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Analysis of energy characteristics of vibration mixing of multicomponent mixtures of agricultural raw materials

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Abstract. Ensuring the efficiency of the use of nutrients of grain, protein, vitamin and mineral feeds in the composition of complete feed mixtures in animal husbandry and crop production, as well as the corresponding reduction in the cost of manufacturing of these products, is the relevance of the presented research and prospects for their development. Therefore, the purpose of the study is to substantiate the effective regime parameters for the preparation of premixes of feed mixtures based on the assessment of the energy parameters of the vibration mixing process. This assessment was carried out by comparing the results of applying vibration, blade, and vibro-blade technological operations. Under the conditions of low-frequency vibrations, a decrease in the working resistance of the loosened layer of the mixture is observed, which provided the effect of reducing energy consumption in this process. Therefore, in comparison with conventional vibrating mixers have a higher specific productivity of 5-6 times, provide a reduction in the mixing time by 2-3 times, metal consumption – by 17%, energy consumption – by 30%, capital costs for manufacturing – by 18%, and drive power – by 30-35%, which leads to a reduction in total energy consumption by 3-4 times. As a result, the zone of minimal energy consumption was substantiated, in which the reduction of the resistance of the technological medium allowed radically reducing the friction forces during mixing, while ensuring uniform distribution with the concentration of the components of the mixture required by technological requirements. An increase in the oscillation amplitude is accompanied by a quadratic increase in power consumption, which is conditioned by an increase in energy dissipation in the mass of the mixture in the form of heat. The implementation of reasonable operating mixing modes allowed reducing the energy consumption of the proposed vibro-blade mixing by 2.0-2.5 times compared to conventional blade processing. The practical value of these developments includes the use of vibro-blade working bodies and the vibration-free operation of the drive shaft, which, together with the minimisation of energy consumption for the process, reduces dynamic loads on the support units of the developed mixer

Keywords: vibro-blade mixing; feed mass; premixes; oscillation amplitude and frequency; drive energy consumption; bulk fluidised bed; low-frequency oscillation

Introduction

Ukrainian and international practice has accumulated extensive experience in the production and use of complete, balanced feed mixtures. These compound feeds contain components of plant, animal and biological origin, biologically active substances, medicines, and flavourings – everything that contributes to the growth and preservation of animal health (Santhiralingam & Sinniah, 2018).

Considering the physiological needs and in order to effectively use nutrients by animals and poultry, and reduce production costs, all grain, protein, vitamin, and mineral feeds are fed only in the form of complete feedstuffs or feed mixtures made according to scientifically based recipes with the necessary ratio of components (Carlson *et al.,* 2018).

Increasing the nutritional properties of such feeds is achieved by introducing amino acids (methionine, lysine, tryptophan, etc.), vitamins, trace elements, enzyme preparations, antioxidants, antibiotics, emulsifiers, tranquilisers, antibacterial substances, and other components (Piñeiro-Vázquez *et al.,* 2018).

It is impossible to immediately introduce such substances into feed mixtures due to their excessively small amount in the total volume of the mixture. The best effect is achieved when they are introduced in the form of complex sets – premixes, which are a homogeneous mixture of biologically active substances in fillers with a concentration that corresponds to the biological norm of their introduction into mixed feed in the amount of 0.5, 1%, and 5% (Liu *et al.,* 2019).

Analysis of publications on the study of regularities of changes in parameters and the course of the process of preparing multicomponent mixtures using mechanical mixing (Wang *et al.,* (2020), Sá-Caputo *et al.,* (2020) and Sun *et al.,* (2019)) showed the lack of a clear theoretical explanation for the relationship between the main parameters and characteristics, in particular, for vibration mixers that are used for adding premixes to mixed feed. Improvement of design and technological schemes of processes and equipment for mixing will allow both improving the quality of processing and technological value of mixed feed, and enabling an increase in livestock growth during feeding, reducing energy resources for the implementation of the study.

