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IMPROVING EFFICIENCY OF HORIZONTAL RIBBON MIXER BY OPTIMIZING ITS CONSTRUCTIONAL AND OPERATIONAL PARAMETERS

POPRAWA EFEKTYWNOŚCI PRACY POZIOMEGO MIESZALNIKA WSTĘGOWEGO POPRZEZ OPTYMALIZACJĘ PARAMETRÓW KONSTRUKCYJNYCH I EKSPLOATACYJNYCH

The homogeneity of mixing various feed mixture ingredients and the reliability of mixers directly depend on the constructional features of mixing devices and operational parameters of their work. This article presents a theoretical underpinning for the structural (design) specifications of a horizontal ribbon auger mixer (blender) with regard to the fulfilment of the condition when the material is transported by auger tapes in different directions, ensuring the efficient mixing of the feed mixture ingredients and timely material unloading from the mixer tank (hopper). The performed optimization of the structural and operational specifications as a result of experimental studies has allowed to increase the reliability of the mixer and to determine the homogeneity coefficient of the finished product, which reaches its the highest value of 94.13% with the forward direction of rotation of the mixer movable operating elements, when mixing time is 13 minutes and when the tank load is 52.4% of its volume.

Keywords: *mixer reliability, ribbon auger, mixing parameters, optimization.*

Jednorodność mieszania różnych składników mieszanki paszowej i niezawodność mieszalników zależy bezpośrednio od cech konstrukcyjnych urządzeń mieszających i parametrów roboczych ich pracy. W artykule przedstawiono teoretyczne podstawy dotyczące parametrów konstrukcyjnych (projektowych) poziomego mieszalnika ślimakowego (mieszarki) wywierających wpływ na warunki przemieszczania (podczas transportu w różnych kierunkach) zapewniających efektywne mieszanie składników mieszanki paszowej i terminowy rozładunek materiału ze zbiornika mieszalnika (zasobnika). Przeprowadzona na bazie badań eksperymentalnych optymalizacja parametrów konstrukcyjnych i eksploatacyjnych pozwoliła na zwiększenie niezawodności mieszalnika i wyznaczenie współczynnika homogeniczności gotowego produktu, który osiąga najwyższą wartość 94,13% podczas przemieszczania przy normalnym kierunku obrotów ruchomych elementów mieszalnika, z czasem mieszania wynoszącym 13 minut, gdy ładunek stanowi 52,4% objętości zbiornika.

Słowa kluczowe: *niezawodność mieszalnika, przenośnik ślimakowy, parametry mieszania, optymalizacja.*

1. Introduction

To increase the productivity of farm livestock (animals and poultry), it is necessary to provide them the right nutrients in the right doses [5, 7, 8, 23]. Achieving this is possible only with the use of mixed feed [1, 3, 5, 6, 11, 13, 25]. Mixing is an operation that is particularly important. It allows combining many components with different properties into one product that meets the assumed requirements [4, 5, 10, 20]. The effectiveness of this operation affects the success of many production processes carried out in enterprises belonging to various industries [2, 4, 10, 12, 13, 20, 26].

The aim and indicator of the effectiveness of mixing is the homogeneity of the final product [5]. However, due to the fact that mixing is a process in which components actually go to random places with random probability, there are some problems with obtaining it [10]. Among the causes of these problems are indicated, among others, differences in mixed fractions (eg shape and size of particles, density, etc.). In the case of feed, the cause of additional problems is the addition of drugs and vitamins [6].

High market requirements force enterprises to streamline their production processes in order to achieve a shorter production cycle time, while ensuring an adequate level of quality of manufactured products and reduction of general costs as well as energy expenses [10, 11].

The uniformity of mixing of various components of the feedstuff, mixing speed and the reliability of mixers directly depends on the constructional (design) features of mixing devices and operational parameters of their work [6, 7, 8, 10, 13, 23, 25].

To date, a large number of mixer constructions have been developed [2, 4, 10, 12, 13, 20]. A number of studies were also conducted to determine the impact of various factors (including the way of providing components) and the construction of mixers on the homogeneity and speed of mixing [1, 2, 3, 4, 10, 16, 26]. Attempts have also been made to achieve uniformity through dilution, or ensuring adequate humidity, the proper temperature and proportion of ingredients [6].

But despite this, the processes occurring in them, which affect the reliability of operation and performance indicators when mixing components, are insufficiently studied [1, 2, 4, 13, 15, 20, 25].

