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IMPROVING THE OPERATION OF A DRUM GRAIN DRYER WITH JUSTIFICATION OF THE LOW-TEMPERATURE MODE PARAMETERS

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The proposed engineering and technological solutions are aimed at improving the operation of a low-temperature drum grain dryer by using a combined mechanical vibration exciter, with the further justification of low-temperature regime parameters. Existing vibration technologies imply the high-temperature drying of food grains with further utilization of spent heat carrier for reheating it. In this case, the high-temperature drying of cereals and seed crops (grains, onions, etc.) does not make it possible to maintain high germination, emphasizing the need for low-temperature treatment, which, in this case, reduces the efficiency of spent heat carrier. Therefore, to improve the efficiency of the drying process and technology, it has been proposed to employ vibration low-frequency technologies that ensure seed quality.

The trajectory and the kinetic energy of the drum container with a combined mechanical vibration exciter have been calculated for the improved vibratory drum grain dryer. The rational vibration intensity for seed drying providing the following kinetic characteristics has been established: vibration speed, to 0.03 m/s; vibration acceleration, 30 m/s^2; vibration intensity, 2.6 m^2/s^2; at amplitude vibration not exceeding 2 mm. It has been also established that the intense warming of a barley layer occurs at a temperature of 50 °C and a humidity of 13.5 %, the final temperature is 42.4 °C, and, at 40 °C, is, accordingly, 35.4 °C. This has confirmed that the low-temperature drying of barley seeds of the variety "Stalker" (Ukraine) takes place during the periods of constant and falling drying speed characterized by a high level of germination (95…93 %)

Keywords: cereal crops, grain dryer, drum container, kinetics, combined mechanical vibration exciter, vibration intensity, vibration speed

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1. Introduction

Changing climatic conditions necessitate special attention to the conditions of the growing and processing of cereals [1]. The high energy costs of grain drying predetermine the development of new approaches to improving the heat-and-mass exchange process [2].

In recent years, dryers with a pseudo-fluidized layer have been increasingly used to process crops, including seeds such as grains or onion seeds [3]. One direction to form a pseudo-fluidized layer when drying crops is the use of vibration technology. The advantage of vibration technologies and equipment that implement them is the creation of a vibroboiling (pseudo-fluidized) layer, which makes it possible to improve the process of grain agitation, thereby ensuring a shorter duration of its heat treatment.

The intensity of drying processes largely depends on the conditions of the transfer of heat and mass at the surface and inside the grain; one of the ways to improve them is to increase the contact area of phase interaction. In most cases, this effect is realized in pneumatic systems, in a vibration field, or under the combined action of these force factors, when a pseudo-fluidized or boiling layer of material is formed in the system. One of the main technological advantages of the boiling layer is the high intensity of heat transfer processes under the conditions of low-temperature changes within the dried layer itself, which positively affects the resulting grain quality.

The process of implementing the vibrational technique of drying produces a vibroboiling effect, as a result of which the volume of the grain layer increases, internal friction in the system is reduced, the grain agitation improves, and, accordingly, the time of heat treatment is shortened. The main technological advantages of the vibroboiling layer include the high intensity of heat transfer processes and the related low-temperature changes within the layer itself. In this case, the movement and pulsation of the drying agent in the vibroboiling layer accelerate the transfer of moisture from the particles to the surface, thereby intensifying the drying process. Vibration is rarely used for drying the seed material while the employment of low-frequency vibrations and low-temperature process makes it possible to preserve the quality characteristics of the grain after heat treatment, which testifies to the relevance of studies into this area.

2. Literature review and problem statement

Paper [4] reports the results of a grain scaling study, which showed that the homogeneity of moisture distribution increases with its size, thus reducing the original moisture content or density. However, there are still unresolved issues related to the influence and change in the physical and chemical properties of the processed raw materials depending on a thermal treatment technique. The reason for this is the objective difficulties associated with the structural and technical features of various dryers, ways of heat supply, and the high cost of simultaneous large-scale research in this direction. The option of overcoming the relevant difficulties may be to model the heat-and-mass exchange process and compile generalization requirements and recommendations for the implementation of high-quality processes of drying cereals, especially when using a pseudo-fluidized layer and the vibration technologies. This approach to studying the benefits of drying cereals in grain dryers was applied in works [5, 6]; however, the authors did not explore the hardware features, the impact of the regime parameters, and the ways to ensure resource efficiency. Study [7] points to the relevance of using the single- and multi-stage dryers with a pseudo-fluidized layer to remove moisture under industrial conditions; at the same time, however, the authors indicate the existence of structural and technological flaws. Namely, the high energy- and metal intensity of the structures used, emphasizing the expediency of finding innovative methods to intensify the drying process and ensure its resource efficiency.

