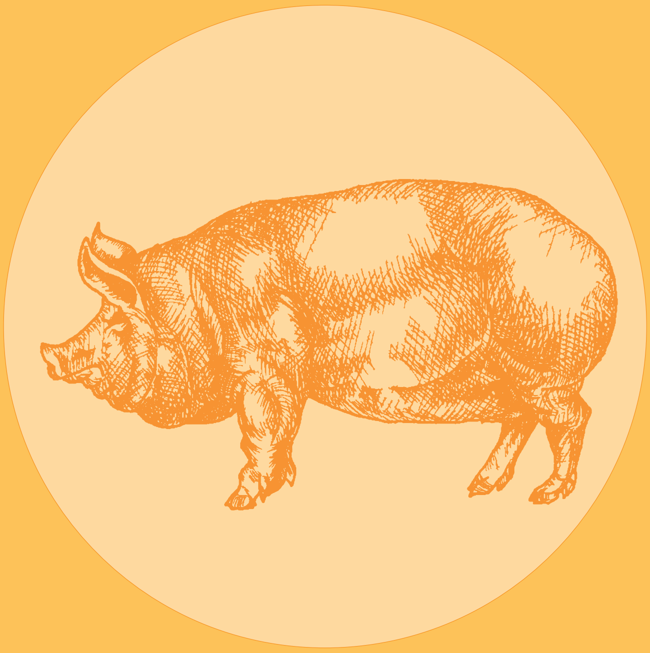
2 • XXXII • 2021, p-ISSN 1024-0845, e-ISSN 2228-4893

Kaastööde esitamiseks ja lugemiseks külastage: https://agrt.emu.ee
For online submission and open access visit: https://agrt.emu.ee/en

AGRAARTEADUS

JOURNAL OF AGRICULTURAL SCIENCE



Akadeemilise Põllumajanduse Seltsi väljaanne
Estonian Academic Agricultural Society publication
Tartu 2021

Agraarteadus
Journal of
Agricultural Science

Vol. **32** No. **2**
December 2021

Toimetuskolleegium / *Editorial Board*

Peatoimetaja / *Editor-in-chief*	
Alo Tänavots	Estonian University of Life Sciences
Tegevtoimetaja / *Managing Editor*	
Irje Nutt	Estonian University of Life Sciences
Toimetajad / *Editors*	
Maarika Alaru	Estonian University of Life Sciences
David Arney	Estonian University of Life Sciences
Tanel Kaart	Estonian University of Life Sciences
Marko Kass	Estonian University of Life Sciences
Evelin Loit	Estonian University of Life Sciences
Marten Madissoo	Estonian University of Life Sciences
Toomas Orro	Estonian University of Life Sciences
Reelika Rätsep	Estonian University of Life Sciences
Ants-Hannes Viira	Estonian University of Life Sciences
Nõukogu / Advisory *Board*	
Timo Arula	University of Tartu, Estonia; University of Maryland, USA
Berit Bangoura	University of Wyoming, USA
Ants Bender	Estonian Crop Research Institute, Estonia
Volodymyr Bulgakov	National University of Life and Environmental Sciences of Ukraine National Academy of Agrarian Sciences of Ukraine
Edward H. Cabezas-Garcia	National University of San Marcos, Peru
Gunita Deksne	Institute of Food Safety, Animal Health and Environment "BIOR", Latvia
Edenio Detmann	Federal University of Viçosa, Brasil
Margareta Emanuelson	Swedish University of Agricultural Sciences, Sweden
Martti Esala	Natural Resource Institute Finland, Luke, Finland
Marek Gaworski	Warsaw University of Life Sciences, Poland
Csaba Jansik	Natural Resource Institute Finland, Luke, Finland
Iveta Kociņa	Institute of Food Safety, Animal Health and Environment "BIOR", Latvia
Zita Kriaučiūnienė	Aleksandras Stulginskis University, Lithuania
Sven Peets	Harper Adams University, UK
Jan Philipsson	Swedish University of Life Sciences, Sweden
Vidmantas Pileckas	Lithuanian University of Health Sciences, Lithuania
Baiba Rivza	Latvia University of Life Sciences and Technologies, Latvia
Aldona Stalgienė	Institute of Economics and Rural Development of the Lithuanian Centre for Social Sciences
Priit Tammeorg	University of Helsinki, Finland
Vita Tilvikienė	Lithuanian Research Centre for Agriculture and Forestry, Lithuania
Merko Vaga	Estonian University of Life Sciences, Estonia
Rein Viiralt	Estonian University of Life Sciences, Estonia

Abstracted / indexed: AGRICOLA, AGRIS, CABI, CABI Full Text, DOAJ, EBSCO, SCOPUS

p-ISSN: 1024-0845, **e-ISSN:** 2228-4893

Väljaandmist toetavad Eesti Maaülikool ja Eesti Taimekasvatuse Instituut
Supported by Estonian University of Life Sciences and Estonian Crop Research Institute

