Mixer for dry concentrated feed

Vyacheslav Ulyanov¹, Vladimir Utolin¹, Nikolai Luzgin¹, Maria Borontova¹, Alexander Kiryanov², Andrey Polunkin²

¹Ryazan State Agrotechnological University by P.A. Kostycheva, Kostychev Str., 1, Ryazan, Russia
²Academy of Law and Management of the Federal Penitentiary Service, Sennaya str., 1, 390000, Ryazan, Russia

E-mail: 6451985@mail.ru

Abstract. In the production of starch products from corn grain, a number of valuable by-products are obtained, the bulk of which are pulp, corn extract, crushed corn grain and oilcake. By-products of starch production in the feeding rations of farm animals are mainly used as separate components, which reduces the effectiveness of their use. It is most advisable to feed them in the form of a dry mixture as concentrated corn feed, which is proposed to be cooked in a spiral mixer. The design and technological scheme of the mixer should include a framework with a spiral installed in it, one end of which is fixed to the eccentric of the leading pin and the other to the driven pin of the feed change mechanism with the possibility of horizontal movement. To justify the design and technological parameters and rational operating modes of the mixer, theoretical, laboratory and production tests were performed, their results are presented. Based on the data obtained, the parameters and operating modes of the spiral mixer are substantiated. As a result of production tests, the developed mixer, used in the processing lines for the preparation of crumbly and granular feed, confirmed its operability

1. Introduction

Currently, a significant part of the grain components in the feeding rations of farm animals is replaced by-products of food and processing industries, including starch. The main by-products of starch production are condensed corn extract, squeezed pulp, oilcake and grain waste (crushed corn) [1-5]. They are most effectively used in the form of complex dry corn feed. For its preparation, it is necessary to mix the components with the homogeneity of the mixture given by the zootechnical requirements. However, due to the different particle size distribution and physico-mechanical properties of the initial ingredients, the quality of the finished mixture often arises when they are prepared in existing mixers [6].

The aim of this study is to increase the process efficiency of the preparing dry feed from by-products of starch production by developing a spiral mixer and optimizing its structural-operational parameters, which will improve the efficiency of using a mixture of corn pulp with extract, crushed corn grain, and in general the quality of the prepared feed.

2. Materials, methods and results

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2. Materials, methods and results

A mixture of corn pulp with extract, crushed corn grain and oilcake has different physical and mechanical properties [7]. Therefore, it is very difficult to mix these components using known mixers
and to obtain a high degree of homogeneity that meets the zootechnical requirements for concentrated feed at low energy consumption [8, 9].

To solve this problem, a machine with a spiral working body is proposed [10,11]. At the department of technical systems of Ryazan State Agrotechnological University named after P.A. Kostychev (Figure 1), the original design of a spiral mixer was developed [12,13]. The novelty of this technical solution of the mixer is confirmed by the Russian Federation patent for the invention [14].

Figure 1. Structural scheme (A) and appearance (B) of the prototype of mixer.
Where: 1 - loading neck; 2 - conical framework; 3 - a cylindrical spiral; 4 - unloading window; 5 - driven pin; 6 - feed change mechanism; 7 – leading pin; 8 - eccentric; 9 - frame; 10 - shutter; 11 – hopper.

The spiral mixer contains a conical body 2 mounted on the frame 9 with an unloading window 4 and a loading neck 1, over which a hopper 11 with a shutter 10 is installed. The hopper inside is divided by two vertical partitions into three compartments with the possibility of proportional change in their volume depending on the required composition of corn feed. A cylindrical spiral 3 is placed in the conical framework of the mixer, fixed on one side by an eccentric 8 and the other on a driven pin 5. The eccentric 8 is mounted on the leading pin 7 and can be displaced in the direction perpendicular to the axis of the leading pin, decreasing or increasing the values of eccentricity. The driven pin is installed in the feed change mechanism 6, with the help of which the inter-turn distance of the spiral is changed by moving it in a direction parallel to the axis of the mixer [15].

Before turning on the spiral mixer, feed components are loaded into its hopper. Then turn on the mixer motor and open the shutter. The components of the feed from the hopper are metered through the loading neck into a conical framework. Inside the conical framework, the feed components are mixed while the mixture is advanced to the uploading window due to the displacement of the feed layers by rotating around its axis and making circular round movements on the eccentric of the cylindrical spiral. The mixer throughput is changed by moving in the horizontal plane of the driven pin, which causes a change in the length of the spiral and, accordingly, its pitch of the turns.

The proposed design of the spiral mixer allows getting complex dry corn feed with a high degree of homogeneity of the mixture.

To determine the rational parameters of the spiral mixer, theoretical and experimental studies of the process of mixing the feed components were used.

When conducting theoretical studies, the well-known laws of physics, theoretical mechanics, and mathematics were used [16–20]. Theoretical studies were aimed at determining the throughput of the new spiral mixer.