Analysis of physical and mechanical properties of raw materials for the production of mixed feeds and premixes, in particular, in the studies by C. Debnath, *et al.,* (2016), O.J. Aboderin *et al.,* (2021), as well as conventional mixing equipment used in feed mills, revealed the following features of the technological process of preparing feed mixtures:

- ➤ multi-stage mixing process, which involves the preparation of preliminary mixtures and their sequential mixing.
- ➤ long mixing cycles: from 6-10 min up to 20-25 min;
- ➤ mixing components in a ratio of 1: 1 to 1:200;
- ➤ mixing components with different physical and mechanical properties;
- ➤ significant energy consumption for the preparation of a unit of production;
- ➤ no vibration mixing machines in feed production.

The purpose of the study is to determine the energy and frequency regime parameters of vibration, blade, and vibro-blade mixing of multicomponent bulk raw materials through the development of experimental equipment, analysis of experimental studies of this process, identification of its regularities when changing the driving force options under vibromechanical technological influence.

To achieve this goal, the following tasks were set: determination of energy consumption for the drive of a vibration-free blade shaft P_B; energy consumption for the drive of the vibration exciter shaft P_V; total energy consumption for mixing depending on the amplitude-frequency parameters of the installation – vibration mode coefficient k; oscillation amplitude A and the speed of rotation of the blade shaft n_S.

One of the most effective methods of implementing the presented properties is the use of vibro-mechanical means of preparing such multicomponent mixtures. The influence of these physical and mechanical factors on these systems is insufficiently investigated, which substantiates the relevance of this study and has broad prospects for development.

Literature Review

Based on the analysis of research papers by Ivanec *et al.*, (2014) and Silva *et al.*, (2014) it can be concluded that the preparation of mixtures of food components is complicated by the presence of active enzymes and microorganisms in them, and instability during storage.

J. Wang *et al.,* (2020), D. Sá-Caputo *et al.,* (2020) and W. Sun *et al.,* (2019) proved that as a result of the oscillatory movement of the machine's operating elements, the technological mass performs both a circulation motion along the trajectory induced by force factors, and the rotation of individual load particles around its instantaneous equilibrium centre, resulting in a decrease in internal friction inside the load mass; intensive mixing and destruction of individual structures; changes in the main rheological characteristics of the processed product.

M. Mushtruk *et al.* (2021) and I. Palamarchuk *et al.* (2020) argued that a significant increase in the material circulation rate can be achieved when the vibrator is removed from the working chamber. The paper shows how the bulk medium is rolled along the inner wall of a cylindrical container as a single body with an amorphous surface, which significantly intensifies the mutual movements of the particles of the mixture components among themselves, but the need to seal the surfaces bounded by spring-loaded membranes significantly complicates the design of the machine; the significant thickness of the product layer in drum structures contributes to the rapid attenuation of the oscillation amplitude as it moves away from the vibration source, which creates some problems in the development of vibration mixers with a large volume of the working chamber.

Based on the research presented in the paper by H. Ding *et al.* (2021), it is proved that the use of low-frequency vibrations ensures a uniform distribution of components of bulk dispersed systems when mixing products and preparing feed mixtures, premixes, and other high-calorie components in a drum working tank.

Thus, numerous studies of the process of preparing various bulk mixtures under the conditions of a vibration field allowed the authors to highlight the main advantages of vibration mixing over conventional mixing: a significant reduction in the effective coefficients of internal and external friction, weakening of the bonds between the particles of the material. Compared to conventional vibrating mixers, they have a higher specific capacity (5-6 times) (Ahmed *et al.,* 2020), provide a 2-3-fold reduction in mixing duration (Huang *et al.,* 2021), metal content – by 17%, energy consumption – by 30%, capital costs for manufacturing – by 18%, and drive power – by 30-35%, which leads to a reduction in total energy costs by 3-4 times (Bunkin *et al.,* 2020).

