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Evaluation of the Energy Efficiency of the Process of Vibratory Mixing of Multicomponent Bulk Raw Material of Food Industries

***Abstract**. An experimental sample of a vibrating drum machine with kinematic excitation of oscillations has been developed, which is a measurement base for evaluating the kinematic and energy characteristics of the executive organs of the oscillatory system. High technological results were obtained when using combined kinematic vibration excitation, which is characterized by a minimum mass of oscillating masses of parts compared to traditional unbalanced vibration exciters, which allows to reduce the energy consumption for the drive of the investigated vibration massage machine by 2-2.5 times.*

***Streszczenie.** Opracowano próbkę eksperymentalną wibrującego automatu bębnowego z kinematycznym wzbudzeniem drgań, która stanowi bazę pomiarową do oceny charakterystyk kinematycznych i energetycznych organów wykonawczych układu oscylacyjnego. Wysokie wyniki technologiczne uzyskano przy zastosowaniu kombinowanego kinematycznego wzbudzenia drgań, które charakteryzuje się minimalną masą mas oscylujących części w porównaniu do tradycyjnych wzbudników drgań niewyważonych, co pozwala na zmniejszenie energochłonności napędu badanej maszyny do masażu wibracyjnego o 2- 2,5 razy. (**Ocena efektywności energetycznej procesu mieszania wibracyjnego wieloskładnikowego surowca sypkiego przemysłu spożywczego**)*

Keywords: kinematic vibration excitation, mixing, energy characteristics.
Słowa kluczowe: kinematyczne wzbudzenie drgań, mieszanie, charakterystyki energetyczne.

Introduction

The need to create energy-saving technologies and equipment for their implementation is due to the following reasons: the predicted decrease in natural resource reserves [1]; increasing productivity, obtaining high-quality products and reducing their cost [2]; strengthening the export potential of Ukraine as an agrarian country that owns significant land resources, which are economically more profitable to use in the form of deep processing products [3]; restriction of import of the raw material base of agricultural products and development of the own market for competitive products of processing and food industries; independence from external technologies and manufacturers is a guarantee of economic freedom and the formation of a strategic foreign trade policy on the world market [4]. The main technological task of the production of combined high-calorie and multifunctional food additives is to obtain a homogeneous mixture [5]. The degree of perfection of this process depends on the economic indicators of production, consumption of energy resources, which affects productivity, product quality, and cost of production [6]. The peculiarity of the mixing process is multi-stage, significant duration, in particular in the production of premixes, the processing time lasts up to 20-25 minutes. with an energy intensity of 1.3-2.3 kWh/t, which is due to the need to simultaneously introduce 10-15 components of premixes with different physical and mechanical properties, the share of which in the total technological mass is 0.5-5% [7]. These are amino acids, vitamins, enzyme preparations, antioxidants, antibiotics, emulsifiers, tranquilizers, antibacterial substances and other components [8, 9, 10]. Mixing, as a rule, is carried out in gravity, screw and blade mixers, none of which provides a combination of high homogeneity of the mixture, speed of the process and low energy consumption [11, 12].

Among various forms of mechanical action on dispersed systems in technological processes, vibrational action occupies an important place as one of the most effective means for creating the necessary dynamic state of dispersed systems [13]. Applying a vibration field to the technological environment significantly activates and intensifies the mixing of the components of the mixture, increases the quality of mixing materials with different physical and mechanical properties, and contributes to reducing the duration of work cycles and energy consumption.

Numerous studies of the process of preparation of various bulk mixtures in the conditions of a vibration field allowed to highlight the main advantages of vibration mixing over traditional mixing. This is, first of all, a significant reduction in the effective coefficients of internal and external friction, a weakening of the bonds between the particles of the material [14]. Compared to conventional vibratory mixers, they have higher specific productivity (by 5-6 times), reduce 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 3…4 times decrease in total energy consumption [15].

In mixing processes, one of the most important technological tasks is not only increasing the intensity of technological action, but also reducing energy consumption in the processing process, which is implemented in vibro-impeller and pendulum schemes of drive devices [16, 17].

Therefore, modern trends in the development of the vibration mixing process are aimed at the application of combined mechanical, pneumodynamic, physico-chemical action on the technological environment, improvement of the structural schemes of working containers, the use of progressive methods of vibration action under the condition of consistency of technological solutions and their constructive implementation [18, 19].