Today the organization of an effective process of mixing components, which depends on the operational performance indicators of the mixers, leading to the production of mixtures corresponding to the zootechnical requirements, is an urgent task [25].

From the zootechnical perspective (considering the safety and correctness of nutrition), it is important not only to introduce the ingredients provided by the ration into the feed mixture composition at the required ratio, but it is also necessary to have them all evenly distributed throughout the entire volume of the mixture. The mixture homogeneity provides the uniform nutritional value of the feed in all parts of its volume [1, 3, 5, 7, 8, 10, 11, 12, 16, 20, 23, 26].

2. Study goals and objectives

The purpose of theoretical and experimental research is to increase the reliability of a horizontal ribbon mixer due to optimization of its constructional and operational parameters by determining the values of the most significant factors affecting the quality of mixing, reliability of equipment and energy intensity of the working process.

3. Techniques

Studies were performed in the livestock breeding mechanization laboratory. The research process have been carried out using monitoring and metering systems cooperating with the computer (in accordance with All-Union States Standards - GOST 15.101-98) [19].

During the research process, a material was used in which the basic factor was a mixture of barley (80%) and rye (20%), the density of which was 742 kg/m^3, and the control factor was pea with a density of 812 kg/m^3 [19]. The sampling procedure was consistent with GOST R ISO 6497-2011 [9] and suited to the procedures implemented in previous research [12, 19, 24].

During the evaluation of the quality of operational efficiency of mixer, homogeneity (understood as a state in which the content of components in any part of its volume corresponds to a given blend composition) was assumed as the main criterion of the final product [19, 21, 22, 24].

Theoretical substantiation of constructional parameters of a horizontal ribbon mixer

Final preparation of feed mixtures is carried out in mixers of various types. The mechanical specifications of movable operating elements of the mixing devices directly affect the reliability and their operational features (performance parameters) [21, 22, 25]. We will be considering a ribbon auger in the horizontal mixer. The outer diameter of the external auger is given in the constructional features of the mixer and is equal to D$_1$ = 1 m. The diameter of the middle D$_2$ and internal D$_3$ augers is taken from the condition of uniform material flow without the formation of stagnant zones and its effective mixing: D$_2$ = 0.75 m, D$_3$ = 0.4 m [17]. The number of cycles required to obtain a high-quality mixture will be set as N = 3; mixing time as t = 5 minutes. Given this, we are going to define the pitch of each auger [18, 25].

Let us calculate the amount of material in the mixer per one operating cycle [18, 25]:

$$M = V \cdot \phi_0 \tag{1}$$

where: M – mass of the mixture,kg;
φ_0 – specific weight of the material, kg/m^3.

Let us determine the volume of the working space in the mixer [18, 25]:

$$V = \frac{\pi \cdot D^2}{4} \cdot l \tag{2}$$

where: D is the diameter of the outer edge of the auger, m;
l – the mixer length, m.

The amount of material transported per one operating cycle of the mixer should be [18, 25]:

$$Q = N \cdot \frac{M}{t} \cdot \gamma_1 \tag{3}$$

where: Q is the capacity of a ribbon screw auger of the mixer, kg/s;
N – number of cycles of material flow by the auger for one mixing cycle;
t – mixing time, s;
γ_1 – load factor of the mixer.

Let us determine the speed of the axial flow of material v, m/s [18, 25]:

$$v = \frac{40 \cdot Q}{\pi \cdot \left(D^2 - d^2\right) \cdot \psi \cdot \phi_0 \cdot c_0} \tag{4}$$

where: d – the diameter of the inner edge of the auger, m;
ψ – fill factor of inter-turn space;
c_0 – coefficient, which takes into account the leakage of the material between the body, the material and the auger flight (screw) surface.

The fill factor of the inter-turn space should not exceed the loading capacity coefficient of the conveyor [18, 25]:

$$\psi = \psi_1 \cdot \psi_2 \tag{5}$$

where: ψ_1 – coefficient taking into account the number of auger revolutions
ψ_2 – coefficient taking into account the auger rotation angle.

The loading capacity coefficients of the screw conveyor are determined using the following empirical formulas:

$$\psi_1 = 1 - 0{,}0006 \cdot n \tag{6}$$

$$\psi_2 = 1 - 0{,}0005 \cdot \beta \tag{7}$$

where: n is the number of screw revolutions per minute;
β – screw axis tilt angle to the horizon, degrees.