Materials and Methods

To perform these tasks, an experimental model of a vibrating mixer was developed (Figure 1), which includes: a mixing tank mounted on an elastic suspension; a vibrating drive for the excitation of vibrations; a single-shaft mixing element with blades, which has a separate drive.

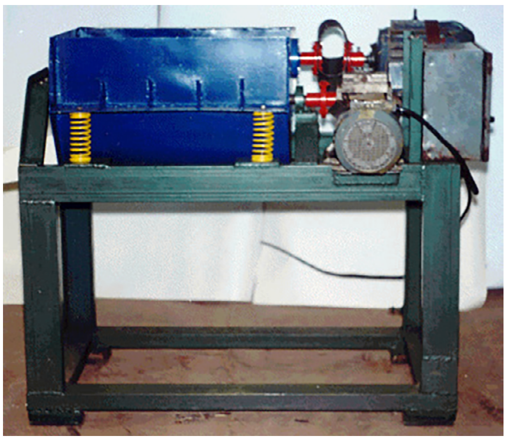

Figure 1. Experimental model of a vibration machine for preparing premixes

When performing the tasks set, experimental studies were conducted according to the developed methodology (Palamarchuk *et al.,* 2020):

➤ evaluation of the amplitude-frequency characteristics of the mixing process using the above laboratory equipment, which allows implementing vibro-blade processing of bulk feed mixture;

- ➤ evaluation of power and energy vibro-blade mixing;
- ➤ evaluation of the amplitude-frequency, power, and energy characteristics of this process when disconnecting the vibration exciter from the scheme of the developed technical system, which ensures the implementation of only the process of blade mixing;
- ➤ disconnection from the developed scheme of the blade shaft drive motor, evaluation of amplitude-frequency, power, and energy characteristics when operating only the vibration exciter, which implements the process of exclusively vibration mixing.

The study was carried out at the speed of rotation of the vibration exciter shaft n_V*=985 min*$^{-1}$, which was measured using a time tachometer TCH 10-R GOST 21339-75 (1977), changing the amplitude of vibrations of the container from 0 to 7 mm. The degree of filling of the container was used as a characteristic that affects energy dissipation in the process environment. This parameter was determined by comparing the volume geometric dimensions according to the technical characteristics of the machine with the actual volume that can be effectively used to implement the process under study. The values of the container oscillation amplitude, vibration velocity, and vibration acceleration were taken using the ROBOTRON measurement system. The value of the drive power of the vibration exciter shaft P_V was taken using a 3-phase wattmeter of type D 124 TU-5007-71.

As a characteristic of the vibration field, a coefficient of the vibration mode is taken, or the dynamism coefficient, which is determined by the equation:

$$k = \frac{A\omega^2}{g}, \tag{1}$$

where A – oscillation amplitude of the container, m; ω_v – angular velocity of vibrations of the mixer container, s^{-1}; g – gravity acceleration, m/s^2.

For a more accurate determination of P_B power consumed by the drive motor of the vibration-free blade shaft during the mixing process, the authors developed the following method, the specific feature of which is the investigation of the time of uniform lowering of the load of the set mass, during which the blade shaft will make two complete revolutions. Further, the average time value is used to analytically determine the torque on the blade shaft and the power value P_B for every instance.

Results and Discussion

The technical system, which consists of a vibrating machine – a vibrating mixer and a process load, is influenced by many factors. The most significant of them are: vibration acceleration of container $A\omega^2$, angular velocity of blade shaft rotation ω_b, physical and mechanical properties of the mixed substance.

When evaluating the energy dissipation in the system, it was found that the optimal degree of filling of the container is φ = 1/2-3/4 of the full load of the working capacity of the vibrating machine J. Wang, *et al.* (2020), M. Mushtruk, *et al.* (2022).