Trükk / Print: Eesti Ülikoolide Kirjastus OÜ. Kaanepilt / Cover image by frimufilms / Freepik

AGRAARTEADUS
JOURNAL OF AGRICULTURAL SCIENCE

2 ◆ XXXII ◆ 2021

Väljaandja: Akadeemiline Põllumajanduse Selts
Peatoimetaja: pm-dr Alo Tänavots
Tehniline toimetaja: pm-mag Irje Nutt
Aadress: Fr. R. Kreutzwaldi 1, 51006 Tartu
e-post: jas@emu.ee
www: https://aps.emu.ee, https://agrt.emu.ee

Agraarteaduses avaldatud teaduspublikatsioonid on retsenseeritud

SISUKORD

TEADUSARTIKLID

KROONIKA

JUUBELID

MÄLESTUSPÄEVAD

TEATED

AGRAARTEADUS
JOURNAL OF AGRICULTURAL SCIENCE

2 ◆ XXXII ◆ 2021

Published by:	Estonian Academic Agricultural Society
Editor in Chief:	Alo Tänavots DSc (agriculture)
Technical Editor:	Irje Nutt MSc (animal science)
Address:	Fr. R. Kreutzwaldi 1, 51006 Tartu, Estonia
e-mail:	jas@emu.ee
www:	https://aps.emu.ee, https://agrt.emu.ee

Research articles published in Agraarteadus are peer-reviewed

CONTENTS

RESEARCH ARTICLES

CHRONICLE

ANNOUNCEMENTS

Agraarteadus
2 • XXXII • 2021 204–213

Journal of Agricultural Science
2 • XXXII • 2021 204–213

CASE STUDY: DYNAMICS OF SUNFLOWER SEED MOVEMENT IN THE VIBRATING TRAY OF THE INFRARED DRYER AND ITS INFLUENCE ON THE DRYING PROCESS

Valentyna Bandura[1], Leonid Yaroshenko[2], Larisa Fialkovska[3], Dmytro Kondratyuk[2], Vladyslav Palamarchuk[3], Yurij Paladiichuk[2]

[1]National University of Life and Environmental Sciences of Ukraine, 19 Henerala Rodimtseva St, 03041 Kyiv, Ukraine
[2]Vinnytsia National Agrarian University, 3 Sonyachna St, 21008 Vinnytsia, Ukraine
[3]Vinnytsia Institute of Trade and Economics of Kyiv National University of Trade and Economics,
87 Soborna St, 21050 Vinnytsia, Ukraine

Saabunud: Received:	03.06.2021
Aktsepteeritud: Accepted:	21.09.2021
Avaldatud veebis: Published online:	21.09.2021
Vastutav autor: Corresponding author:	Valentyna Bandura

E-mail: bandura_3@ukr.net

ORCID:
0000-0001-8074-3020 (VB)
0000-0002-0261-006X (LY)
0000-0002-4353-0963 (LF)
0000-0003-1827-1717 (DK)
0000-0002-7478-9521 (VP)
0000-0003-4257-9383 (YP)

Keywords: vibration, dynamics of movement, sunflower seeds, infrared drying.

DOI:10.15159/jas.21.24

ABSTRACT. Analysis of researches on the study of the material particle movement on the vibrating surface of the container machine intended for seed drying in the infrared field is carried out. Comparison of traditional devices for dehydration of raw materials with energy supply of infrared irradiation is performed. It is shown that current tendencies of the development of heat and mass transfer equipment are connected with the use of electromagnetic generators of infrared energy. The purpose of the work is to study the process of movement of sunflower seeds on a vibrating tray dryer. To achieve this goal, a dynamic scheme of the vibrating tray has been proposed and theoretical and experimental studies of the process of grain movement have been carried out. It has been established that when the speed of drive electric motors increases from 950 to 970 rotations per minute, the speed of vibro-transportation increases as well, but when reaching a certain value of speed, under a further increase in speed, the speed of vibro-transportation decreases. Experimental studies have allowed to specify the design parameters of vibrating trays and select rational parameters of the technological process of drying, namely the oscillation frequency of the vibrating tray, which is $f = 100\ \mathrm{s}^{-1}$.

Introduction

Analysis of recent research and publications

Zare *et al.* (2014) studied the kinetics of paddy drying using a hot air-infrared dryer. They used three levels of inlet air temperature (30, 40 and 50 °C), three levels of air velocities (0.01, 0.015 and 0.020 m s^{-1}) and three levels of infrared radiation intensity (2000, 4000 and 6000 W $\mathrm{m}^{2\,-1}$). They reported that the application of low-intensity infrared radiation with lower values of inlet air temperature and moderate values of inlet air velocity can effectively improve the final quality of paddy in terms of bending stress and percentage of cracked kernels.

Nindo *et al.* (1995) stated that although infrared heating is a rapid drying method, it is suitable for surface heating applications. When the increase in the grain bed depth is desired, the layer close to the infrared source dries more quickly compared to the deeper layers. One of the methods for faster and uniform drying of grains is the use of vibration.