Let us determine the auger flight (screw) pitch S, m [18, 25]:

$$S = \frac{60v}{n} \tag{8}$$

Angular screw rate is ω , s^{-1}:

$$\omega = \frac{\pi \cdot n}{30} \tag{9}$$

Let us calculate the rotation angle of a layer of material in the direction of the auger rotation [18, 25]:

$$\phi' = arctg\left(f_2 \cdot tg\left(\alpha + p_1\right)\right) \tag{10}$$

where: f_2 – the coefficient of friction of the material against the steel surface of the body when in motion;

α – the angle of elevation of a screw thread of the auger along the outer edge;

p_1 – the angle of friction of the material against the steel surface of the auger in motion.

$$\alpha = arctg\left(\frac{S}{\pi \cdot D}\right) \tag{11}$$

$$p_1 = arctg \cdot f_1 \tag{12}$$

where: f_1 – is the coefficient of friction of the material against the steel surface of the auger when in motion.

According to the accepted values [18, 25], after the calculations made we get: the design pitch distance for each auger: external S_1 = 0.264 m, middle S_2 = 0.496 m, and internal one S_3 = 0.48 m [18]. Based on the findings of the experimental research presented in [15, 19 and 24], and proceeding from the continuity of the mixing process, constructional (design) possibilities of making ribbon augers, reliability and operating performance, as well as the uniform flow of material by each auger taken separately, we assume the pitch distance for each mixer auger as follows: the external S_1 = 0.3 m, the middle S_2 = 0.4 m, the internal S_3 = 0.24 m.

4. Experimental research

4.1. Findings of the experimental research of the mixer

In order to determine the most effective mixing of components in a horizontal ribbon mixer, experimental studies of the direction of rotation of the mixer auger shaft for its operation cycle were carried out. In addition, the reliability of the mixer ribbon auger was assessed depending on the direction of its rotation and operational performance indicators. As the research criteria under consideration, the following rotation directions were chosen: forward (direct), backward (reverse), forward-and-backward with a 1-minute interval. According to the results of experimental studies, dependencies of the finished product homogeneity coefficient on the mixing time have been built (Fig. 1).

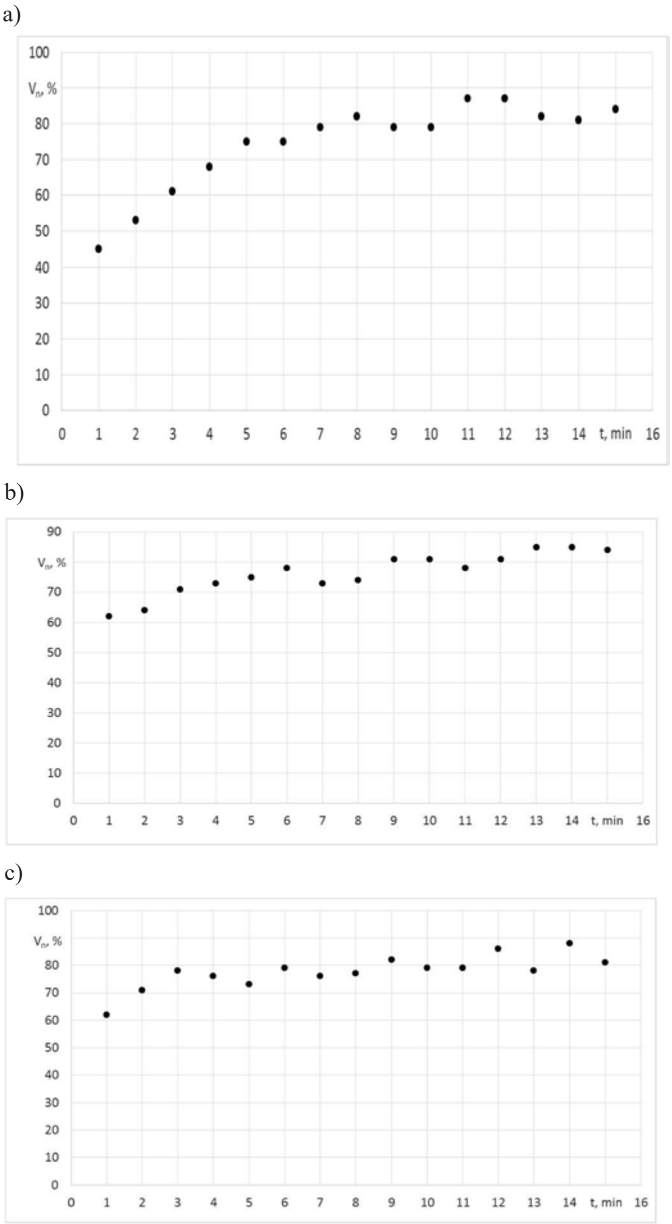

Fig. 1. Dependencies of the finished product homogeneity coefficient on the auger rotation time: a) forward, b) backward, c) forward-and-backward