Analytical determination of the drive power is impossible due to the lack of clear dependencies that would describe the patterns of interaction of the vibrating surface of the U-shaped container of the vibration mixer and its working body with the particles of technological loading – a mixture of agricultural grain crops; the behaviour of this loading under the influence of a vibration field. The limiting of the study of the influence of these factors on the drive power of the technical system to conducting one-factor experiments leads to the need to perform a large number of experiments. The amount of work will be significantly reduced by using methods of matrix planning of the experiment.

The support units of the designed vibrating blade agitator perceive sufficiently intense power loads due to the combined technological action and the presence of alternating accelerations of the working elements, which becomes the main reason for the depreciation of the technical system under study. Therefore, for the effective implementation of technological tasks, a new scheme of an elastic system was proposed, the parameters of which directly affect the change in the regime characteristics of the mixing process. Such a design measure was the installation of additional elastic elements between the working container and the drive shaft. The selection of the stiffness of these elements was carried out on the condition that the transmission of working vibrations to the drive unit was levelled, that is, the blade shaft was made vibration-free. This improvement has significantly increased the efficiency and reliability of the support system of the developed vibration mixer. This improvement is the main difference between the proposed scheme and the conventional one. The main structural elements of a vibrating mixer (Fig. 2) are: container 3 with an inertial vibration exciter 1, which is mounted on a fixed frame using elastic supports 2. The container has a capacity of 70 litres. The shaft 6 with blades 7 passes through the mixer casing and is installed in bearing units 5, which are rigidly fixed in fixed racks 12 and placed outside the casing. When the mixer is running, the shaft with blades does not perform oscillatory movements, which significantly relieves the bearing units 5, increases their durability and reliability. In addition, the oscillating mass of the mixer decreases, which leads to a decrease in energy consumption. The flexible kinematic connection between the blade shaft and the mixer body is ensured by seals 4. An elastic coupling connects shaft 6 to the electric motor 9, which drives it in rotational motion. Components are loaded through the neck 10, and the mixture is unloaded through the hatch 11.

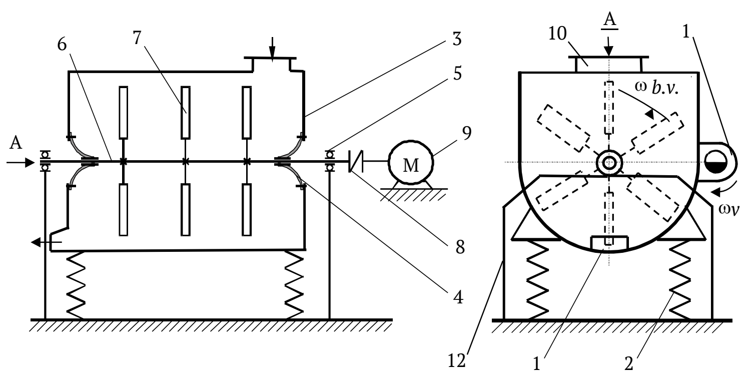

Figure 2. Diagram of a vibration mixer with a vibration-free blade shaft:
Notes: 1 – vibration exciter; 2 – spring suspension; 3 – mixer casing; 4 – seals; 5 – support units; 6 – shaft; 7 – blades; 8 – elastic coupling; 9 – electric motor; 10, 11 –pipes for entering components and unloading the mixture; 12 – fixed rack

Based on the obtained experimental data, graphical dependences of the oscillation amplitude of container A on the driving force of unbalances F are obtained (Fig. 3), showing the regularities of the introduction of loading into the mass, i.e., the degree of permeability of low-frequency vibrations in the process under study. Vibration exciter power consumption P_V during the mixing process increase due to an increase in the strength of the vibrational component of the oscillatory system and an increase in the part of the energy dissipated in the loading mass (Fig. 4). Changes in the vibration mode coefficient k, depending on the degree of load of the working container, also have a significant impact on the mixing process (Fig. 4 *a*, 5).