Finzer *et al.* (2003) studied the drying of coffee berries in a hot air vibration dryer. They reported that vibration can improve product quality. In addition, the combination of hot air vibration reduces the time of drying.

In their article, Das *et al.* (2009) reported that both heating and drying of high moisture paddy using vibrating platform coupled with infrared heating source dryer give uniform and quick-drying by exposing every grain uniformly to the IR source. A laboratory apparatus capable of modulating both frequency and amplitude of vibration has been developed to study vibration aided drying characteristics of high moisture paddy. The effective moisture diffusivity of the grain during drying under this model has been evaluated. The drying characteristics of high moisture paddy have been studied under different vibrating conditions for five levels of radiation intensity (1509, 2520, 3510, 4520 and 5514 Wm$^{2\ -1}$) and four levels of grain bed depths (single kernel thickness of 3, 6, 12 and 25 mm). The optimum frequency and amplitude of the vibrations are in the range of 20–22 Hz and 8–9 mm for all the three-grain bed depths of paddy (25, 12 and 6 mm) for obtaining nearly complete and uniform mixing (mixing index ffi 1.0).

Some of the authors as Tripathy, Kumar (2008); Coradi *et al.* (2016) focused on the mathematical modelling of various drying processes and process identification. Using a proper model, it is possible to predict the final moisture content in a product, and therefore models are often used as tools to estimate the optimal heating or cooling time to optimize product quality.

Drying behaviour of corn and modes of drying bed (fixed and vibratory) were investigated on grain moisture variation during the drying process by Nourmohamadi-Moghadami *et al.* (2017). Corn kernels were dehydrated from the initial moisture content of 24.5 ± 0.5% (w.b) to the final moisture content of 14 ± 0.2%. The thin layer drying characteristics were experimentally investigated and appropriate mathematical drying models were correlated with temperature and radiation intensity. Among models fitted to experimental data, the Page model was found to be the best model for describing the drying behaviour of corn in thin layer drying form. The effective moisture diffusivity ranged from 0.6170×10^{-8} m^2 s^{-1} for the vibratory bed mode.

Bulgakov *et al.* (2018) proposed technologies of targeted energy supply for intensification of heat-and-mass transfer when drying rapeseed and other food raw materials. Bandura *et al.* (2019) describe the technological features of drying sunflower seeds using infrared energy supply and substantiates the prospects of vibration monolayer drying sunflower seeds. Specific energy costs in the process of infrared drying of the product are determined. An infrared dryer design has been developed, which ensures uniform drying of sunflower seeds by the principle of vibration fluidization. Vibrators installed on both sides of the machine provide the necessary vibration parameters of the working body of the vibrating dryer. Even when the product is fed to the working body of the vibrating dryer, a uniform, completely distributed flow of raw materials is created through vibration. This saves space and increases the efficiency and quality of drying.

Formulation of the problem

Traditionally, convective drying technologies are widely used in the food and processing industry and implemented in dryers of various designs, including mine, band, drum-type ones, in which heat is transferred to raw materials utilizing a drying agent, through the outer shell of the product to inner layers. Analysis of the most widespread technologies of convective drying reveals that drying equipment does not meet modern requirements by the energy consumption, ecological regulations, and safety of grain goods. Reduction of energy costs for drying oilseeds as the most energy-intensive process in its production is considered to be the most important task in the development of new drying technologies and designs of dryers as well as the improvement of existing ones. Any modernization of the dryer can be considered quite effective if the reduction of specific energy costs is achieved under compulsory maintenance of the product quality.

Traditional approaches to drying technologies have faced several insurmountable contradictions. On the one hand, to intensify the processes of heat-and-mass transfer, it is necessary to increase the speed (*i.e.* consumption) of the drying agent. On the other hand, the higher the coolant consumption is, the more heat energy is lost with the emissions of the installation. The way out for resolving this contradiction is surely based on changes in the principles of energy supply to grain. The proposed idea, which is defended in this paper, is based on two provisions. Firstly, it is necessary to remove from the air the task of the coolant and leave only the task of the diffusion medium, which provides an effective "reception" of moisture from the product. Secondly, it is necessary to organize the process of grain rotation to dry it evenly. This process can provide a combination of infrared energy supply and the use of vibration. However, if the drying processes in the infrared field have been sufficiently researched, the vibration processes, namely the dynamic process of grain movement, have been studied much less.

The purpose of the work is to study the movement of sunflower seeds on the vibrating tray dryer and rational parameters of the technological process of drying.

Material and Methods

In the vibrating dryer, the technological processing of grain is carried out in the course of its movement on the working body of the machine. In this regard, the decisive influence on the efficiency of the process of technological processing of the product is made by the observance of necessary modes (speed) of vibratory movement and heat transfer to the processed product. When determining effective modes of transport and technological machines, it is of great interest to establish the dependence of the transportation speed, energy consumption of the process, the degree of speed transfer to the processed product, its mixing intensity, the combination of vibration boiling conditions, *etc.* on the parameters of oscillation modes(shape of the trajectory, frequencies, amplitudes, phase shift angle between harmonic components of double-component oscillations, the vibration angle and the angle of the working body). The study of the influence of characteristics of the environment, degree of filling of the working body and operating conditions on the listed parameters of the process of vibration transport and technological processing is equally important.