Papers [8–10] report research into the drying of plant cereals and seed crops (rapeseed, grains, *Batyra* onion seeds, etc.) in dryers utilizing vibration technologies. It should be noted that the use of passive grain activators in the drum dryer makes it possible to intensify the drying process involving the agitation of grain material, resulting in the flow turbulization in the treatment area. In this case, the proposed counter-flow movement scheme of the material and the heat carrier is, in turn, an element of accelerating the drying process as well. For example, in a drum grain dryer with a turbulator driven by an inertial element of varying mass. To exert an inertial mechanical influence with adjustable parameters on the examined material, the hollow blade shaft hosts a partition with metallic balls. When the blade shaft rotates, the balls are exposed to a centrifugal force that presses them to the inner surface of the shaft, which creates a vibration, technological field. The outer side of the shaft hosts a perforated pipe to pass the heat carrier into the grain material. After drying the grain, the heat carrier comes out through the perforated drum, thus ensuring the evenness of the drying in all directions. The disadvantage of this technique is the high inertial loads on the bearings mounted on the shaft of the drum.

Work [11] describes laboratory tests of the drum dryer with a stirrer, at different drum loading coefficients (10...25 %) and the speeds of its rotation (0.32...1.58 s^{-1}). As a result, it was found that these parameters were greatly influenced by the humidity of the material and the speed of rotation of the mixing device, thus emphasizing the need to create kinematic models to simplify the design. However, the data on the kinematic component of a given process were not detailed, nor the factors affecting the quality of the finished product, which is relevant for understanding the full pattern of heat-and-mass exchange. One should note the need to find innovative engineering solutions for the intensification of heat-and-mass exchange when drying plant raw materials with the possibility of introducing resource-effective technologies and reducing the energy and metal intensity of the equipment used [12, 13]. One of these approaches, reported in paper [14], implies the spatial correlation of the material's microstructure during drying, as well as studying the effect of the process on the thermal-physical properties of the material. However, there are still unresolved issues related to increasing the open porosity of the grain fraction layer during drying and its effect on reducing the duration of heat treatment. The reason for this may be the incomplete study and representation of the features of changes in the properties of raw materials and heat carriers depending on the duration of the heat-and-mass exchange. One option to overcome the relevant difficulties may be the use of modeling, which makes it possible to confirm, at minimal cost, the effectiveness of engineering solutions before designing the device.

Paper [15] reports research into a change in the specificity of drying pollen grains using the proposed dryer with a pseudo-fluidized layer under infrared radiation. The result is the data on the kinetics of drying, power consumption, and the quality of the resulting product; however, certain issues relating to the comparative studies with similar ones were left unresolved. The reason for this may be the lack of proposed ways to structurally and technologically improve a given process to enhance its resource efficiency. One option for overcoming the relevant difficulties may be to use mathematical modeling, taking into consideration experimental data on the intensification of a pseudo-fluidized layer by improving the vibrational impact on the drum grain dryers.

This is due to that most designs of cereal dryers represented in the market require improvement of the technological schemes of vibration-heat treatment. Therefore, it is a relevant task to undertake research aimed at improving the drum grain dryers through the use of combined mechanical vibration exciters; the recommended regime parameters should be substantiated in order to ensure the resource efficiency of the process.

3. The aim and objectives of the study

The aim of this study is to intensify and optimize the drying processes of seed grain under the influence of a vibration field.

To accomplish the aim, the following tasks have been set:

– to improve the model structure of a drum grain dryer with a combined mechanical vibration exciter and calculate the system's kinetic energy;

– to calculate the combined mechanical vibration exciter and determine its kinematic characteristics experimentally;

– to explore the kinetics of low-temperature seed drying in the improved drum grain dryer with a combined mechanical vibration exciter.