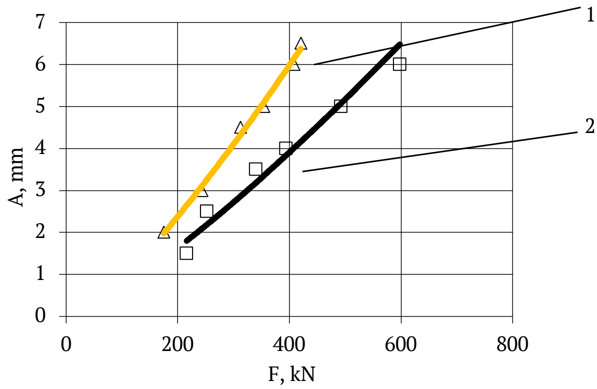

Figure 2. Dependence of the oscillation amplitude of the mixer container A on the value of the driving force F: 1 – loading of the mixer by 1/2 of the full volume; 2 – loading of the mixer by 3/4 of the full volume

According to the method presented above, experimental studies were conducted to determine the values of the amplitude-frequency, power, and energy characteristics of the studied processes of vibro-blade, blade, and vibration mixing. As experimental studies have shown, the value of the amplitude of container vibrations *A* increases exponentially as the driving force *F* increases (Figure 3), which is explained by the fact that with an increase in the load mass, the resistance to penetration of the force action into the working volume increases. Magnitude of the driving force *F* is determined solely by the mass of unbalanced elements of the drive mechanism.

The coefficient of the vibration mode k shows how much the force component of the "vibration field" exceeds this characteristic from the action of the gravitational force, which increases for large masses of the load (Figure 4*a*). Accordingly, power consumption P_v, developed by the vibration exciter, also increases with increasing technological mass. Moreover, this change is proportional to the different operating modes of the vibration installation (Fig. 4 *a, b*).

As can be seen from Figures 3 and 4, an increase in the magnitude of the driving force F leads to a proportional increase in the amplitude of vibrations of mixing container A and the power consumption by the electric motor of the drive shaft of the vibration exciter P_v. An increase in the degree of loading is accompanied by a decrease in the amplitude of oscillations of the container and an increase in the power consumption P_v. But an increase in the amplitude of vibrations A (Figure 4 a) and the vibration mode coefficient k (Fig. 4 b) is accompanied by a quadratic increase in power consumption P_v, which is conditioned by an increase in energy dissipation in the mass of the mixture in the form of heat.

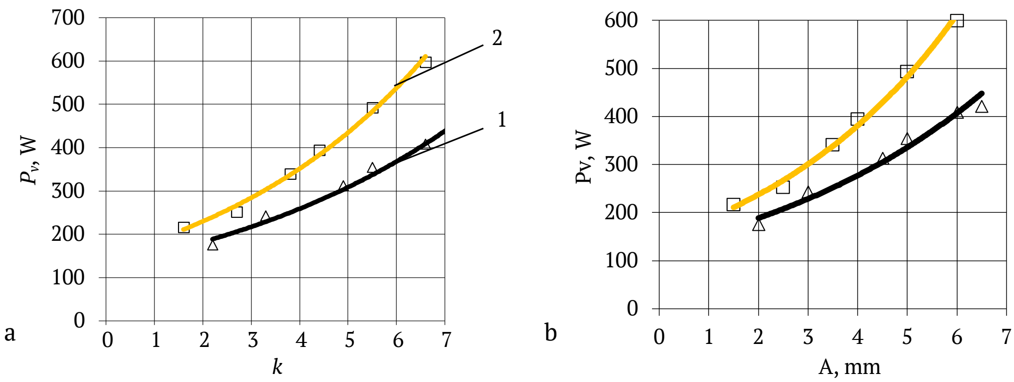

Figure 2. Dependence of the power consumed by the electric motor of the vibration exciter shaft Pv, from the vibration mode coefficient k (a) and the oscillation amplitude of the container A (b):
Notes: 1 – loading the mixer by 1/2 of the full volume; 2 – loading the mixer by 3/4 of the full volume

