1, is for dry material and is located on a cylindrical support, the other one is internal 3, is for a liquid binding component and is made in the form of a truncated cone with calibrated orifices 4 in its bottom, in the upper part, on the outside of the hopper, stirring blades 5 are located at different levels, while the lower part of the inner hopper is inserted into the central hole of the matrix, and its surface is made in the form of a truncated cone with radially located teeth with conical pressing channels, the central axis of which is mounted perpendicular to the working surfaces of the rolling heads fixedly arranged, and made in the form of gears, the matrix and the inner hopper, being connected to the rotary drive, installed with ability to rotate in one direction; on the bottom side of the matrix a scraper 9 at an angle of 45° to cut the output material is located. The drive shaft is located in the lower part of the support and passes through the central hole of the matrix, in which the lower part of the internal hopper is installed.

![Figure 1. The technological design scheme of the gear pelletizer: 1 – the external hopper, 2 – the support, 3 – the internal hopper, 4 – the calibrated orifices, 5 – the stirring blades, 6 – the rolling heads, 7 – the matrix, 8 – the conical pressing channels, 9 – the scraper.](image)

The description of the gear pelletizer working process: a feed mixture of pre-crushed grain components is delivered into the external hopper due to gravity. Dry material is mixed by stirring blades, entering the matrix by gravity. A binding component is delivered through the neck of the inner hopper, passing through calibrated orifices in the lower part of the inner hopper, mixing with the dry feed mixture just before it enters the compression zone, the mass being formed is pressed by moving gears, the working surface of which is located at an angle of 90° to the central axis of the cone pressing channel. The prepared mixture passes through the inlets of the matrix conical pressing channels, in which the mixture undergoes a barothermic compression process, the adhesive bonding between the binding component and the feed mixture occurs; as a result, the compacted, compressed material in the channel...
is converted into granules and, at the exit, it is cut with a scraper located at an angle of 45° to the bottom of the matrix.

The feed mixture may be considered as a combination of small-sized particles, of which the linear dimensions vary from 0.01 mm to 2-3 mm. The dimensions should be selected so small as to ensure the uniform stresses distribution in all directions within the volume filled with feed mixture [3].

3. Results and discussions

Under this approach, the feed mixture may be considered as a continuous medium, a continuum, to which terms of continuous medium mechanics and fluid mechanics are applicable. Within the selected elementary volume, the stress state changes, as a rule, in space and in time. The mechanics of the phenomena occurring in the feed mixture are associated with the processes of compaction, deformation, destruction and adhesion of the particles forming the mixture. These mechanical properties of the mixture are determined by corresponding measurements of such quantities as density (volume and bulk), elasticity, mechanical stress, compression ratio, etc.

Suppose, at a certain moment, all mixture particles have the same velocity vectors. If vectors do not change in time, a stationary process or flow takes place (analogy with a laminar fluid flow) (figure 2). The velocity of the feed mixture particle, entering the working compression zone, may be indicated by velocity vector, emanating from the particle in the direction of movement, the length of which is proportional to the absolute value of the particle velocity [4].

The motion of the feed mixture in the mixing hopper and in the space between the matrix and gears is turbulent, and in the pressing channel the motion may be considered as both stationary and laminar flow (figure 3).

At a certain time the mixture flow may be described by flow lines – the curves, for which the tangents at each point coincide with velocity vectors at this point in time. In a stationary flow the flow lines

Figure 2. The laminar character of a feed mixture flow in a pressing channel.

Figure 3. Turbulence of a feed mixture motion in the mixing zone.
remain unvarying with time. In this way particles motion paths (flow paths) coincide with the flow lines. In a non-stationary flow the pattern of the flow lines disposition refers only to a single moment, and there is no simple dependence between the flow lines and the flow paths [5].

Each element of the volume when describing the process at a given point in time may be quantified by deformation. At the same time, the distribution of compaction and directions of the main deformations can be determined. Comparing a similar instantaneous pattern with the pattern observed earlier, it is possible to define the degree of compaction and deformation.