The developed vibrating dryer and the schematic diagram of the machine are shown in Figures 1 and 5, respectively.

The machine consists of a closed housing *1*, on the platforms *2* of which using elastic elements *3* thermal *4* and grate *5* trays are installed. The working path of thermal tray *4* is made of heat-resistant sheet steel. The working path of the grate tray is formed by longitudinal vertical strips *7* welded to the brackets *8*, so that there is a longitudinal gap δ = 1.5–2.0 mm between them. In the middle of each tray, vibratory drives containing two centrifugal vibrators installed on the sides of the tray are mounted.

Figure 1. Photo of the experimental vibrating tray infrared dryer

Each centrifugal vibro-exciter comprises a shaft with unbalanced loads *9*, which is connected through elastic coupling *10* with the asynchronous drive electric motor *11*. Moreover, in each vibratory drive, electric motors *11* are connected in such a way that when connected to the network, their rotors rotate towards each other. Shafts with unbalanced loads *9* are mounted on bearings parallel to each other at an angle β to the planes of the working paths of the trays. Above the surfaces of thermal trays *4,* there are fixed heat generators *12* (IR emitters). At the top and sides, thermal tray *4* is closed by thermal insulation *13*. Above the beginning of the thermal tray 4, the feeding throat 14 is fixed, and at the end of the impeller *15*, at the beginning of the grate tray *5* there is fan discharge pipe *16,* and above the receiving hopper *6*, there are outlet pipes *17* with adjusting gates *18*. At the end of the grate tray *5,* there is a receiving hopper *6*.

The machine works this way, when the drive electric motors *11* are switched on, their rotors start to rotate towards each other in each vibratory drive, which leads to dynamic synchronization of their rotation, as a result of which translational oscillations of trays *4* and *5* at an angle β to the planes of their working paths are generated. Bulk products are fed through the feeding throat *14* on the tray surface, where under the action of oscillations they are distributed in a monolayer. Under the action of oscillations of the trays between their surface and the particles of bulk products, there arises an asymmetry of friction forces, which leads to the directional movement of particles of bulk products (vibro-transportation) along the surface of the trays. The points on the surface of the trays oscillate relative to some centre without directional movement as a whole for a period of one oscillation. By changing static moments of the unbalanced loads *9* relative to the axis of rotation, the mode of vibro-transportation is established with the continuous tossing of particles of bulk products during their movement along with the trays. The continuous tossing of product particles leads to their chaotic rotation when moving along the thermal trays *4*, above which are heat generators *12* can be found and this contributes to their uniform irradiation on all sides with infrared rays, which leads to intensive, rapid and uniform heating of bulk granules.

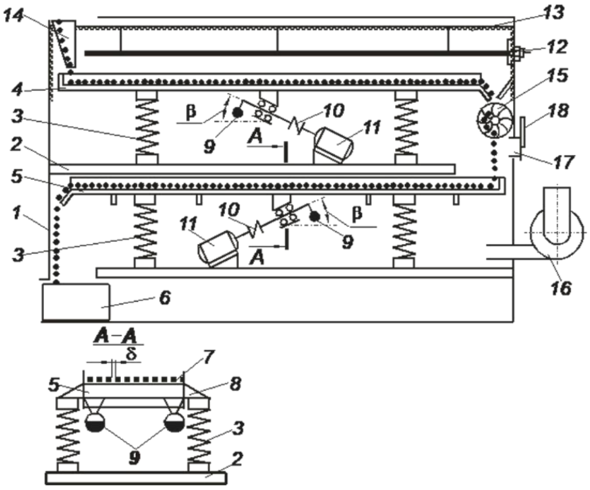


Figure 2. Scheme of laboratory vibrating dryer:
1 – housing; 2 – platform; 3 – elastic elements; 4 – thermal tray; 5 – grate tray; 6 – receiving hopper; 7 – longitudinal vertical strips; 8 – bracket; 9 – unbalanced load; 10 – elastic coupling; 11– electric motor; 12 – heat generators; 13 – thermal insulation; 14 – feeding throat; 15 – impeller; 16 – fan; 17 – outlet pipes; 18 – adjusting gate

Having passed the thermal tray, the heated bulk products are fed through the drum impeller *15* to the grate tray *5*, where it is blown by atmospheric air from the fan *16*. At the same time, continuous chaotic tossing and turning of product particles also improve the uniformity of their blowing with the air, which leads to an imbalance in the moisture content in product particles, when the water vapour pressure in them becomes greater than the partial vapour pressure of water in the air, as a result of which moisture begins to evaporate intensively (Bandura *et al.,* 2019). Having passed the grate tray *5*, the processed products are fed into the receiving hopper *19*. The drum impeller *15* prevents access of cold air flow from fan *16* into the high-temperature chamber above the thermal tray *4* and at the same time allows the product to flow from the thermal tray *4* to the grate tray*5*. The intensity of airflows is regulated by gate *18*. The speed of vibro-transportation of bulk products, and therefore its time on the surface of the trays is regulated by changing the static moments of unbalanced loads *9* relative to their axis of rotation, or angle β. Since the infrared radiation of the heat generator *12* allows to create a very intense heat flow, which promotes rapid heating of product particles, and the process of moisture evaporation from them requires a longer time, the speed of vibro-transportation on the grate *5* is set higher and it is made with wider working paths.