When conducting the experimental studies, pea was used as a control component (its specific density is 812 kg/m^3) along with the base (a mixture of barley (80%) and rye (20%) with a specific density of 742 kg/m^3) [19]. The pea weight was 100 kg, the base weight was 700 kg, the percentage ratio of the components was 12.5% - pea, 87.5% - the base, which meets the zootechnical requirements when feeding with leguminous crops. Forward (direct) rotation of the auger was considered to be the rotation when the external auger shifts the material to the centre of the mixer. Backward (reverse) rotation was considered to be the auger rotation when the external auger shifts the material from the centre to the edges (ends) of the mixer hopper. Forward-and-backward (direct-reverse) is the alternate rotation of the auger with a 1-minute interval in the forward and backward directions. The point corresponding in the dependences presented in Figure 1 to 1 minute of time, shows the value of the finished product homogeneity coefficient at the moment when material loading is finished. Then sampling from the mixer was carried out with a 1-minute interval for all selected directions of auger rotation. The selected operating modes of the mixer ribbon auger also allow evaluating its reliability.

Analysis of Figure 1a shows that with forward rotation of the auger within the interval from the 1st to the 12th minute of mixing, a smooth increase in the homogeneity coefficient of the finished product to its maximum of 86.7% occurs. After the 12th minute, its decrease and relative independence from the mixing time is observed, which indicates the achievement of the maximum value of the homogeneity coefficient.

Analysis of Figure 1b shows that with backward (reverse) rotation of the auger within the interval from the 1st to the 14th minute of mix-

Table 1. Mixture ratio

Degree of tank filling, %	45	55	65	75	85	95
Mixture weight, total, kg	450	550	650	750	850	950
Pea weight, kg	54	66	78	90	102	114
Basis weight, kg	396	484	572	660	748	836

ing, the homogeneity coefficient of the finished product increases to its maximum of 86%.

Analysis of Figure 1c shows that with forward-backward (direct-reverse) auger rotation within the interval from the 1st to the 15th minute of mixing, there is a slight increase in the finished product homogeneity coefficient to its maximum of 86%. That is, the value of the homogeneity coefficient during the entire time of the experiment varies insignificantly (from 73.6% in the 2nd minute to 86% in the 14th minute) and has a pronounced cyclical "more-less" trend, depending on the direction of the auger rotation.

Thus, the analysis of dependencies presented in Figure 1 shows that in further experimental studies forward auger rotation will be used, since this direction of rotation leads to the highest homogeneity coefficient of the finished product at the level of 86.7% in the shortest period of time of 11 minutes. At the same time, the throughput capacity of the mixer is 0,939 kg/s, and the specific energy consumption is $9{,}612 \cdot 10^{-3}$ MJ/kg.

Specific design features and operating modes of the ribbon auger also allow us to conclude that forward rotation of the auger shaft provides for the highest reliability of the mixer.

In further studies, we are going to determine the dependence of the homogeneity coefficient of the finished product and the reliability of the mixer auger on the filling level of the tank (hopper). Filling the mixer hopper was carried out according to Table 1. Percent control component (pea) in the amount of material in the hopper is 12% across all experimental procedures. Mixing time, without reference to loading time, is 10 minutes.

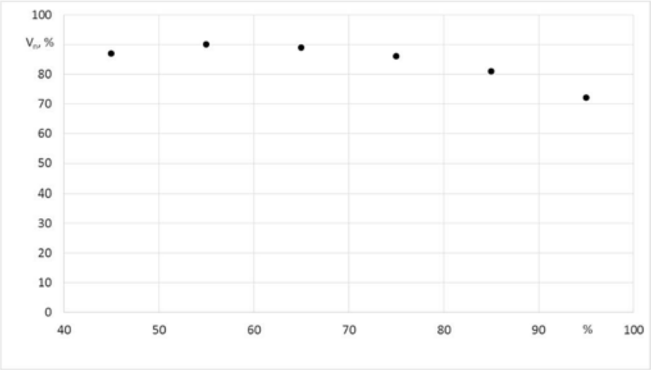

Fig. 2. Dependency of the finished product homogeneity coefficient on the degree of mixer tank filling

According to the experimental findings, the dependence of the homogeneity coefficient of the finished product on the filling degree of the mixer hopper (Figure 2) is constructed.