Two approaches are possible to study the process of mixture movement, changes in velocity, and other parameters in time [6].

Based on the Lagrange theorem, a certain infinitely small volumetric element is distinguished in a continuous medium, and observing it, the changes in time of its kinematic characteristics are being studied. With this approach, the changes occurring with it are considered as functions of time and, thus, the whole path of the selected element is traced. This motion path of the element may be restored from the velocity field, that is, from the velocity distribution pattern.

L. Euler suggests considering the change in the processes occurring at a fixed point in a continuous medium in a selected coordinate system instead of studying the motion paths of individual particles. Then the continuous medium at the considered point is constantly replaced by another medium, but the values of the studied quantity, e.g., the movement velocity, are compared. An example may also be the study of stress fluctuations in time at the entrance to the pressing channel and other characteristic points of the channel.

The process must satisfy three basic conditions: equations describing mechanical properties, differential equilibrium equations, and boundary conditions [7].

Suppose that such properties of the considered continuous medium as compressibility, compression ratio, deformability, compression resistance, friction between the mixture and the channel, as well as the mixture adhesion to the surface of the material, are known. These mechanical properties for a volume element are presented in the form of equations of the stress dependence on a deformation.

It is assumed that the processes are determined by the combination of volume elements and that the stress on the volume element edge are distributed evenly, in fact however, there are small differences in stresses at different points of the element, which are a significant factor.

Normally, some external conditions are imposed on the process, which it must satisfy at any time, for example, the pressure at the outlet of the pressing channel.

Most types of feed mixtures are dispersed systems consisting of two or more components. All these dispersed mixtures may be modeled in the form of a loose body, Newtonian and non-Newtonian fluids, as well as a number of special models [8].

The feed mixtures processing is often not only mechanical or hydrodynamic, but also thermal, which are accompanied by complex physicochemical or microbiological phenomena. The main task of feed preparation is to control the mechanical processes of the formation, deformation and destruction of dispersed systems of various types and to obtain feed materials on this basis with specified technological and nutritional properties.

The physical properties of feed mixtures are humidity, granulometric composition (particles size and their ratio), volume mass, density, porosity, water absorption, water loss, hygroscopicity, thermal capacity, thermal conductivity, etc. Among these, the property of feed moisture, which significantly affects other properties, is of the utmost importance. Many technological processes occur only at a certain humidity level: grain grinding by impact, granulation and briquetting, etc. [9]

The feed mechanical properties are described by the ratios of external and internal friction, horizontal thrust, repose angle, and the characteristics of compression resistance.

The most significant properties of feed mixtures for any given technological process are those that determine their response to external mechanical influences. Such properties are called technological, they may be from among physical or mechanical. F.e., for feed pressing processes – deformation properties, for grinding feed grain – its strength properties [10].
The physical, mechanical and technological properties of any feed are interrelated. Often this is a deterministic relation, in other cases – a weaker, correlated one.

The feed mixture in its composition, size and density of particles obtained by grinding and mixing, may be very diverse. In the analytical justification of the compression process, let us accept the following assumptions: considering the crushed feed mixture homogeneous in its density and granulometric composition; particles sizes are much smaller than radiuses of pressing channel orifices; moistening the mixture leads to increase in granule formation and decrease in the friction ratio on the pressing channel conical surface [11];

Consider the movement of the selected part of the feed mixture in the form of a truncated cone with a height of \( dx \) through the pressing channel [12].

\[ ds = \rho \cdot d \cdot dx , \]

![Figure 4. The part of a feed mixture in the pressing channel in the shape of a truncated cone.](image)

Due to a channel axial symmetry, let us pass to a cylindrical coordinates system \((\rho, \varphi, x)\), where \( x \) is the channel axis of symmetry, then the part of lateral surface area is [13]:

\[ dS = \rho \cdot d \cdot \rho \cdot \varphi \cdot dx. \]

where \( \rho \) – the polar radius,

\( \varphi \) – the polar angle,

\( x \) – the point coordinate.