Results and Discussion

An experimental-industrial sample of a vibration machine (Bandura *et al.*, 2019) for drying sunflower seeds allows a wide range of drying temperature control (from 20 to 180 °C), air velocity varies within 0.5–2.5 mm s^{-1}, oscillation amplitude of the working body of the vibration dryer, *i.e.* vibrating tray (0.5–6.0 mm).

The dynamic scheme of the vibration tray is shown in Figure 3. The working body (tray) is considered to be a rigid solid body, which is mounted on a fixed base through sufficiently soft elastic elements with rigidity k and resistance coefficient b. Two unbalanced vibrators are mounted on the tray, symmetrically to the vertical axis, at the distance l from each other. The axes of rotation of vibrators are in the plane that passes through the centre of the mass of the vibrating tray. Vibrators are equipped with drive electric motors that rotate towards each other. The generalized coordinates of the system are as follows: x, y and φ, which correspond to the horizontal, vertical and angular movement of the tray. Chubyk, Yaroshenko (2011) in their work showed the differential equation of motion of the vibrating tray under uniform rotation of vibrators will be as follows:

$$M\frac{d^2s}{dt} + b\frac{ds}{dt} + k \cdot s = F_0 \cdot \sin(\omega \cdot t), \qquad (1)$$

where M – the reduced mass of the vibrating tray;
s – movement of the vibrating tray;

$b =-\frac{f}{s}$; (f – friction forces, air resistance);

k – rigidity of the elastic system of the vibrating tray;
F_0– cyclic coercive force.

The cyclic centrifugal coercive force that occurs during the rotation of imbalances, the location of which on the drive shaft is shown in Figure 4, will be equal to:

$$F = m_{unb} \cdot e \cdot \omega^2, \qquad (2)$$

where m – the mass of the unbalanced load of vibrators;
e – eccentricity of an unbalanced load of vibrators;
ω – angular velocity of the drive shaft rotation.

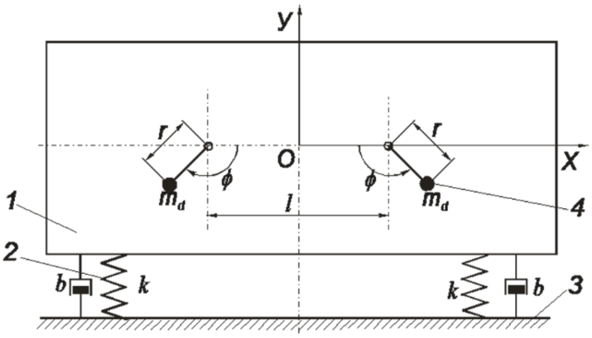


Figure 3. Calculation scheme of the unbalanced vibro-exciter of oscillationsof the vibration tray:1 – working body; 2 – spring; 3 – support frame; 4 – unbalanced load

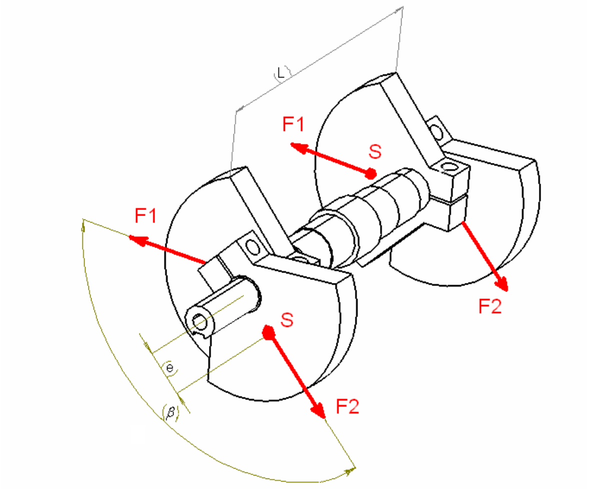


Figure 4. The layout of imbalances on the drive shaft

Analyzing the initial Equation (1), it can be concluded that if the circular frequency ω of the external coercive forceF_0 is small compared to the natural frequency $\omega_0$of the vibrating tray, then in the left part of the Equation (1), according to Timoshenko *et al.* (1985), a substantial role is played only by the member $k \cdot s \approx F_0 \cdot \sin(\omega \cdot t)$. Therefore, under $\omega<\omega_0$the external force is mainly spent on overcoming the elastic forces in the mechanical system, and the amplitude of the displacement ($s_0 = \frac{F_0}{k}$) coincides with the phase with the external force.