Analysis of the dependence presented in Figure 2 shows that the finished product homogeneity coefficient reaches its maximum when the tank is 55% full, so it is 90.5%.

When tank (hopper) is filled at the level from 60% to 95%, the value of the finished product homogeneity coefficient is reduced to 72.3%. It stems from the formation of zones where the transportation of material is not as intense due to the congestion of the mixer auger and, therefore, it affects the homogeneity of the finished product.

When the hopper is filled less than 55%, the amount of material is insufficient for its effective transportation with all three ribbon augers, therefore, we can observe that the quality of mixing is decreased.

Reducing the amount of material in the mixer hopper significantly increases the reliability of its operation by reducing the load on the operating elements.

Thus, the analysis of the experimental studies allows us to draw a conclusion that the value of the homogeneity coefficient of the finished product reaches the maximum of 90.5% with the forward direction of rotation of the mixer shaft, with 10 minutes of mixing, and with the tank load at the level of 55% of its volume. At the same time, the throughput capacity of the mixer is 1,072 kg/s, and the specific energy consumption is $7{,}308 \cdot 10^{-3}$ MJ/kg.

4.2. Optimization of constructional and operational parameters

In order to establish the optimal constructional parameters of the mixer after the implementation of single-factor experiments, studies were carried out using the multifactor experiment planning method [19, 22]. According to the results of the single-factor experiments, the following factors were selected for examination: x_1 - mixing time, min; x_2 - rotation direction of the mixer auger shaft; x_3 - the amount of material in the mixer hopper as a percentage of its possible maximum load, %. The following indicators were selected as optimization criteria: y_1 - mixture homogeneity coefficient ν_n, %; y_2 - specific energy consumption q, MJ/kg; y_3 - throughput capacity Q, kg/s. During the tests, Box-Behnken design matrix was implemented (Table 2).

The implementation of the multifactor experiment allows obtaining approximate mathematical models of the process, which link together all the factors taken into account. The experimental studies allow determining the numerical values of coefficients in equations of the mathematical models, and based on them one can estimate the degree of influence of the corresponding factors [14, 22]. The experimental findings were processed using a computer, and the following regression equations were obtained (with insignificant factors excluded):

$$y_1 = 90.49 + 4.12 \cdot x_1 - 0.16 \cdot x_2 + 0.17 \cdot x_3 - 0.75 \cdot x_1^2 - 1.18 \cdot x_1 \cdot x_2 - 1.62 \cdot x_1 \cdot x_3 - 5.12 \cdot x_2^2 - 2.93 \cdot x_3^2; \tag{13}$$

$$y_2 = 3.33 + 0.53 \cdot x_1 - 0.48 \cdot x_3 + 0.03 \cdot x_1^2 + 0.18 \cdot x_3^2; \tag{14}$$

$$y_3 = 2.36 - 0.63 \cdot x_1 + 0.44 \cdot x_3 + 0.13 \cdot x_1^2 - 0.12 \cdot x_1 \cdot x_3. \tag{15}$$

Analysis of the obtained regression equations (13-15) (based on the significance of the coefficients of the regression equations) allows us to draw a conclusion that the rotation direction of the mixer auger shaft (x_2) does not affect the optimization criteria under consideration. The mixture homogeneity coefficient ν_n (y_1), the specific energy consumption q (y_2) and the throughput capacity Q (y_3) are predominantly influenced by the mixing time of the material (x_1).

The analysis of the regression equations (13-15) and two-dimensional sections of the response surfaces (Figure 3) allow us to draw the following conclusions.

In Figure 3 it can be seen that the maximum homogeneity coefficient of the finished product ν_n = 94.13 % is achieved with the forward direction of rotation of the mixer auger shaft (x_2), 13 minutes of mixing the components (x_1) and the amount of material in the tank (hopper) equal to 52.4% of the maximum mixing chamber capacity. The through-

Table 2. Box-Behnken design matrix, intervals and levels of factors variation

Parameters	Factors		
	Mixing time, minutes	Rotation direction of the mixer auger shaft	Amount of material, %
	x_1	x_2	x_3
Upper level (+)	13 minutes	forward-backward	65
Basic level (0)	10 minutes	forward	55
Lower level (-)	7 minutes	backward	45