The experimental studies of the power P_b are necessary to substantiate the effective operating modes of the drive of a vibration-free blade shaft under different modes of vibration and mechanical action. Changes in the vibration parameters and speed of rotation of the blade shaft also affect the energy consumption for mixing. Dependences in Fig. 5 show that an increase in the number of revolutions of the blade shaft leads to an increase in the power consumption of the drive electric motor, and an increase in the value of the vibration mode coefficient k leads to its significant decrease. Under the action of the "vibration field", the circulation movement of the mixture in the mixer container creates some pressure on the blades, which causes additional resistance to the loading mass when they are counter-moving.

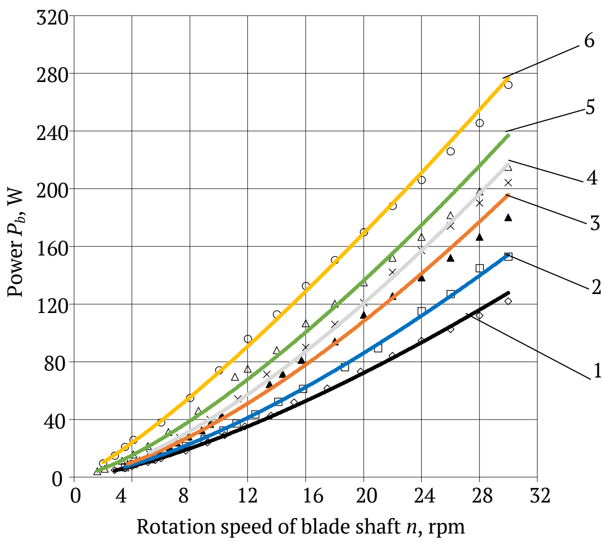

Figure 5. Dependence of power consumption P_b on the speed of rotation of the vibration-free blade shaft nb when the value of the vibration mode coefficient k is:
1–k=6.6; 2–k=5.5; 3–k=4.4; 4–k=3.8; 5–k=2.7; 6–k=1.6

A significant decrease in the power value for the vane shaft drive with an increase in the vibration mode coefficient k is explained by a decrease in the effective coefficients of internal and external friction under the influence of low-frequency vibrations. When summarising the results of experimental studies in Fig. 6, the dependences of the power consumed by the electric motor of the drive shaft of the vibration exciter P_v and the electric motor of the drive of the vibration-free blade shaft P_b are obtained, their total capacity P_Σ based on the parameters of the vibration field, which are expressed in terms of the coefficient of the vibration mode *k* at the speed of rotation of the blade shaft $n_b = 30\ min^{-1}$ and the vibration exciter shaft $n_v = 985\ min^{-1}$.

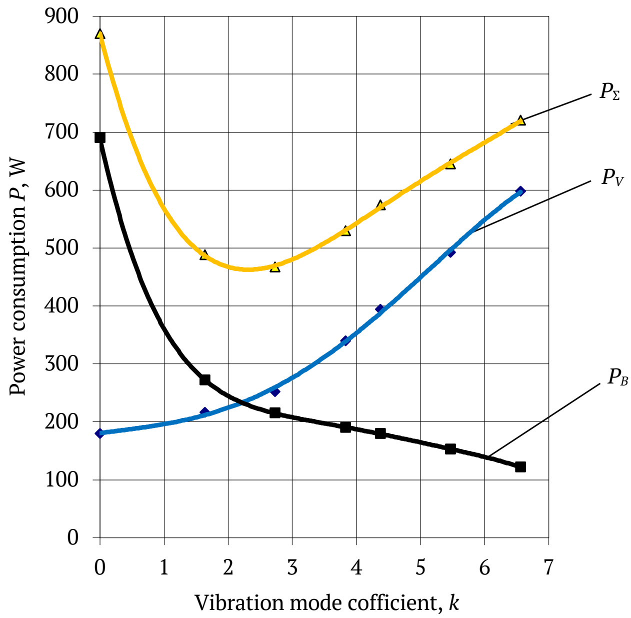

Figure 6. Dependence of the energy parameters of the vibration mixer on the value of the vibration mode coefficient k (at n_b=30 min-1, n_v=985 min^{-1}); $P\Sigma = P_v + P_b$ – total energy costs in the mixer