It is known expression for determining the throughput of spiral conveyors \( Q \), (kg/s):

\[
Q = S_{sec} \cdot \gamma \cdot \varphi \cdot v_{av},
\]

where \( S_{sec} \) - framework area in front of the mixer outlet without taking into account the cross-sectional area of the spiral, m\(^2\);
\( v_{av} \) - average particle velocity, m/s;
\( \gamma \) - bulk mass of the mixed material, kg/m\(^3\);
\( \varphi \) - fill factor.

Let us determine the average speed of movement of dry feed, for which we consider the movement of the particle along the spiral surface of the mixer (Figure 2A).

The parametric equation of a helical surface has the form:

\[
\begin{align*}
    x &= x(u, v) = (a + c \cdot \cos u) \cdot \sin v, \\
    y &= y(u, v) = (a + c \cdot \cos u) \cdot \cos v, \\
    z &= z(u, v) = c \cdot \sin u + b \cdot v
\end{align*}
\]  

\[
0 \leq u < 2\pi; \quad -\infty < v < \infty \), \quad a > 0 \text{ and } b > 0 - \text{arbitrary but fixed numbers.}
\]
Figure 2. Schemes for theoretical research: helical surface of the spiral (A); movable and fixed coordinate systems (B).

The vector equations of the relative motion of the particle in a spiral, taking into account Figure 2B, have the form:

\[ m\ddot{x} = -\mu \cdot N \frac{\dot{x}}{v_r} + N \cdot \dot{v}_x - mg \cdot \cos \varphi + 2m \cdot \omega \cdot (\dot{y} \cdot \cos \alpha - z \cdot \sin \alpha) + m \cdot \omega^2 \cdot x, \]  
(3)

\[ m\ddot{y} = -\mu \cdot N \frac{\dot{y}}{v_r} + N \cdot \dot{v}_y + mg \cdot \cos \varphi - 2m \cdot \omega \cdot \dot{x} \cdot \cos \alpha + m \cdot \omega^2 \cdot \cos \alpha \cdot (y \cdot \cos \alpha - z \cdot \sin \alpha), \]  
(4)

\[ m\ddot{z} = -\mu \cdot N \frac{\dot{z}}{v_r} + N \cdot \dot{v}_z - mg \cdot \sin \alpha \cdot \sin \varphi + 2m \cdot \omega \cdot \dot{x} \cdot \sin \alpha + m \cdot \omega^2 \cdot \sin \alpha \cdot (z \cdot \sin \alpha - y \cdot \cos \alpha), \]  
(5)

Initial conditions for determining the position of a particle moved by a spiral:

\[ u\big|_{t=0} = u_0, \quad \dot{u}\big|_{t=0} = \dot{u}_1, \]  
\[ v\big|_{t=0} = v_0, \quad \dot{v}\big|_{t=0} = \dot{v}_1, \]  
(6)

To solve a statically indeterminate system, we add the spiral surface equation (2), which will ensure the transition from three dependent variables \( x, y, z \) to two independent \( u \) and \( v \). Assuming that \( u=u(t) \) and \( v=v(t) \), we recalculate the derivatives of \( x, y, z \) and after dividing by \( m \), we write Equation (3)

\[ -c \cdot \ddot{u} \cdot \sin u \cdot \sin v + (a + c \cdot \cos u) \cdot \dot{v} \cdot \cos v = -c \cdot (\dot{u})^2 \cdot \cos u \cdot \sin v - (a + c \cdot \cos u) \cdot (\dot{v})^2 \cdot \sin v - 2 \cdot c \cdot \dot{u} \cdot \dot{v} \cdot \sin u \cdot \cos v = \]  
(7)
As a result of solving equations (7-9) by a numerical method using the MathCAD 14 computer program, an approximate expression was obtained for determining the average velocity \( v_{av} \) (mm/min) of a particle moving in the form

\[
\begin{align*}
 v_{av} &= -5.50 + 0.0054n + 0.083s + 0.063k + 0.0008n \cdot s + 0.0006n \cdot k - 0.0028s^2 + 0.0032s \cdot k - 0.0021k^2
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\]

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\]

The cross-sectional area \( S_{sec} \) (m²) of the mixer framework, taking into account the geometric parameters of the spiral, is determined by the formula

\[
S_{sec} = \frac{\pi}{4} \left[ D_{win}^2 - (d_{out}^2 - d_{in}^2) \right]
\]

where \( D_{win} \) is the diameter of the discharge window, m;
\( d_{out}, d_{in} \) - respectively the outer and inner diameters of the spiral, m.