If the frequency ω of the external coercive forceF_0 is large compared to the natural oscillation frequencyω_0 of the vibrating tray, then in the left part of Equation (1), according to Timoshenko *et al.* (1985), an important role is played only by the term ($M\frac{d^2s}{dt^2}$), therefore, $M\frac{d^2s}{dt^2} \approx F_0 \cdot \sin(\omega \cdot t)$,*i.e.* under $\omega>\omega_0$ the external force is mainly spent to give acceleration to the vibrating tray. The amplitude of the acceleration $A_\infty = \frac{F_0}{m}$ coincides by the phase with the external force, and the displacement has the opposite phase. In the field of resonance, when $\omega\approx\omega_0$ members ($M\frac{d^2s}{dt^2}$), and $(k \cdot s)$ are approximately the same by their meaning but opposite to the sign. Since the oscillations of the vibrating tray occur according to the law $s = S \cdot \sin(\omega \cdot t)$, then:

$$M\frac{d^2s}{dt^2} = -M \cdot \omega^2 \cdot S \cdot \sin(\omega \cdot t), \qquad (3)$$
$$k \cdot s = k \cdot S \cdot \sin(\omega \cdot t)$$

Hence, $\frac{k}{M} = \omega_0^2$; ω≈ω₀, therefore: $-(M\frac{d^2s}{dt^2}) \approx ks$.

Both of these terms compensate each other in Equation (1) and as a consequence:

$$b\frac{ds}{dt} \approx F_0 \cdot \sin(\omega \cdot t). \qquad (4)$$

Based on Equation (4) and considering the research conducted by Timoshenko *et al.* (1985), it can be concluded that in the field of resonance ($\omega \approx \omega_0$) the elastic system itself, overcoming external forces, gives necessary acceleration to the mass *m*; the role of the external force is reduced to overcoming the forces of friction, and the amplitude of the velocity ($V_{max} = \frac{F_0}{b}$) coincides by its phase with the external force. Moreover, the external force F_0 performs the most useful work because the direction of the vibrating tray constantly coincides with the direction of external coercive force. And vice versa, when ω is substantially different from ω_0, the direction of movement of the vibrating tray coincides with coercive force during some part of the period, and during the second part of the period, it is opposite to it. Therefore, from the energy point of view, the phenomenon of resonance is caused by the fact that when the frequencies $\omega \approx \omega_0$ coincide, the most favourable conditions are provided for the entry of energy into the system from an external source.

According to Timoshenko *et al.* (1985) and Povidailo (2004), the solution of a differential Equation (1) can be expressed as the following:

$$S(t) = S \cdot \sin(\omega \cdot t - \varepsilon), \qquad (5)$$

where $S = \frac{F}{\sqrt{(-M \cdot \omega^2 + k^2) + (b \cdot \omega)^2}} = \frac{F}{M \cdot \sqrt{(\omega_0^2 - \omega^2)^2 + 4 \cdot \alpha^2 \cdot \omega^2}} = \frac{q}{\omega_0^2} \cdot \frac{1}{\sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + \gamma^2 \cdot \frac{\omega^2}{\omega_0^2}}}$,

where $q = \frac{F}{M}, \omega_0^2 = \frac{k}{M}$,

$$\varepsilon = \arctan\left(\frac{b \cdot \omega}{-M \cdot \omega^2 + k}\right) = \arctan\left(\frac{2 \cdot \omega \cdot \alpha}{\omega_0^2 - \omega^2}\right) = \arctan\left(\frac{\gamma \cdot \frac{\omega}{\omega_0}}{1 - \frac{\omega}{\omega_0}}\right)$$

The concept of dynamic coefficient of the gain coefficient is introduced for resonant machines designed by Timoshenko *et al.* (1985); Povidailo (2004). This coefficient characterizes the dynamic properties of resonant machines throughout the amplitude-frequency response and can be expressed as follows:

$$\mu = \frac{1}{\sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + \gamma^2 \cdot \frac{\omega^2}{\omega_0^2}}} = \frac{1}{\sqrt{(1 - z^2)^2 + \gamma^2 \cdot z^2}}, \qquad (6)$$

where $z = \frac{\omega}{\omega_0}$ – the adjustment coefficient (Povidailo, 2004).

Vibrating trays are devices for the continuous supply of bulk (grain) material. The vibrating tray is usually inclined at an angle α to the horizon (Fig. 5) and receives a reciprocating movement with small amplitude and significant frequency in the direction at an angle β to the working surface of the tray.

If the translational movement of the tray is slow and the reverse one is fast, then the particle of bulk material lying on the tray will move only translationally. Since the movement of the particle occurs under the action of friction, which cannot be greater than Gf, then the maximum acceleration of the particle W_{cr} (so-called critical) will determine the nature of the particle movement. If the acceleration of the tray is greater than the critical one, then the particle will slip on the tray in the direction that is opposite to the movement of the tray.