4. Materials, methods to study the improved low-temperature drum grain dryer

To solve the main task of this research, it was proposed to improve the model structure of the drum grain dryer with a combined mechanical vibration exciter. And give a detailed description of its structural and technological component with further calculation and justification of the regime parameters, to confirm the effectiveness of the engineering solutions taken in the development.

The improved structure of the low-temperature drum grain dryer with a combined mechanical vibration exciter was tested by drying barley seeds of the variety "Stalker" (Ukraine), harvested in 2020 [16]; the seed moisture content was also determined (W=19.2 %). We studied the drying process in the drum grain dryer with a combined mechanical vibration exciter at a height of the seed layer of h=200 mm. The ambient air humidity was d=10 g/kg dry air, the ambient temperature was t_{envir}=20 °C, based on standard calculation procedures.

5. The low-temperature drum grain dryer with a combined mechanical vibration exciter

5. 1. Development of an improved model structure of the low-temperature drum grain dryer with a combined mechanical vibration exciter

The drum grain dryers that are commercially available have some shortcomings in their structural execution and technological purpose, which, in turn, artificially increases the metal and energy intensity of the drying process in general. Our analysis has allowed us to identify innovative solutions for improvement by modernizing the vibration system, thereby intensifying the vibroboiling layer and reducing the duration of the thermal treatment of raw materials.

The implementation of the first task is based on the creation of an improved model structure of a low-temperature drum grain dryer with a combined mechanical vibration exciter (Fig. 1), which consists of a DC engine, a spring clutch, a combined mechanical vibration exciter, a perforated drum. It includes branch pipes for the supply and discharge of the technological flows of grains and a drying agent.

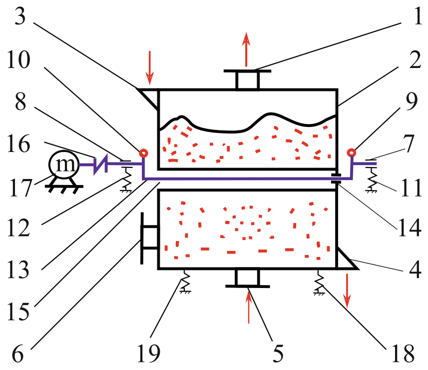


Fig. 1. Schematic of the improved model of a low-temperature drum grain dryer with a combined mechanical vibration exciter: 1, 5, 6 — branch pipes for supplying and discharging a drying agent; 2 — perforated drum; 3, 4 — branch pipes for supplying and discharging grains; 7, 8, 14, 15 — bearings; 9, 10 — balancing masses; 13 — shaft; 11, 12, 18, 19 — spring elements; 16 — clutch; 17 — electric motor

The scheme shown in Fig. 1 implements the vibrational movement of the container by employing the cumulative action of the balancing masses and shaft arranged eccentrically relative to the axis of the engine.

For the case of a high-frequency mode, it is advisable to use eccentric drives only in balanced vibratory systems.

The use of eccentric drives provides greater stability of the mechanism in low-frequency vibratory systems with minimal dynamic loads on the support nodes and the system's capability to function with a slight slowdown due to the natural frequency of system vibrations. The use of eccentric drives under high-frequency modes is advisable only when providing balancing vibrational systems. In this case, adjusting the frequency of the DC engine rotation makes it possible to change the oscillation intensity of the platform that hosts a perforated drum. The balancing masses created in this case make it possible to ensure statistical balancing of the system in general while the presence of elastic elements in the platform allows leveling off the parasitic fluctuations of the system.

5. 2. Calculating the vibration excitation of the improved design of the drum grain dryer and its regime parameters

To determine the effectiveness of the structure for vibration excitation and ensure that it minimizes vibratory masses in the improved drum grain dryer, as well as justify its optimal regime parameters, we shall consider its scheme, shown in Fig. 2.

The proposed vibratory system is characterized by 4 characteristic masses: of the working container with a technological loading m_1, of the drive eccentric shaft with support nodes m_2, of the platform m_3, of the balancing masses m_4 (Fig. 2). It has 5 degrees of freedom: horizontal, vertical, and angular displacement of the center of mass of the drive shaft, respectively, x_2, y_2, and φ; the angular movement of the working container γ and the platform ψ [10, 17].