The decisive factor affecting the mixture in the channel is the pressure \( P \) from the side of the channel walls. This pressure is generated by the normal reaction \( dF' \) on the elementary area \( dS \) of the lateral surface (figure 4) of the selected cone:

\[ P = \frac{dF'}{dS}, \]

where \( F' \) – the channel wall natural reaction, N;

\( S \) – the square (the area), m\(^2\);

\( P \) – the pressure, Pa

or

\[ dF' = P \cdot dS = P \cdot \rho \cdot d\varphi \cdot dx. \]

Obviously, the natural reaction of the channel wall to the lateral surface of the cone will be found by integration over the entire lateral surface of the cone:

\[ F' = \int_{\varphi=0}^{\pi} P \cdot \rho \cdot d\varphi \cdot dx = \int_{\varphi=0}^{\pi} \int_{\theta=0}^{\theta} P \cdot \rho \cdot d\varphi \cdot dx. \]

As a result of converting, the common expression for natural reaction is obtained:

\[ F' = 2\pi \int_{0}^{l} P \cdot \rho \cdot dx. \]
Further calculations depend on the type of the dependence of a radius and pressure on a point coordinate.

The polar radius for a selected cone is the point coordinate function:

\[ \rho = r + a \cdot (L - x), \]  \hfill (6)

\[ a = \tan \alpha = \frac{R - r}{L}, \]  \hfill (7)

\[ \sin \alpha = \frac{R - r}{\sqrt{L^2 + (R - r)^2}}, \]  \hfill (8)

\[ \cos \alpha = \frac{L}{\sqrt{L^2 + (R - r)^2}}, \]  \hfill (9)

where \( R \) – the inlet channel radius, m;
\( r \) – the outlet channel radius, m;
\( k \) – the proportionality coefficient;
\( L \) – the channel length, m.

Suppose, the dependence of pressure \( P \) on a lateral surface of a selected cone on a point coordinate is linear:

\[ P(x) = P_{inl} + k \cdot x, \]  \hfill (10)

where \( P_{inl} \) – the feed mixture pressure at a channel inlet, Pa;
\( k \) – the proportionality coefficient, Pa/m;
\( x \) – the current point coordinate of a lateral surface, m;
\( P_{out} \) – the outlet channel pressure required for granulating, Pa.

Substituting the expression (5) and (6) in the expression (3), and integrating it, the expression for natural reaction is obtained:

\[
F' = 2\pi \int_0^L P \cdot \rho \cdot dx = 2\pi \int_0^L (P_{inl} + x) \cdot \left( r + a \cdot (L - x) \right) \cdot dx = 2\pi \int_0^L (P_{inl} \cdot r + k \cdot r \cdot x + P_{inl} \cdot a \cdot (L - x) + k \cdot a \cdot (L - x) \cdot x) \cdot dx = 2\pi \left( P_{inl} \cdot r \cdot L + k \cdot r \cdot \frac{L^2}{2} + P_{inl} \cdot a \cdot L^2 - P_{inl} \cdot a \cdot \frac{L^2}{2} - k \cdot a \cdot \frac{L^3}{2} - k \cdot a \cdot \frac{L^3}{3} \right) \]  \hfill (11)

or in a simplified form:

\[
F' = 2\pi \cdot \left( P_{inl} \cdot r \cdot L + \frac{k \cdot r + P_{inl} \cdot a}{2} \cdot L^2 + k \cdot a \cdot \frac{L^3}{6} \right). \]  \hfill (12)

The expression for the outlet channel pressure is obtained.

It is possible to determinate the stress state of any feed mixture element. The first step is defining the volume element deformation state. Then certain assumptions, relating to mixture mechanical behavior,
are made (f.e., assuming the mixture behaves as a resilient material in the channel) and the stress is defined according to deformation state. It makes possible to define the directions and values of principal stresses [14].

Pressing feed mixture passing through the channel undergoes the following deformation types: the longitudinal compression, the transverse compression, the torsion, the curving.

