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Effect of design and kinematic parameters on energy requirement in inclined screw mixer*

V. F. Khlystunov[1], S.V. Braginets[2], A.S. Alferov[3], M.V. Chernutskiy[4]**
[1] Don State Technical University, Rostov-on-Don, Russian Federation
[2,3,4]Agricultural Research Centre "Donskoy", Zernograd, Rostov Region, Russian Federation

Влияние конструктивных и кинематических параметров на энергоёмкость процесса в наклонном шнековом смесителе***

В. Ф. Хлыстунов[1], С. В. Брагинец[2], А. С. Алфёров[3], М. В. Чернуцкий[4]**
[1] Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
[2,3,4]Аграрный научный центр «Донской», г. Зерноград, Ростовская область, Российская Федерация

Introduction. Rational parameters and modes of an inclined batch screw mixer are validated to achieve the lowest energy-intensive feed mixing under observance of the zootechnical requirements for the feed quality on uneven mixing. The establishment of functional dependences between parameters and modes enables to design power-efficient equipment for the on-farm feed production.

Materials and Methods. Experimental studies of the feed mixing were implemented on an inclined screw batch feed mixer. The experimental design included variation of four independent factors: mixer shaft speed, filling ratio of the mixing chamber, mixing time, and mixing chamber angle. Mixing irregularity and energy intensity of the process were taken as optimization criteria characterizing the mixing efficiency.

Research Results. The optimization criteria versus the variability level factor, which are two-dimensional sections of the second-order response surfaces, are plotted. The rational values at mixing irregularity of less than 5% were as follows: mixer shaft speed was 27.5-36.5 min-1, filling ratio of the mixing chamber was 0.43–0.51, mixing time was 3.0–4.2 min, mixing chamber angle was 22°–25°. At such parameter values, the mixing irregularity will be minimal, and it will be 4.10–4.18%, and the process intensity is from 2.08 to 2.16 kW • h/t

Discussion and Conclusions. The dependences obtained as a result of the experimental studies allowed establishing the domain of rational design parameters and modes of an inclined batch screw mixer. The results obtained can be used in further studies under the development of initial requirements for the

Введение. Обоснованы рациональные параметры и режимы наклонного шнекового смесителя периодического действия для достижения наименьшей энергоемкости приготовления кормосмеси при условии соблюдения зоотехнических требований к качеству приготовляемых кормов по неравномерности смешивания. Установление функциональных зависимостей между параметрами и режимами позволяет проектировать энергоэффективное оборудование для внутрихозяйственного комбикормового производства.

Материалы и методы. Экспериментальные исследования процесса приготовления кормосмеси проводили на наклонном одновальном шнековом смесителе кормов периодического действия. План эксперимента включал варьирование четырьмя независимыми факторами: частотой вращения вала смесителя, коэффициентом заполнения камеры смесителя, продолжительностью смешивания и углом наклона смесительной камеры. В качестве критериев оптимизации, характеризующих эффективность смешивания, были приняты неравномерность смешивания и удельная энергоемкость процесса.

Результаты исследования. Построены графические зависимости критериев оптимизации от уровня варьирования факторов, представляющие собой двумерные сечения поверхностей отклика второго порядка. Рациональные значения при неравномерности смешивания менее 5% составили: частота вращения вала — 27,5-36,5 мин$^{-1}$, коэффициент заполнения камеры смесителя — 0,43–0,51, продолжительность смешивания — 3,0–4,2 мин.; угол наклона смесительной камеры — 22°–25°. При таких значениях параметров неоднородность смешивания будет минимальной и составит 4,10–4,18%, а энергоёмкость процесса составила от 2,08 до 2,16 кВт·ч/т

Обсуждение и заключения. Зависимости, полученные в результате экспериментальных исследований, позволили установить области рациональных конструктивных параметров и режимов наклонного одновального шнекового смесителя периодического действия. Полученные результаты могут быть использованы в

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**E-mail:vniptim@gmail.com, sbraginets@mail.ru, alfa-8303@yandex.ru, m1chaelc@yandex.ru
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creation of new technical means with a gravitation effect of intensive mixing.

дальнейших исследованиях при разработке исходных требований на создание новых технических средств с гравитационным эффектом интенсивного смешивания.

Keywords: design engineering, inclined mixer, screw, gravitation shattering, mixing irregularity, mixing intensity.

Ключевые слова: проектирование, наклонный смеситель, шнек, гравитационное осыпание, неравномерность смешивания, энергоемкость смешивания.