The technological features of the vibration action determine the possibility of creating equipment with perfect constructive solutions. At the same time, a number of technological processes of agricultural processing production require fast and high-quality mixing of solid, dusty, viscous and liquid components [20, 21]. Taking into account the wide range of physical and mechanical properties of the materials being mixed, the number of components and their concentration, the possible occurrence of the phenomenon of segregation, it is possible to intensify these processes and guarantee the level of quality of the final product with the help of vibration technologies, which justifies the relevance of the conducted research.

The purpose of this scientific work is to substantiate the energy-efficient technological mode of preparation of multicomponent loose mixture using the developed design of the vibrating mixer, determined energy parameters of the oscillating system and grapho-analytical analysis of their changes.

Materials and methods

During the theoretical analysis and substantiation of the force, moment and energy characteristics of the developed apparatus for dissolution with vibro-centrifugal agitation of the technological environment, methods of mathematical analysis and their processing in the MathCAD mathematical environment were used to obtain the necessary graphic and analytical dependencies of the main mode parameters of the system [22, 23].

When performing experimental studies, the desired parameters of vibration machines were obtained using Robotron equipment, namely, spectrum analyzers, level meters and vibrometers, which allow obtaining, for given processing modes, the values of vibration amplitude, vibration speed and vibration acceleration, vibration trajectories and other parameters of vibration technological action [24].

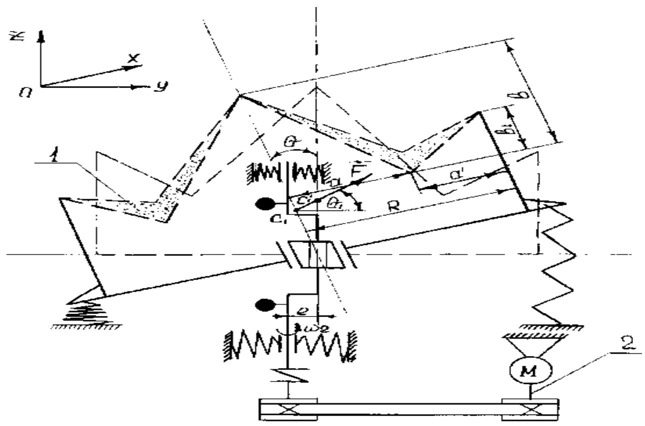

Fig. 1. Calculation scheme of the investigated vibration drive with combined mechanical vibration excitation of the spatial movement of executive bodies: 1 – technological loading, 2 – drive

When performing theoretical studies of the specified vibration drive, we make its mathematical model in the form of a calculation scheme (Fig. 1).

This drive is characterized by a kinematic method of vibration excitation and the presence of elastic elements of the drive shaft.

To the degrees of freedom of the oscillating system presented in Fig. 1, where:

x_1, y_1, z_1 – linear movements of the working container along the selected coordinate axes;

φ_1 – angular movement of the working container around the vertical axis *0Z*;

φ_2 – angular movement of the drive shaft of the vibration exciter around the *0Z* axis;

Θ_1 – angular movement of the working container in the horizontal plane.

Among the main masses of the studied system can be noted:

$$m_1 = m_k + \xi_m m_d$$

$$m_0 = m_1 + m_2$$

$$m_2 = m_в + m_p + m_{p1}$$

where: m_k is the mass of the working container; m_d – loading mass; ξ_m – coupling mass coefficient; $m_в$ – mass of the drive shaft of the vibration exciter; m_p – mass of bearing assemblies; m_{p1} – mass of counterweights; m_0 is the total mass of the system.

Results and discussion

Mathematical modeling using the Lagrange formula allowed us to obtain the equation of motion of the oscillating container (Fig. 1):

(1)

$$x = \frac{Pg\cos\omega t}{2G_2(\omega^2-\omega_0^2)}(2\cos\omega t - e^{\omega_0 t} - e^{-\omega_0 t}) + \frac{1}{2\omega_0^2}(2 - e^{\omega_0 t} - e^{-\omega_0 t});$$

$$z = \frac{Pg\cos\omega_0 t}{\omega_0 G_2(\omega^2-\omega_0^2)} + \left(\frac{G_2}{G_z} - \frac{G_1}{\omega_0^2}\right)\cos\omega_0 t + \frac{G_1}{\omega_0^2} + \frac{Pg\sin\omega t}{G_z(\omega^2-\omega_0^2)},$$

where: *P = (m1 +m2)g* is the mass of the moving parts of the vibration drive; $G_2 = m2g$; $G_1 = m1g$; ω and ω_0 – forced and free rotation frequency, respectively; t – processing time; C_z is the stiffness of elastic elements in the direction of the *0Z* axis.