Let us make simplifying assumptions regarding the absence of deformation of a torsion and curve types, which corresponds to a laminar flow, considering the mixture to be homogeneous, and the character of interaction with a channel wall at each point of channel cross section is identical.

Let us distinguish an elementary volume of a feed mixture in the pressing channel of a cylindrical form, which changed as a result of pressing in size from the $R$ radius at an inlet and the $H$ height, to the $r$ radius at an outlet and the $h$ height. As a result of passage of that cylinder through the channel it undergoes the volumetric compression deformations [15]:

$$k = \frac{V_1}{V_2},$$

(13)

where $V_1 = \pi R^2 H$ – the initial volume of a cylinder before the compression at a channel inlet; $V_2 = \pi R^2 h$ – the volume of a cylinder after the compression at a channel outlet.

Thus, the compression ratio is defined by the expression:

$$k_v = \frac{R^2 H}{r^2 h}.$$  

(14)

The formula analysis indicates that the volume compression ratio increases $n^2$ times when decreasing the channel radius $n$ times, and invariably numerically is more than 1.

Given that the mass of a selected mixture cylinder remains unchanged in a compression process, the dependence between the densities before and after compression will be defined by the expression:

$$\frac{\rho_2}{\rho_1} = \frac{m/V_2}{m/V_1} = \frac{V_1}{V_2} = k_v.$$  

(15)

Hence, the pellet density after the compression will be:

$$\rho_2 = k_v \rho_1.$$  

(16)

![Figure 6.](image)

Figure 6. The stresses of a selected cylinder in the mixture: the longitudinal compression (above), the transverse compression (below).

The longitudinal compression is characterized by a normal stress:

$$\sigma = \frac{F_{\text{long}}}{S},$$

(17)

where $F_{\text{long}}$ – the longitudinal compression power, H;

$S$ – the base square, m$^2$. 


\[ \sigma = \frac{F_{\text{long}}}{\pi R^2}. \]  

(18)

The transverse compression:

\[ \tau = \frac{F_{tc}}{S}, \]  

(19)

where \( F_{tc} \) – the transverse compression power, \( \text{H} \);

\( S \) – the lateral surface square, \( \text{m}^2 \);

\[ \tau = \frac{F_{tc}}{2\pi rh}. \]  

(20)

The result of a combined simultaneous action of the longitudinal compression power and the transverse compression power of a channel wall natural reaction is manifested in pellets formation at the channel outlet.

The channel outlet pressure is found by division of the natural reaction into the lateral square surface of a truncated cone:

\[ P_{\text{out}} = \frac{F'}{S_{\text{lat}}} = \frac{2(P_{\text{inl}}rL + k\pi + P_0 - aL^2)}{(R+r)(\sqrt{(R-r)^2}+L^2)}. \]  

(21)

As a result of a theoretical justification of a pressing process, the expression (21) that allows determining a necessary \( L \) length of a pressing channel with known inlet and outlet radiiuses and feed mixture pressure required for pellets formation, was obtained.

The channel outlet pressure is connected with geometrical dimensions of a gear pelletizer by the expression (22):

\[ P_{\text{out}} = \frac{2(P_{\text{inl}}rL + k\pi + P_{\text{inl}} - aL^2)}{(R+r)(\sqrt{(R-r)^2}+L^2)}, \]  

(22)

where \( P_{\text{inl}}, P_{\text{out}} \) – the channel inlet and outlet pressures, respectively, \( \text{Pa} \);

\( L \) – the pressing channel length, \( \text{m} \);

\( R, r \) – the pressing channel inlet and outlet radiiuses, respectively, \( \text{m} \);

\( k \) – the proportionality coefficient of a pressure, \( \text{Pa/m} \);

\( a \) – the proportionality coefficient of a polar radius.

By analogy with the continuity equation for the steady motion of a continuous medium in the pressing channel, we obtain the equation for the feed mixture velocities at the inlet and outlet of the channel.

\[ \mathcal{V}_1 = \mathcal{V}_2. \]  

Figure 7. Feed mixture motion in the pressing channel.