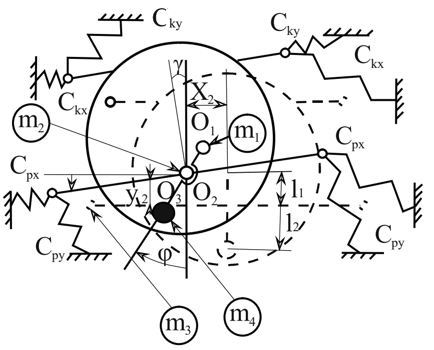


Fig. 2. Estimation scheme of the drum container with a combined mechanical vibration exciter

By using the estimation scheme of the drum container with a combined mechanical vibration exciter (Fig. 2), the kinetic energy of the vibratory system can be represented in the following form:

$$T = T_1 + T_2 + T_3 + T_4; \tag{1}$$

where T_1 is the kinetic energy of the container, J; T_2 is the kinetic energy of the drive shaft, J; T_3 is the kinetic energy of the platform, J; T_4 is the kinetic energy of the counterweight, J.

After transformation, the kinetic energy of the examined vibratory system will be equal to:

$$\begin{aligned}T &= 0.5 \cdot m \cdot \left(\dot{x}_2^2 + \dot{x}_2^2\right) + 0.5\left(I_1 + \left(I_2 + I_4\right) \cdot \dot{\varphi}^2 + I_3 \dot{\psi}^2\right) + \\ &+ m_1 \cdot l_1 \cdot \dot{\varphi}\left(0.5 l_1 \dot{\varphi} - \dot{x}_2 \cos\varphi - \dot{y}_2 \sin\varphi\right) + \\ &+ m_3 \cdot l_3 \cdot \dot{\psi}\left(0.5 l_3 \dot{\psi} + \dot{x}_2 \cos\psi - \dot{y}_2 \sin\psi\right) + \\ &+ m_4 \cdot l_2 \cdot \dot{\varphi}\left(0.5 l_2 \dot{\varphi} - \dot{x}_2 \cos\varphi - \dot{y}_2 \sin\varphi\right).\end{aligned} \tag{2}$$

The motion trajectory of the controlling elements of the kinematic combined vibration drive of the improved drum grain dryer was measured experimentally; it is shown in Fig. 3.

Our analysis of the dependence of the amplitude-frequency characteristics of the improved dryer (Fig. 3) has shown the following:

– when the machine's controlling elements are moving, there is a resonance mode on the *z* axis at an amplitude of 7 mm at an angular speed of the drive shaft of ω=28...42 rad/s;

– on the *x* axis, the transition through the resonance frequency is smooth and stabilizes at an oscillation amplitude of 2.2 mm.

This phenomenon is caused by the installation of rubber dampers, which significantly reduce the probability of entering the resonance by the proposed system. As a result of this phenomenon, the peak values of the total oscillation amplitude are 6.5 mm; they are observed when the engine drive shaft rotates in the range of 28...42 rad/s.

We calculate the basic parameters of the drum grain dryer:

– vibration speed:

$$\text{v} = \sqrt{\left(\dot{x}^2 + \dot{y}^2\right)}; \tag{3}$$

– vibration acceleration:

$$a = \sqrt{\left(\ddot{x}^2 + \ddot{y}^2\right)}; \tag{4}$$

– vibration disturbance force:

$$F = (m \cdot a); \tag{5}$$

– disturbance force power:

$$N = F \cdot \text{v}; \tag{6}$$

– vibration field intensity:

$$I = s \cdot \text{v}. \tag{6}$$

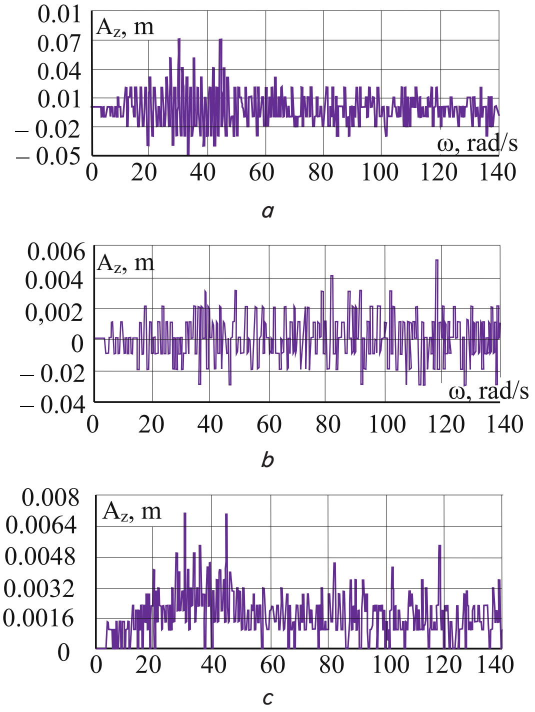


Fig. 3. Motion trajectories of the controlling elements of the kinematic combined vibration drive of the flat oscillations of the machine with a hard drum container (*x*, *y* — linear movements of the working container): *a* — oscillation amplitude along the *x* axis; *b* — oscillation amplitude along the *y* axis; *c* — cumulative oscillation amplitude of the *x* and *y* axes

Formulae (3) to (7) were used to perform calculations and build graphical dependences (Fig. 4) on the values of angular speed and duration of the experiment.

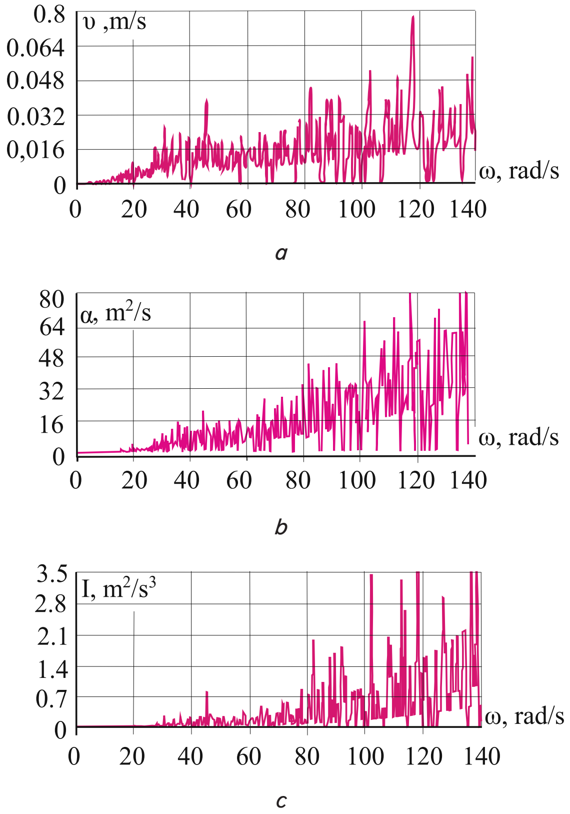
The analysis of the kinematic characteristic of the vibration drive of the grain dryer (Fig. 4) can be conditionally divided into three zones:

– 1 – 0 to 20 rad/s – a low-intensity vibration zone (pre-resonance mode), at the following values: vibration speed, to 0.003 m/s; vibration acceleration, 1.8 m/s^2; vibration intensity is zero;

– 2 – 20 to 80 rad/s – a zone of medium vibration intensity, values increase by an order of magnitude: vibration speed, to 0.03 m/s, vibration acceleration, 30 m/s^2; vibration intensity, 2.6 m^2/s^2. In this zone, the seeds are dried at the low amplitude-frequency characteristics – the amplitude of vibration does not exceed 2 mm;

– 3 – 80 to 140 rad/s – a high-intensity vibration zone, it corresponds to the following parameters: vibration speed, to 0.60 m/s; vibration acceleration, 80 m/s^2, vibration intensity, 3.5 m^2/s^2. In this zone, the materials and raw materials are crushed.

Therefore, when the angular velocity of the electric motor's shaft increases, the values of vibration speed, vibration acceleration, and vibration intensity increase. For further research, the following vibration parameters will be used: angular speed, 60 rad/s; oscillation amplitude, A_Z=2 mm; vibration speed, v=0.024 m/s; vibration acceleration, a=16 m/s^2; vibration intensity, of the I=0.3 m^2/s^2. They ensure the low-temperature oscillations of the system necessary for the steady operation of the equipment and the preservation of the quality characteristics of grain seeds.



a

b

c

Fig. 4. The kinematic characteristics of the vibration drive of the improved drum grain dryer: *a* — vibration speed; *b* — vibration acceleration; *c* — intensity of the vibration field

5. 3. Studying the kinetics of low-temperature seed drying in the improved drum grain dryer

We studied the kinetics of the process of low-temperature drying of barley seeds of the variety "Stalker" in the improved low-temperature drum grain dryer (Fig. 5, 6) at a temperature of 40–50 °C and a speed of 0.6 m/s.