Given that some components of equations (1) characterize the system's own oscillations, such movements have a damping character for steady motion. The components of these equations describing the forced oscillations of the system determine the operating mode parameters [25, 26]. Among the latter, expressions of the amplitude of oscillations and the speed of movement of the working container can be noted.

(2)

$$A_p = \frac{Pg}{G_2(\omega^2 - \omega_0^2)} = \frac{m_2 e \omega^2}{m_2(\omega^2 - \omega_0^2)};$$

$$\upsilon_x = \dot{x} = \frac{2Pg\ \omega \sin 2\omega t}{G_2(\omega_0^2 - \omega_0)};$$

$$\upsilon_z = \dot{z} = \frac{Pg\ \omega \cos \omega t}{G_2(\omega^2 - \omega_0^2)}.$$

The study of the amplitude-frequency characteristics of the studied oscillating system revealed that up to the value of the angular velocity ω = 28 rad/s, a resonant processing mode can be noted, which is characterized by a jump-like change in the operating amplitude, which complicates the process of regulating and stabilizing the operating mode. After reaching the value of the angular velocity ω = 45…50 rad/s, a more stable resonance mode is observed, which facilitates the conditions of dynamic equilibrium control in the system. This mode is characterized by the constancy of the operating amplitude, which contributes to a significant reduction of dynamic loads on support nodes.

Using formulas (1) and (2), we determine the dependencies for accelerating the movement of the working container a_v and its components ah and z according to the formulas

(3) $$a_x = \dot{\upsilon}_x = \frac{4Pg\ \omega^2 \cos 2\omega t}{G_2(\omega_0^2 - \omega^2)}$$

(4) $$a_z = \dot{\upsilon}_z = \frac{Pg\ \omega^2 \sin 2\omega t}{G_2(\omega_0^2 - \omega^2)};$$

(5) $$a_k = \sqrt{a_x^2 + a_y^2} = \frac{Pg\omega^2}{G_z(\omega_0^2 - \omega^2)}\sqrt{4\cos^2 \omega t + \sin^2 \omega t}.$$

The amplitude value of the forcing force, which disturbs the oscillatory motion, is

(6) $P = m_1 e \omega^2$

We determine the power consumption for giving the container oscillating motion as

(7) $$a_k = P\upsilon_k = \frac{m_1^2 e^2 \omega^3}{m_2(\omega^2 - \omega_0^2)}\sqrt{4\cos^2 \omega t - 4\sin^2 2\omega t}.$$

When constructing the given characteristics of the studied oscillating system, we vary the *m1/m2* ratio at a fixed value of the eccentricity e of the drive shaft; as well as the amplitude-frequency characteristics of the vibromassage container when the eccentricity e changes at a fixed ratio *m1/m2*.

Using formula (5), we construct graphs of acceleration of the motion of the oscillating system under study. At the same time, we vary the ratio *m1/m2* (Fig. 2), assuming a constant value of the eccentricity ***e*** = 2 mm.

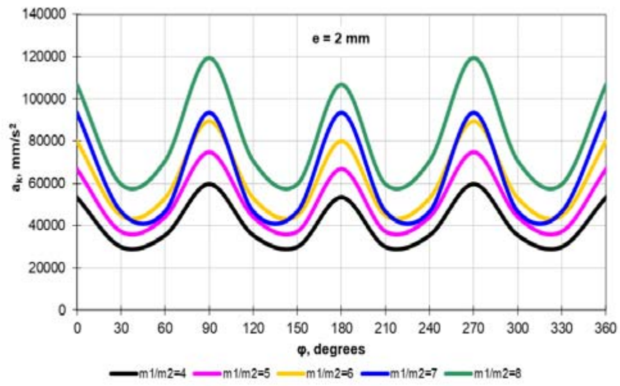

Fig. 2. Dependencies of the acceleration of the movement of the center of mass of the working container of the oscillating system under study with a change in the ratio *m1/m2* and a constant value of the eccentricity *e* = 2 mm