The mass of the selected volume of feed mixture at the channel inlet is equal to its mass at the channel output:

\[ dm_1 = dm_2. \]  

(23)
The masses are related to density and volume by the ratios:

\[ dm_1 = \rho_1 dV_1, \]
\[ dm_2 = \rho_2 dV_2, \]

where \( \rho_1, \rho_2 \) – the densities of the feed mixture at the channel inlet and outlet, respectively, kg/m\(^3\).

Considering that cylinder selected volumes at the channel inlet and outlet are connected with \( S_1, S_2 \) – section areas of the orifices, we will get:

\[ dV_1 = S_1 dl_1, \]
\[ dV_2 = S_2 dl_2, \]

where \( dl_1, dl_2 \) – the heights of the selected cylinders, m.

The heights of the selected cylinders are connected with feed mixture velocities by the ratios:

\[ dl_1 = v_1 dt, \]
\[ dl_2 = v_2 dt. \]

By substituting formulas for section areas \( S_1=\pi R^2, S_2=\pi r^2 \) in the formula (20), we will get:

\[ \rho_1 S_1 v_1 dt = \rho_2 S_2 v_2 dt. \]

The feed mixture densities at the channel inlet and outlet (figure 4) are calculated as ratio of the mass to the volume:

\[ \rho_1 = \frac{m}{\pi R^2 H}, \]
\[ \rho_2 = \frac{m}{\pi r^2 h}. \]

Hence, densities ratio is equal to the ratio of volume compression:

\[ \frac{\rho_1}{\rho_2} = \frac{R^2 H}{r^2 h} = k_v. \]

The velocities are interrelated by the formula:

\[ v_1 = \frac{H}{h} \cdot v_2. \]

Basing on the homogeneity of the feed mixture as a continuous medium that is preserved during volume compression, we define the ratio of the linear dimensions of the selected volume (figure 4) before and after compression as the cube root of the volume compression ratio:

\[ \frac{H}{h} = \sqrt[3]{k_v}. \]

The performance of a single pressing channel is:

\[ q = \frac{dm}{dt} = \frac{\rho_2 S_2 dt_2}{dt} = \rho_2 \pi r^2 v_2 = \rho_2 \pi r^2 \cdot \frac{1}{\sqrt[3]{k_v}} \cdot v_1. \]

The feed mixture movement speed at the inlet is:

\[ v_1 = \omega \cdot \left( r' + \frac{b}{2} \right), \]
\[ \omega = \frac{\pi n}{30}, \]

where \( \omega, n \) – the angular speed and the rotation speed of the rolling head, respectively.

Therefore:
\[ v_1 = \frac{\pi n}{30} \cdot \left( r' + \frac{b}{2} \right). \]  

Then the performance of a single channel will be:

\[ q = \frac{\pi r^2}{\sqrt{k_p}} \cdot \frac{\rho_2 n}{30} \cdot \left( r' + \frac{b}{2} \right). \]  

Thus, the total performance of the pelletizer will be:

\[ Q = q \cdot N = \frac{\pi r^2}{\sqrt{k_p}} \cdot \frac{\rho_2 n N}{30} \cdot \left( r' + \frac{b}{2} \right), \]  

where \( N \) – the number of channels,

\( r' \) – the distance between the internal hopper rotation axis and the operating space, m.

\( b \) – the rolling head width, m.

### 4. Conclusion

As a result of the study, an analytical dependence of the pressure indicators at the inlet and outlet of the pressing channel on the geometric parameters of the gear pelletizer (with the conical channel shape) was obtained, as well as the derived formula for the overall performance of the pelletizer, which permits us to infer the scientific hypothesis confirmable.

This dependence allows us to determine at the design stage such basic structural and operational parameters of the gear-type pelletizer as the number of pressing channels, the distance from the axis of rotation of the pelletizer’s internal hopper to the operating space, and the rolling head width.

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