Formula (1) for determining the throughput (Q, kg/s) of the developed spiral mixer taking into account expressions (11) and (10):

\[
Q = \frac{\pi}{4} \left[ D_{win}^2 - (d_{out}^2 - d_{in}^2) \right] \cdot \frac{\phi \cdot Y}{60} \cdot (-5.50 + 0.0054n + 0.083s + 0.0638k + 0.0008n \cdot s + 0.0006n \cdot k - 0.0028s^2 + 0.0032s \cdot k - 0.0021k^2)
\]
factor experiments were carried out [18]. Moreover, in addition to mixing uniformity, the energy consumption for the mixing process and the throughput (productivity) of the mixer were taken into account as a criterion. The changes in these parameters from the frequency of rotation of the spiral, its pitch and the eccentricity of the working body of the mixer were studied. The studies were carried out using a laboratory prototype mixer [15] with a set of interchangeable working bodies. The following instruments were used as control and measuring equipment: measuring device K-50, scales (VSP-0.5-1), stopwatch, grain tester of 1 liter PH-1, engine speed converter “DELTAVFDL-3.0kW”, caliper.

A three-factor experiment was conducted to identify rational design and technological parameters and operating modes of the spiral mixer during the preparation of feed from corn pulp with extract, crushed corn grain and oilcake.

The design and technological parameters at which the performance of the spiral mixer is realized depend on the frequency of rotation of the working body, the pitch of the spiral and the magnitude of the eccentricity. As a result of one-factor experiments, the factors and the limits of their variation were determined: the rotation frequency of the working body was from 100 to 300 min\(^{-1}\), the spiral pitch - from 55 to 95 mm, the eccentricity value - from 55 to 85 mm.

Based on the results of processing a multifactor experiment using computer programs STATISTICA 8, Wolfram Mathematica 9, the following adequate regression models were obtained [21].

To determine the uniformity of the mixture, \(\theta\) (%)

\[
\theta = 83.96247 + 0.011385x - 4.16667 \times 10^{-7}x^2 - 0.11281y - 0.00019xy - 0.00014y^2 + 0.29898z + 0.0001xz + 0.025yz - 0.00279x^2, (13)
\]

where \(x, y, z\) - value of independent factors

To determine the specific energy consumed, \(N_{sp}\) (W∙h/kg)

\[
N_{sp} = 2.21076 - 0.00171x + 0.000004x^2 - 0.05603y + 6.25 \times 10^{-7}xy + 0.00037y^2 + 0.00459z - 8.33333 \times 10^{-7}xz + 6.12818 \times 10^{-19}yz - 0.00001z^2, (14)
\]

Mathematical models (13, 14) allow the calculation to determine the numerical values of the homogeneity of the mixture and the consumed specific energy within the variation limits of the experimental factor levels.

As a result of laboratory studies, it was found that with an increase in the rotation frequency of the spiral from 100 to 350 min\(^{-1}\) (Figure 3), the consumed power and productivity increase from 81 to 645 W and from 397 to 2970 kg/h, respectively.
Figure 3. The graphical dependence of changes in productivity and consumed power of a spiral mixer on the rotation frequency of the working body.

With an increase in the spiral pitch from 35 to 95 mm (Figure 4), the consumed power increases from 150 to 270 W, while the maximum value of 270 W is achieved with a spiral pitch in the range of 80...95 mm. The productivity of the spiral mixer increases from 853 to 1586 kg/h with a change in the pitch of the spiral from 35 to 95 mm, reaching a maximum value at a pitch of 80 mm.

With an increase in the eccentricity from 55 to 105 mm, the consumed power increases from 220 to 750 W, and the productivity decreases from 1004 to 890 kg/h. Moreover, with a pitch from 55 to 68 mm, it increases from 1004 to 1024 kg/h, and with values from 68 to 105 mm it decreases from 1024 to 890 kg/h (Figure 5).

Figure 4. Graphical dependences of the change in productivity and consumed power of the spiral mixer on the pitch of the spiral.
Figure 5. Graphic dependences of changes in productivity and consumed power on the eccentricity of the spiral.

The obtained second-order regression models are analyzed and investigated to identify the optimal parameters of the specific energy consumption and the degree of homogeneity of the mixture. Based on the results of a multivariate experiment, graphical dependencies of particular sections of the specific energy consumption and the degree of homogeneity of the mixture are constructed for fixed values of the rotation frequency of the working body of the mixer, the pitch of the spiral and the eccentricity of the working body (Figure 6).

\[ y = 0.1162x^2 - 8.092x + 316.19 \quad R^2 = 0.9996 \]

\[ y = -0.1114x^2 + 15.592x + 482.28 \quad R^2 = 0.9986 \]

Figure 6. The response surface, characterizing the degree of homogeneity of the mixture (A) and the specific energy consumption (B) of the rotation frequency \( n \) and the spiral pitch \( s \) with an eccentricity \( k=70 \) mm.