Figure 6 shows that an increase in the vibration parameters (coefficient *k*) is accompanied by a slight increase in the power consumption of the electric motor of the vibration exciter shaft and a significant decrease in energy consumption on the drive of the vibration-free blade shaft. This leads to the appearance of a minimum of total energy consumption for the mixer drive at the value of the vibration mode coefficient *k*≈2,5-3, that is, in the mode of continuous throwing of particles of the materials under study.

Comparative analysis of the studies by C. Debnath *et al.,* (2016), O.J. Aboderin *et al.* (2021) and L.A. Roy *et al.* (2020) showed that the main condition for achieving maximum uniformity is the creation of significant gradients of shear strain rates in micro- and macro-volumes, which is not possible in conventional mixers, which, in addition, have high specific energy consumption and long duty cycles.

The experimental studies by Y.U.E. Caixu *et al.* (2019) and M. Wathelet *et al.* (2020) show trends towards a sharp decrease in the effective coefficient of friction in the vibrating bed. However, these studies do not specify the ranges of effective vibro-mechanical parameters for processing technological masses.

Premixes with a rate of introduction into mixed feed of 0.5% qualify as impurities of increased concentration, compared to 1% they contain twice the amount of biologically active substances by reducing the mass of filler, rheological and structural-mechanical properties of raw materials for the food and pharmaceutical industries, feed preparation, microbiological industries (Singh & Agarwal, 2021); (Li *et al.,* 2019). However, no effective design schemes of technological equipment were recommended for the implementation of these processes.

Based on the results of the study by M. Mushtruk *et al.* (2022), the influence of the design of the mixing chamber on the mixing intensity was established: vibrational mixing of the material ended after 15 seconds, while in a rotating drum, a uniform distribution of components was not achieved even after 360 seconds. vibration-pulse motion converters, in which the energy of the main or driving system is used to create the technological movement of the driven system.

Drum diagrams of machines that were presented in the paper by Ding *et al.* (2021) do not reveal the technological potential of vibro-mechanical influence on the processed products. In modern technological processes, it is quite effective to implement the mixing of bulk masses by creating shear deformations in the entire mass of the product using a complex action of shovels, augers, vibrations of working tanks or individual elements of the mixer's executive bodies.

To obtain a high-quality multicomponent mixture, it is necessary to introduce high-tech equipment for the production of mixed feed, which is advisable to produce in small feed mills or directly in fattening complexes, where the specifics of local raw materials are considered and there are no significant costs for transporting finished products (Mushtruk *et al.* (2021) Palamarchuk *et al.* (2020)). In the conditions of Ukraine, where there is a whole network of inter-district feed mills, this experience, combined with domestic achievements, should be effectively implemented in production without significant additional costs.

Conclusions

During the analysis of the findings of experimental studies, relationships were established between the power consumed by the vibrator drive motor (P_v) and the drive motor of a vibration-free blade shaft (P_b), as well as their total capacity ($p\sigma$). These dependencies correlated with the vibration field parameters expressed in terms of the vibration mode coefficient k. Studies were conducted at the speed of rotation of the vane shaft $n_L = 30$ revolutions per minute and the vibration exciter shaft $n_v = 985$ revolutions per minute. An increase in vibration parameters (coefficient k) is accompanied by a slight increase in power consumption by the electric motor of the vibration exciter shaft and a significant decrease in energy consumption on the drive of a vibration-free blade shaft. This minimises the total power consumption of the mixer drive at values of the vibration mode k≈2,5-3 coefficient k of about 2.5-3. This occurs in the mode of continuous ejection of particles of the analysed materials.