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Introduction. An urgent task in the design of new feed mixing equipment is to ensure a lower cost of feed preparation [1-3]. Thus, it is necessary to reduce the energy intensity of the processes while maintaining the required quality of the feed. High-quality feed mixing is most effectually performed by a periodic (batch) mixer [4, 5]. Among them, blade mixers and screw ones [6] are widespread. This is due to the fact that the feed composition is characterized by the presence of dry crushed grain (more than 90%), which does not change its properties in the process of mixing with additives. That is, the rheological properties of the mixture can be considered unchanged throughout the experiment [7].

One of the advanced models of the circulation mixers is a model with an inclined bunker, inside which one or two screw working bodies are installed. Herewith, the reduction of the process energy intensity is achieved due to the fact that the forced supply of the mixed material at the upper horizontal level is replaced by its gravitation shattering from the upper part of the bunker [8]. Unlike horizontal mixers, the practical absence of “pressing” feed layers in the top part of the screw improves significantly the diffusion mixing of the product [9]. When using modern crushers [10, 11], the intensive movement of the material and the equalized granulometric raw material composition enables to minimize the segregation effects that occur under shattering [12].

Materials and Methods. The experimental studies were carried out on AKM-3, an inclined single-shaft screw batch feed mixer developed in “Donskoy” Agricultural Research Centre. AKM-3 feed mixer (Fig. 1) with the capacity of 2.5 m^3 is designed to obtain a homogeneous mixture of dry powdered components (grain, farinaceous, protein-mineral raw material) under the batch (periodic) operation mode. It consists of a frame, housing with a mixing chamber in which a shaft with a spiral tape counterflow winding is placed, and of blades in the top part of the bunker. It is possible to install the housing on the strain gauges.

Fig. 1. General view of inclined single-screw batch mixer

In such a mixer, under the shaft rotation, the displacement of material particle groups from one place to another (convective mixing) is performed as follows: a screw transports the material to the upper part of the inclined bunker, and then its gravitation shattering to the lower part of the bunker takes place. Therefore, the main advantage of an inclined mixer, compared to vertical and horizontal ones, is the absence of dead zones between the working bodies and the walls of the mixing chamber [13].

Irregularity in the dispersion of the reference ingredient in the mixture and the process specific energy intensity were taken as criteria that characterize the mixing efficiency. Shredded wheat with moisture content up to 15% with dense loaded density of 750 kg / m^3 was used in the experiments as the basic ingredient (filler) of the mixture.

As a result, a two-component mixture composed of shredded wheat - 99%, ground common salt - 1% (by weight) was prepared.

Ground common salt was used as the reference ingredients to determine the mixing irregularity. Its distribution was determined by taking 20 samples weighing 50 g each from different points of the mixing chamber [14]. The selection of a specific sample was made according to GOST 13 496.0–80. The content of the dry reference component (table salt) in the samples was determined through the ionometric technique according to GOST 13 496.1–98. The variation coefficient of the actual distribution of the reference component in samples ν, % (y_1) was used as an index of mixing irregularity.

$N_{уд}$ (y_2) specific energy intensity of the mixing process was defined as the total energy intensity related to the mass of the feed mixture measured using a three-phase electric meter [15].

The mixer shaft speed was changed by DELTAVFd-075E frequency converter through the current frequency variation of the asynchronous motor.

A three-tier second-order design was implemented during the experiment. The experiments were carried out in triplicate [16,17].

The design of the experiments involved the variation of four independent factors affecting the mixing process (Table 1).

It is established that the signification of the mixing irregularity index is much higher than that of the latter factor which should be considered accessory.

Table 1

Factors and levels of variation

Factor	Coded identification	Variability range	Variability interval
Shaft speed, min^{-1}	x_1	20–40	10
Filling factor of mixing chamber	x_2	0.4–0.6	0.1
Mixing cycle (time), min	x_3	2–6	2
Tilt angle of mixing chamber, grade	x_4	15–35	10

Research Results. After processing the experimental results, the regression equations in coded form were obtained, and the corresponding correlation coefficients were determined:

$y_1 = 4.06 – 0.96x_1 + 0.29x_2 + 0.16x_3 – 0.88x_4 – 0.14x_1x_2 – 0.19x_1x_3 +0.54x_1x_4 + 0.28x_2x_3 – 0.39x_2x_4 – 0.20x_3x_4 + 0.56x^2{}_1 + 0.27x^2{}_2 + 0.34x^2{}_3 + 0.64x^2{}_3$,

correlation coefficient $R_1 = 0.9607$;

$y_2 = 2.26 + 0.99x_1 + 0.42x_2 – 0.07x_3 – 0.28x_4 + 0.22x_1x_2 – 0.15x_1x_3 +0.35x_1x_4 + 0.13x_2x_3 + 0.47x_2x_4 – 0.08x_3x_4 + 0.73x^2{}_1 + +0.37x^2{}_2 + 0.14x^2{}_3 + 0.84x^2{}_3$,

correlation coefficient $R_2 = 0.9781$.