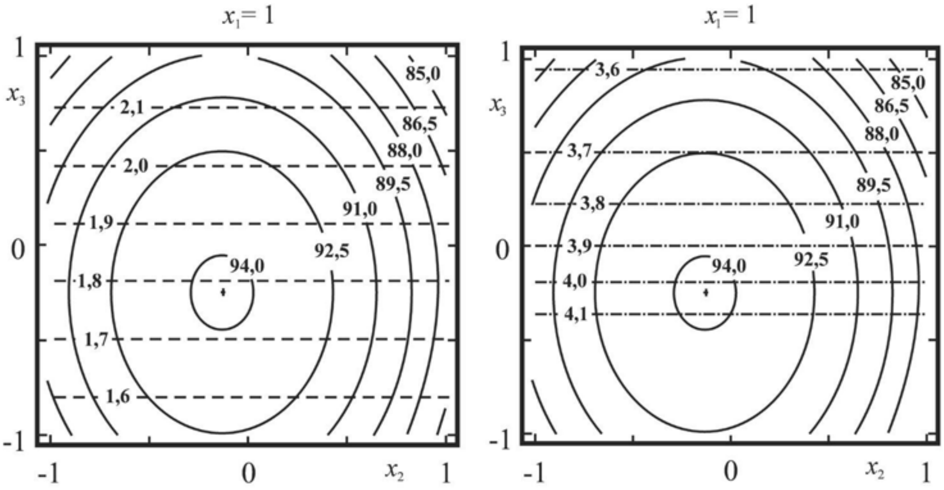

Fig. 3. Two-dimensional sections of the response surface characterizing the influence of the mixing time (x1), the rotation direction of the mixer auger shaft (x2) and the amount of material in the mixer hopper (x3) on the: a) finished product homogeneity coefficient vn (———— - y1), throughput capacity of the mixer Q (— — — — - y3); b) finished product homogeneity coefficient vn (———— - y1), specific energy consumption q (-·-·-·-·-·· - y2)

put capacity of the mixer Q is 0,494 kg/s (1.78 t/h), and the specific energy consumption is $15{,}012 \cdot 10^{-3}$ MJ/kg (4.17 kWh/t).

When the amount of material in the tank is increased (x_3) from 45 to 65%, the throughput capacity of the mixer Q increases from 0,444 to 0,583 kg/s (1.6 - 2.1 t/h) and the specific energy consumption q decreases from $14{,}76 \cdot 10^{-3}$ to $12{,}96 \cdot 10^{-3}$ MJ/kg (4.1 - 3.6 kWh/t).

The rotation direction of the ribbon auger mixer shaft (x_2) does not affect the performance indicators.

The throughput capacity of the mixer Q reaches its maximum of 1,022 kg/s (3.68 t/h) when mixing time (x_1) is 7 minutes and the amount of material in the mixer hopper (x_3) equals 65%.

The specific energy consumption q reaches its minimum of $9{,}144 \cdot 10^{-3}$ MJ/kg (2.54 kWh/t) when mixing time (x_1) is 7 minutes and the amount of material in the mixer hopper (x_3) = 65%.

5. Conclusions

1. A theoretical substantiation of the consructional parameters of a horizontal ribbon auger mixer was carried out taking into account the fulfilment of the condition of transporting the material by auger ribbons in different directions in order to ensure effective mixing of the mixture components and timely unloading of the material from the mixer tank (hopper). On the basis of theoretical studies, and proceeding from the continuity of the mixing process, constructional (design) possibilities of making ribbon augers, reliability and operating performance, as well as the uniform flow of material by each auger taken separately, the pitch distance for each mixer auger was assumed as follows: the external $S_1 = 0.3$ m, middle $S_2 = 0.4$ m, internal $S_3 = 0.24$ m.
2. Structural specifications and operating modes of the ribbon auger also allow us to conclude that forward (direct) rotation of the auger shaft provides the highest mixer reliability, while the decrease in the amount of material in the mixer tank (hopper) greatly increases the reliability of its operation by reducing the load on the working elements.
3. Optimization of the constructional (design) and operational parameters as a result of the experimental studies made it possible to determine that the finished product homogeneity coefficient reaches its highest value of 94.13% when there is forward rotation direction of the mixer operating elements, mixing time is 13 minutes and the tank load is 52.4% of its volume. At the same time, the mixer throughput capacity is 0,494 kg/s (1.78 t/h), and the specific energy consumption is $15{,}012 \cdot 10^{-3}$ MJ/kg (4.17 kWh/t).

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