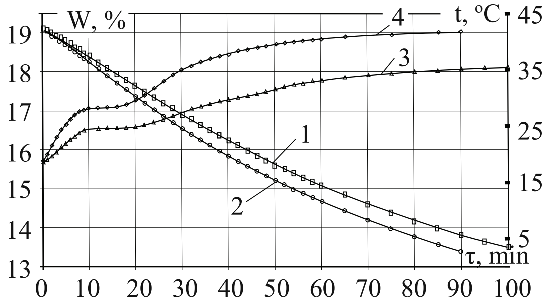


Fig. 5. The process of drying the barley seeds of the variety "Stalker" in the improved low-temperature drum grain dryer: the curves of drying (1, 2) and the temperature curves (3, 4), at a different drying agent temperature (1, 3 — 40 °C; 2, 4 — 50 °C)

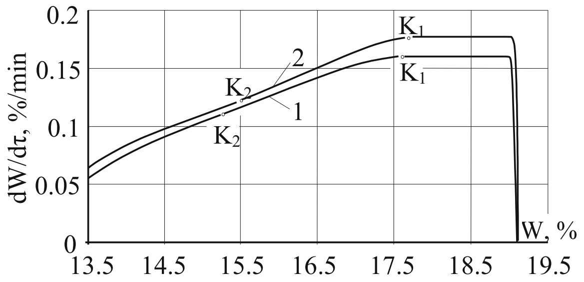


Fig. 6. Curves of the process of drying the seeds of barley of the variety "Stalker" in the improved low-temperature drum grain dryer at a different temperature of the drying agent: curve 1 — 40 °C; curve 2— 50 °C

Increasing the temperature by 10 °C (curves 1, 3) reduces the drying process duration by 12 % (Fig. 5). The most intense warming of the barley layer occurs at a heat carrier temperature of 50 °C and a humidity of 13.5 %, the final temperature is 42.4 °C, and, at 40 °C, respectively, 35.4 °C. The maximum drying speed at a heat carrier temperature of 50 °C at point K_1 is 0.181 %/min; at 40 °C, 0.155 %/min. In the period of decreasing drying rate, the second critical point K_2 is observed at a humidity of 11.5...12 % (Fig. 6).

Photography was used to determine the effect exerted on the germination of the barley seeds of the variety "Stalker", dried in the improved low-temperature drum grain dryer at 40–50 °C, on day 7 of their germination (Fig. 7).

a *b*

Fig. 7. Effect of temperature regime drying parameters on the germination of barley seeds of the variety "Stalker": *a* — T=40 °C (C=95 %); *b* — T=50 °C (C=93 %)

An analysis of the data obtained (Fig. 7) characterizes the efficiency of the temperature range (40–50 °C) as the germination of barley seeds, dried in the improved low-temperature drum grain dryer, remains at 95 % and 93 %, respectively. And the energy of their growth on days 2–4 changes, compared to original, by 2...4 %.

6. Discussion of results of improving the low-temperature drum grain dryer with a combined mechanical vibration exciter

Our findings are based on the use of modern procedures for measuring vibration and the possibility to record the results with their subsequent processing. In this case, the application of modern drying methods makes it possible to determine the low-frequency, low-amplitude, and low-temperature modes for drying seed grains. It should be noted that any changes and violations of the recommended parameters will lead to a warranted reduction in the structural and technological parameters of grain drying, as well as a decrease in the quality of the resulting products.

We have experimentally and practically determined the kinematic characteristics for the vibration drive in the improved grain dryer with the following intensity zones. A low-intensity vibration zone (pre-resonance mode) from 0 to 20 rad/s, with the following values: vibration speed, to 0.003 m/s; vibration acceleration, to 1.8 m/s^2, vibration intensity is zero. A medium-intensity vibration zone (20 to 80 rad/s): vibration speed, to 0.03 m/s; vibration acceleration, 30 m/s^2; vibration intensity, 2.6 m^2/s^2. These parameters make it possible to carry out the process of drying the seed material at low amplitude-frequency characteristics – the amplitude of vibration does not exceed 2 mm. A high-intensity vibration zone (80 to 140 rad/s), with a vibration speed up to 0.60 m/s, a vibration acceleration of 80 m/s^2, and a vibration intensity of 3.5 m^2/s^2, leads to grain crushing (Fig. 4).