The model adequacy was evaluated by the Fisher criterion. The tabular value of the Fisher criterion with the significance level $\Delta = 0.05$ equals to $F = 2.8$. The Fisher criterion value in the models is as follows: mixing irregularity - $F = 2.51$; energy intensity of the mixing process - $F = 2.65$. Comparison of the calculated values with the tabulated values has shown that their calculated values are less than the tabulated values. Consequently, regression models adequately describe the process under study. The experimental values of the Cochran test do not exceed the tabulated values. Dispersions are homogeneous.

Turning from the coded values of the factors (X_1, X_2, X_3, X_4) to natural ones (n, k, t, φ), we have obtained dependences of the mixing irregularity indicators (δ, %) and the mixing energy intensity (N, kW • h) on the basic factors in the following form:

– mixing irregularity:

$\delta = 3.76 + 11n – 0.15k – 1.02t – 2.35\varphi + 16nk – 21nt – 59n\varphi – 0.06kt + 0.98k\varphi + 2.35t\varphi + 2.15n^2 + 4.33k^2 + 3.65t^2 +0.75I^2$;

– mixing energy intensity:

$$N = 2.19 + 23n + 4.13k + 6.25\varphi - 13nk - 3.4n\varphi - 5.23k\varphi + 0.99n^2 + 0.48k^2 + 0.39\varphi^2.$$

The experimental data processing has resulted in plotting characteristic curves of the optimization criteria versus the factor variation level. They are combined two-dimensional sections of second-order response surfaces.

Figures 3 and 4 show some two-dimensional response surfaces of the factor influence to the mixing process. In particular, the dependences of the effect of the shaft speed and the loading factor of the mixing chamber on the mixing irregularity and the process energy intensity are shown.

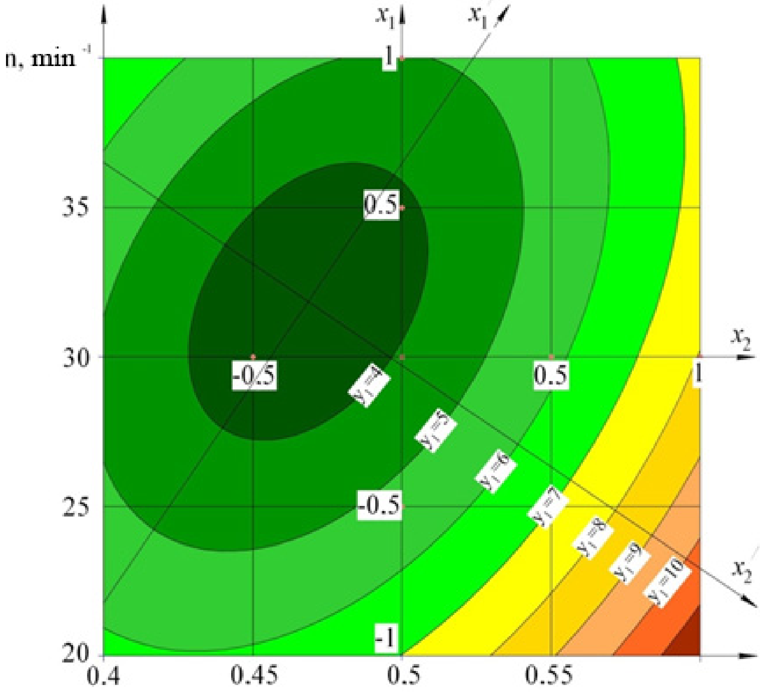

Fig. 3. Effect of shaft speed and loading ratio of the mixing chamber on mixing irregularity