As a result of pitch processing of the obtained data and analysis of graphic dependencies, rational numerical values of factors were revealed. At a rotation frequency of the working body of the spiral mixer 180, 220, 260 (min\(^{-1}\)), the spiral pitch and the eccentricity are 85, 70, 75 (mm) and 65, 70, 70 (mm), respectively. The minimum specific energy consumption by the developed spiral mixer was 0.15 W∙h/kg.
The obtained numerical values of the factors made it possible to optimize the design parameters of the spiral mixer for manufacturing an experimental prototype and conducting its further production tests [22].

**Table 1. Technical characteristics of the production model of the spiral mixer.**

| Name                        | Indicators          |
|-----------------------------|---------------------|
| 1 Overall dimensions        | 1.8×0.65×1.45       |
| (height × width × long), m  |                     |
| 2 Diameter of a spiral, m   | 0.065               |
| 3 Spiral pitch, m           | 0.085               |
| 4 Rotation frequency of the | 4.0                 |
| working body, s⁻¹           |                     |
| 5 Productivity, t/h         | 1.3                 |
| 6 Drive power, kW           | 0.75                |
| 7 Weight, kg                | 95                  |

The developed spiral mixer as a part of the production line for the preparation of crumbly and granular feed from by-product of starch production was tested and implemented at the enterprises of Rassvet LLC, Klepikovsky District, and AMKOR LLC, Shilovsky District, Ryazan Region.

![General view of the preparation line for crumbly complex corn feed](image)

**Figure 7.** General view of the preparation line for crumbly complex corn feed, where: 1 - spiral mixer; 2 – component storage hopper; 3 - pneumatic crusher DKR-1; 4 - measuring kit K-50.

Production tests of the mixer were carried out by introducing it into the composition of the production line of crumbly complex corn feed (Figure 7). It included a spiral mixer, a component storage hopper, a pneumatic crusher DKR-1, and a measuring kit K-50.
As a result of production tests, the developed mixer, used in the processing lines for the preparation of crumbly and granular feed, confirmed its operability. At the same time, its throughput was 1300-1400 kg/h, the specific energy consumption was 0.22 kW∙h/t with an average degree of homogeneity of the dry feed mixture of 95%.

3. Discussion

By-products of starch production are valuable components in the feeding ration of farm animals, underestimated in full by Russian producers. One of the key factors hindering their widespread use as feed is the significant differences in the physicommechanical properties of the components. This imposes certain limitations when preparing combined mixtures from them. When using well-known machines in feed preparation lines from by-products of starch production, it is not possible to obtain a mixture with uniformity required by zootechnical means.

We have proposed the design of a spiral mixer for the preparation of dry concentrated feed from by-products of the processing of corn grain into starch - a mixture of pulp with extract, crushed grain and oilcake by mixing them in a developed spiral mixer. The mixer must contain a framework with a spiral mounted in it with fixed ends, one on the eccentric of the leading pin making additional circular round movements, and the other on the driven pin of the feed change mechanism with the possibility of horizontal movement.

According to the results of the study, it was found that the most significant factors affecting the energy and quality indicators of the mixer are the rotation frequency of the spiral and its pitch. An analytical dependence of the average speed of mass transfer in a spiral mixer on the rotation frequency of the working body, spiral pitch and eccentricity within the limits of their change from 100 to 350 min⁻¹, from 35 to 95 mm, 55 to 105 mm, respectively, is obtained.

It has been established that when the rotation frequency of the mixer spiral is changed from 100 to 350 min⁻¹, the pitch is from 35 to 95 mm and the eccentricity is from 55 to 105 mm, the mixer productivity increases from 397 to 2970 kg/h, from 853 kg/h to 1234 kg /h, from 1004 to 1024 kg/h, respectively, and the consumed power increases from 81 to 645 W, from 150 to 270 W and from 220 to 750 W, respectively.

Based on the results of a multivariate experiment, the rational parameters of the developed spiral mixer were established: the rotational frequency of the working body from 180 to 260 min⁻¹, the spiral pitch is 70...85 mm, the eccentricity is 65...75 mm, which ensures a uniformity of the feed mixture of 96...98% at a specific energy consumption 0.15...0.2 kW/h/t.

4. Conclusions

The mixer offered by us is efficient, provides uniformity of the mixture of 95%. Indicators of specific power for mixing the product are lower than those of mass-produced machines. In the future, to save on transportation and storage, consideration should be given to the production of compressed feed from by-products of starch production.

As a result of the research, rational parameters of the developed spiral mixer were established: the rotational frequency of the working body is from 3 to 4.3 s⁻¹, the spiral pitch is 0.070...0.085 m, the eccentricity is 0.065...0.075 m, which ensures a uniformity of the feed mixture of 96...98% with a specific energy consumption of 0.15...0.2 kW/h/t.

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