The results of the experimental study established the operating mode of the installation, in which there is a clearly defined minimum use of total power on both drive electric motors for the materials under study, which is achieved at the coefficient of vibration mode k≈2,5-3, which allows reducing energy costs for the process by 2-2.5 times, considering the design complexity and implementation of two energy flows during vibro-blade mixing.

Due to the combined action of low-frequency vibrations of the working capacity and working blades for the mode k≈2,5-3, it is possible to achieve a mixture inhomogeneity value in the range of 0.8-3% with a process duration of 80-100 seconds with minimal total energy consumption.

Dependencies of energy consumption for the mixing process on the amplitude of vibrations of the working container A and from the mode coefficient k are almost identical; there is an increase in energy by 15-20% with an increase in these parameters by 25-30%, accompanied by a quadratic increase in power consumption P_v due to an increase in energy dissipation in the mass of the mixture in the form of a bulk process medium. Thus, the implementation of energy-saturated technological operations that require the use of combined vibro-mechanical action can be implemented in a less expensive way when choosing such a processing mode, when reducing the internal friction forces and, accordingly, the mechanical resistance of the medium through vibration action will significantly reduce the energy consumption of the process. Such processes include the grinding of a material with a complex composite structure; contact processes in a large volume, when insignificant ingredients need to be evenly distributed throughout the entire volume of the working chamber. These areas are relevant for further study when using vibration wave effects in the processes of food processing and production.

Acknowledgements

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Conflict of Interest

None.

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Анотація. Забезпечення ефективності використання у тваринництві та рослинництві поживних речовин зернових, білкових, вітамінних та мінеральних кормів у складі повнораціонних кормових сумішей, а також відповідне зниження витрат на виробництво даної продукції, становить актуальність представлених досліджень та перспективи їх розвитку. Тому метою представлених досліджень є обґрунтування ефективних режимних параметрів приготування преміксів кормових сумішей внаслідок оцінки енергетичних параметрів процесу вібраційного перемішування. Дана оцінка проводилась шляхом порівняння результатів застосування вібраційного, лопатевого та вібролопатевого технологічного впливу. В умовах дії низькочастотних коливань спостерігається зменшення робочого опору розпушеного шару суміші, що дозволило отримати ефект зниження енерговитрат на процес. Тому у порівнянні із звичайними вібраційні змішувачі мають більшу питому продуктивність у 5-6 разів, забезпечують зменшення тривалості змішування у 2-3 рази, металомісткості – на 17%, енергомісткості – на 30%, капітальних витрат на виготовлення - на 18% і потужності привода – на 30-35%, що зумовлює зниження загальних витрат енергії в 3-4 рази. У результаті було обґрунтовано зону мінімальних енерговитрат, у якій зменшення опору технологічного середовища дозволило радикально зменшити сили тертя у процесі перемішування за умов забезпечення рівномірного розподілу з необхідною за технологічними вимогами концентрацією складових суміші. Збільшення амплітуди коливань супроводжується квадратичним підвищенням споживаної потужності, що зумовлене збільшенням розсіювання енергії у масі суміші у вигляді теплоти. Реалізація обґрунтованих робочих режимів перемішування дозволила зменшити енерговитрати запропонованого вібролопатевого перемішування у 2,0-2,5 рази порівняно з традиційною лопатевою обробкою. До практичної цінності приведених розробок можна віднести застосування вібролопатевих робочих органів та виконання приводного валу неколивним, що разом із мінімізацією енерговитрат на процес дозволяє зменшити динамічні навантаження на опорні вузли розробленого змішувача

Ключові слова: вібролопатеве перемішування; кормова маса; премікси; амплітуда та частота коливань; енерговитрати на привод; сипкий псевдозріджений шар; низькочастотні коливання