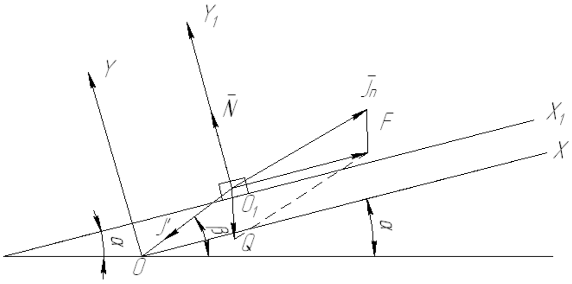


Figure 5. Scheme of action of forces on a particle of bulk material, which is placed on a vibrating tray

If the forward movement of the particle requires an oscillating motion (Povidailo, 2004), with different accelerations in the forward and reverse directions, then in the case of the forward movement of the tray, the acceleration will be less W_{cr}, *i.e.* $W_{tr}^f < W_{cr}$ and the particle will move together with the tray without slipping, in the case of the tray movement back under $W_{tr}^b > W_{cr}$, the particle will slide forward on the tray. Critical acceleration, the excess of which will create a sliding particle relative to the tray "back – down", is equal to:

$$W_{cr}^{H} = g(f \cos \alpha - \sin \alpha), \tag{7}$$

According to Povidailo (2004), the critical acceleration, the excess of which will create sliding of the particle relative to the tray "forward – up", is equal to:

$$W_{cr}^{b} = g(f \, cos \, \alpha - \sin \alpha), \tag{8}$$

where g – acceleration of gravity;
f – coefficient of friction of the particle on the tray.

When the tray moves up, the force of inertia of the particle will act opposite to the direction of movement and press the particle to the tray, increasing the friction force under the action of which the particle moves. When the tray moves down, the force of inertia will reduce the pressure of the particle on the tray and thereby reduce the friction force, creating conditions for forwarding sliding of the particle on the tray. Depending on the tray acceleration and angles βandα, there may be different modes of particle movement, both detachable, when the material particle – part of each cycle – flies without touching the tray surface, and continuous, when the particle is constantly in contact with the tray surface.

In our opinion, detachable modes are the most effective modes of operation of the vibrating tray, which enable to obtain high speeds of movement under high efficiency and maintenance of high stability of the particle movement. The main conditions that determine the particle movement are the angles of the tray and direction of vibration, speed and acceleration of the tray, as well as the coefficient of sliding friction $f$between the particle and the tray.

To describe the oscillatory movement of the vibrating tray, it is possible to accept two coordinate systems, *i.e.* axes of coordinates: the first one is XOY – motionless (on a bed of the bunker), connected with a motionless bed, the second one is $X_1O_1Y_1$ – relative, and connected with a mobile tray (Fig. 5). When considering the movement of the particle of bulk material on a tray inclined at an angle $\alpha$to the horizon, which performs harmonic oscillations at an angle β (under $\beta > \alpha$), the equation of the tray movement in the coordinate system XOY is as follows:

$$\ddot{x}_{tr} = \frac{A_{tr}}{2} \omega^2 \cos \varphi, \tag{9}$$

$$\dot{x}_{tr} = \frac{A_{tr}}{2} \omega \sin \varphi, \tag{10}$$

$$\ddot{y}_{tr} = \frac{A_{tr}}{2} \omega^2 \cos \varphi, \tag{11}$$

$$\dot{y}_{tr} = \frac{A_{n}}{2} \omega \sin \varphi, \tag{12}$$

where A_{tr} – amplitude of tray oscillations in the direction in parallel to its working surface;
A_n – amplitude of oscillations in the direction perpendicular to the working surface of the tray;
ω– angular frequency of the tray oscillations;
$\varphi = \omega t$ –phase angle of oscillations;
t – time.

Differential equation of motion of the particle of bulk material and the initial period relative to the tray in the coordinate system $X_1O_1Y_1$connected with the tray is as follows:

$$m\ddot{x}' = -mg \sin \alpha - m \frac{A_{tr}}{2} \omega^2 \cos \varphi + F, \tag{13}$$

$$m\ddot{y}' = -mg \cos \alpha - m \frac{A_{tr}}{2} \omega^2 \cos \varphi + N \quad , \tag{14}$$

Where m – the mass of bulk material;
g – acceleration of gravity;
N – normal reaction;
F– force of friction.