Experimentally, it has been established that the intense warming of a barley layer occurs at a heat carrier temperature of 50 °C and a humidity of 13.5 %, the final temperature is 42.4 °C, and, at 40 °C, respectively, 35.4 °C (Fig. 5). The maximum drying speed at a heat carrier temperature of 50 °C at point K_1 is 0.181 %/min; at 40 °C, 0.155 %/min. In the period of decreasing drying rate, the second critical point K_2 is observed at a humidity of 11.5...12 % (Fig. 6). Temperature increase by 10 °C (curves 1, 3 – temperature: 40...50 °C) reduces the drying process duration by 12 %. The germination of barley seeds, dried in the improved drum grain dryer, is at a high level of 95...93 %, with the energy of their growth on days 2–4 changed by 2...4 % of the original (Fig. 7).

Certain limitations in the experimental part are due to the testing of the low-temperature drum grain dryer with a combined mechanical vibration exciter using the barley seeds of the variety "Stalker" under specific regime parameters. That has conditioned the need for more detailed testing not only for other varieties of barley but also other types of grains that can be dried before further treatment. Appropriate recommendation conditions should be compiled for the regime parameters, taking into consideration the changing physical and chemical properties of the studied raw materials.

To date, further scientific and practical research is continuing to determine ways to increase the intensification of the vibratory systems of grain dryers and their impact on the heat-and-mass exchange process in general, as well as the quality of raw materials provided. The main issues in the development of this study include the need to obtain the low-frequency and low-amplitude data in the testing of regime parameters.

7. Conclusions

1. We have improved the structure of the low-temperature drum grain dryer with a combined mechanical vibration exciter and adjusted frequency control over the DC engine, which makes it possible to create balancing masses, thereby enabling the statistical balancing of the vibration exciter system. The existence of elasticity in the elements of the platform makes it possible to level the parasitic fluctuations of the platform. The amplitude-frequency characteristics of the movement of the machine's controlling elements indicate the presence of a resonance mode on the z axis at an amplitude of 7 mm and an angular speed of the drive shaft within the range ω=28...42 rad/s. In this case, the transition through the resonance frequency is smooth on the x axis and stabilizes at an oscillation amplitude of 2.2 mm.

2. Combining the estimation data on the main parameters of the drum grain dryer with the kinematic characteristics of its vibration drive can be conditionally divided into three zones. The first zone, from 0 to 20 rad/s (a low-intensity vibration zone, "pre-resonance mode"), has the following values: vibration speed, to 0.003 m/s; vibration acceleration, 1.8 m/s^2; vibration intensity is equal to zero. From 20 to 80 rad/s, the second zone of medium vibration intensity; values increase by an order of magnitude: vibration speed, to 0.03 m/s; vibration acceleration, 30 m/s^2; vibration intensity, 2.6 m^2/s^2. In this zone, the seeds are dried at the low amplitude-frequency characteristics: the amplitude of vibration does not exceed 2 mm. From 80 to 140 rad/s: the third zone of high vibration intensity; it corresponds to the following parameters: vibration speed, to 0.60 m/s; vibration acceleration, 80 m/s^2; vibration intensity, 3.5 m^2/s^2; which leads to crushing the materials and raw materials.

3. The intensive warming of a barley layer occurs at a temperature of 50 °C and a humidity of 13.5 %, the final temperature is 42.4 °C, and, at 40 °C, respectively, 35.4 °C. The maximum drying rate at a heat carrier temperature of 50 °C at point K_1 is 0.181 %/min, and, at a temperature of 40 °C, 0.155 % /min. In the period of falling drying speed, the second critical point K_2 is observed at a humidity of 11.5...12 %. An increase in temperature by 10 °C (curves 1, 3 – temperature: 40–50 °C) reduces the drying process duration by 12 %. The germination of the barley seeds, dried in the improved drum grain dryer, is at a high level of 95...93 %, with the energy of their growth on days 2–4 changed by 2...4 % of the original.

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