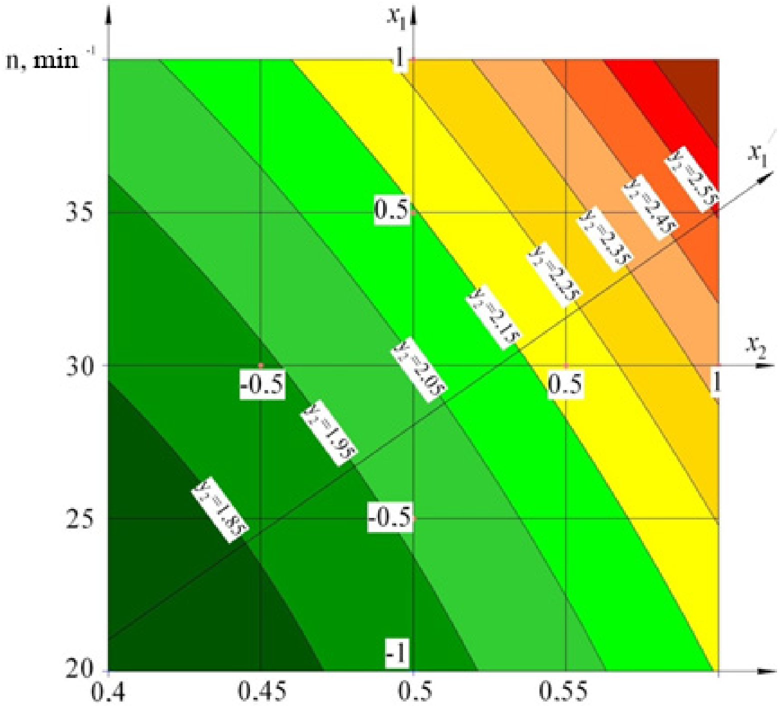

Fig. 4. Effect of shaft speed and loading factor of the mixing chamber on mixing energy

The research has resulted in determining the rational values of parameters and operation modes of the inclined single-shaft screw batch mixer with the capacity of 2.5 m^3 during the preparation of feed mixtures that meet the zootechnical requirements on mixing irregularity under the condition of minimum energy intensity of the process. The rational values to obtain mixing irregularity up to 5% are the following: shaft speed is

n = 27.5–36.5 min^{-1}; loading factor of the mixing chamber is k = 0.43–0.51; mixing time is t = 3–4.2 min; tilt angle of the mixing chamber is φ = 22–25°. In this case, the energy intensity of the process was equal to 2.08 – 2.16 kWh/t.

Besides, as a result of the experimental studies, the smallest mixing irregularity of 3.2% is set under the following mixing modes and parameters of the mixer: shaft speed is n = 35 min^{-1}; loading factor of the mixing chamber is k = 0.5; mixing time is t = 3 min; tilt angle of the mixing chamber is φ = 30°. In this case, the energy intensity of the process was 2.2 kWh / t. The smallest energy consumption of 2.1 kWh / t under mixing irregularity of 5% is obtained at the following values of parameters and operating modes of the mixer: shaft speed is n = 30 min^{-1}; loading factor of the mixing chamber is k = 0.55; mixing time is t = 3 min; tilt angle of the mixing chamber is φ = 25°.

Discussion and Conclusions. The dependences resulting from the experimental studies enable to establish domains of rational design parameters and modes of the inclined single-shaft screw batch mixer. The results can be used for the development of technical means for the production of complete feed, as well as for the modernization of existing mixed feed industry to increase their energy efficiency.

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Authors:

Khlystunov, Victor F.,
professor of the Technologies and Processing Equipment for Agro-Industrial Complex Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), Dr.Sci. (Eng.), professor,
ORCID: http://orcid.org/000-0002-2743-0698
vniptim@gmail.ru

Braginets, Sergey V.,
Senior Research Scholar, Agricultural Research Centre "Donskoy" (14, Lenin St., Zernograd, Rostov region, RF), Cand.Sci. (Eng.),
ORCID: http://orcid.org/0000-0001-7137-5692
sbraginets@mail.ru

Alferov, Alexander S.,
Research Scholar, Agricultural Research Centre "Donskoy" (14, Lenin St., Zernograd, Rostov region, RF), Cand.Sci. (Eng.),
ORCID: http://orcid.org/0000-0001-5210-781X
alfa-8303@yandex.ru

Chernutskiy, Mikhail V.,
senior engineer, Agricultural Research Centre "Donskoy" (14, Lenin St., Zernograd, Rostov region, RF),
ORCID: http://orcid.org/0000-0002-9936-1978
mux346@yandex.ru