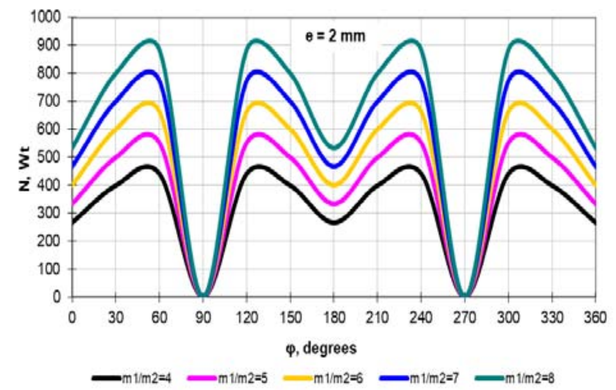

Fig. 3. Dependencies of power consumption for providing the working container with oscillating motion when the ratio m1/m2 changes and the eccentricity constant *e* = 2 mm

Using formula (7), we construct the energy characteristics of the studied oscillatory system. At the same time, we vary the *m1/m2* ratio (Fig. 3) at a constant eccentricity value of *e* = 2 mm; with a change in the eccentricity e and a constant ratio *m1/m2* = 5 (Fig. 4).

Dependencies of the amplitude-frequency characteristics indicate that at the value of the angular velocity *ω* = 50 rad/s there is stabilization of the working mode of processing loose products at the value of the amplitude of oscillations *A* = 6.5 mm. Therefore, in further grapho-analytical research, we believe that the working parameters of the vibratory mixer are *ω=ωp*=50 rad/s and *A* = *Ar* = 6.5 mm.

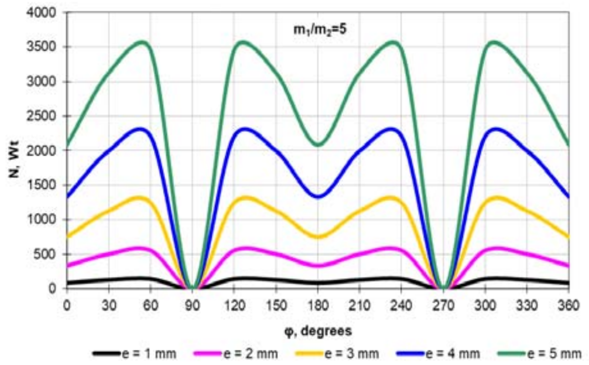

Fig. 4. Dependencies of power consumption for providing the working container with oscillating motion with a change in the eccentricity ***e*** and ***a*** constant ratio *m1/m2* = 5

Dependencies of energy characteristics (Figs. 3 and 4) indicate that for the working parameters of the vibromassage *ω* = *ωp* = 50 rad/s and *A* = *Ap* = 6.5 mm, the eccentricity value e = 2 mm and the ratio *m1/m2* = 5, minimization of power consumption is observed to provide the working container with oscillating motion with sufficient intensification of the mass transfer process in the product mass.

Conclusions

A structural and technological diagram of a vibrating mixer has been developed, which implements kinematic vibration excitation of the movement of the working container, which, thanks to the reduction of oscillating masses, makes it possible to reduce the power consumption for the process by 1.5…2 times.

The main operating parameters of the oscillating system under study are substantiated: angular speed of the drive shaft *ωp* = 50 rad/s; vibration amplitude *Ap* = 6.5 mm, the eccentricity of the drive shaft ***e*** = 2 mm and the mass ratio of the container and the kinematic vibration exciter *m1/m2* = 5, under which the minimization of power consumption is observed to provide the working container with oscillating motion with sufficient intensification of the mass transfer process in the products.

On the basis of mathematical modeling, the main operating parameters of the oscillating system under study were determined: angular speed of the drive shaft *ωp*=50 rad/s; vibration amplitude *Ap* = 6.5 mm, the eccentricity of the drive shaft ***e*** = 2 mm and the mass ratio of the container and the kinematic vibration exciter *m1/m2* = 5, under which there is a minimization of power consumption to provide the working container with oscillating motion with sufficient intensification of the mass transfer process in the product mass.

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