The process of movement of the particle of bulk material in the modes with its separation from the tray in the general case can be considered in five stages. At the first stage (acceleration stage), the particle of bulk material is in the plane of the tray ($\ddot{y}' = 0$). The equation of the particle movement at the first stage is as follows:

$$\ddot{x}'_a = g(f \cos \alpha - \sin \alpha) + \left(\frac{A_n}{2} f - \frac{A_{tr}}{2} \right) \omega^2 \cos \varphi. \tag{15}$$

While the equation of absolute motion (*i.e.* relative to a fixed coordinate system) will be as follows:

$$\ddot{x}_a = g(f \cos \alpha - \sin \alpha) + \frac{A_n}{2} f U^{-2} \cos \varphi, \tag{16}$$

$$\dot{x}_a = \frac{g}{W} (f \cos \alpha - \sin \alpha) + \frac{A_n}{2} f W \sin \varphi + C\text{'} \tag{17}$$

where ($\varphi = 0$, $C = 0$)

According to Bandura *et al.* (2019), since the tray performs harmonic oscillations, the particle slides relative to the tray and moves with the acceleration determined by the formula (16). The speed of the particle increases along the curve expressed by Equation (17) until the speeds of the particle and the tray are equalized. At this point there comes the second stage, which is called the stage of the first braking. The particle begins to move with deceleration on the tray, which slows down, but faster than it.

The equation of the particle movement at the stage of braking is as follows:

$$\ddot{x}_{b_1} =- g(f \cos \alpha + \sin \alpha) - \frac{A_n}{2} f^2 \, cos \, \varphi, \tag{18}$$

$$\dot{x}_{b_1} =- \frac{g}{\omega} (f \cos \alpha - \sin \alpha) \varphi - \frac{A_n}{2} f \omega \, sin \, \varphi, \tag{19}$$

In the second quarter of the period of movement, acceleration of the tray will be negative and the force of inertia of the particle (Fig. 5) will be directed upwards, and at the moment when the normal reaction *N* becomes zero, the particle will separate from the tray.

The phase angle at which the separation of the particle from the tray begins is equal to:

$$\varphi_0 = \arccos\left(-\frac{2\,g\cos\alpha}{A_n\omega^2}\right). \qquad (20)$$

The mode of the particle movement, during its separation and its falling on the tray, depends on the magnitude of the amplitude of the normal acceleration of the tray $\frac{A_n\omega^2}{2}$, which is convenient to be set by a generalized dimensionless parameter:

$$\xi = \frac{A_n\omega^2}{2\,g\cos\alpha}, \qquad (21)$$

$$\varphi = \arccos\left(-\frac{1}{\xi}\right). \qquad (22)$$

From the moment the particle is separated from the tray, the third stage of the movement, *i.e.* a microflow of the particle in the air with the speed of separation, begins. Absolute acceleration of the particle along *X* axis, if the air resistance is neglected, will be as follows:

$$\ddot{x}_f = g\sin\alpha, \qquad (23)$$

$$\dot{x}_f = -g\frac{\varphi}{\omega}\sin\alpha. \qquad (24)$$

After the microflow, the duration of which depends on the mode of the tray operation, which is determined by the value of parameter ξ, the particle falls on the tray and the fourth stage of its movement, *i.e.* the stage of the second braking, begins. The phase angle of contact of the particle with the tray can be determined by the following formula:

$$\varphi_b = \varphi_0 + \sqrt{\xi^2 - 1} + \sqrt{\xi^2 + 2\xi\cos\varphi\varepsilon + 1}. \qquad (25)$$

Under efficient modes of the vibrating tray operation, the speed of the particle at the time of meeting with the tray (provided that the impact of the particle on the tray is not elastic) will be greater than the speed of the latter, so during the fourth stage, the particle will move with negative acceleration, as determined by the equations 23 and 24, until the velocities of the particle and tray equalize.

Then there begins a cycle, in which the particle will slip on the tray and its speed will increase, when the speeds of the particle and the tray get equalized, there will begin three other stages, movement of the next period. As a result of the first oscillation, the particle acquires a certain speed, the second oscillation leads to the particle acceleration to a slightly higher speed. During the next few oscillations, the increase in the speed of the particle will continue until the mode of steady motion begins.

The latter will begin when the increase in the speed of the particle during acceleration will be equal to the sum of the speed drops during decelerations. The speed of the particle in the steady mode of operation will vary and range from υ_{max} to υ_{min}. Under certain conditions, in addition to four stages of movement considered, there begins the fifth joint movement of the particle and the tray without slipping. This stage can occur either at the end of acceleration or at its beginning if at these moments tray acceleration will be less than critical. The occurrence of this condition can be recorded in general terms, considering the sum of projections of all forces on X_1 axis (Fig. 5).

$$m\frac{A_{tr}}{2}\omega^2\cos\varphi \leq \pm F - mg\sin\alpha \qquad (26)$$

In Equation 26 the sign "plus" is put for the segment of the particle acceleration, and the sign "minus" is put at the stopping segment.

If the tray is given oscillating motion with accelerations equal in absolute value in both directions, the action of the particle lying on it on the tray will not be the same when the tray moves in one direction or another, namely, when lifting the tray, the particle pressure on the tray will be higher when lowering it – smaller. So, the pressure of the particle on the tray when moving it up will be equal to:

$$Q_1 = m(q_n + J_n), \qquad (27)$$

where *m*– the mass of the particle;

q_n – component of acceleration of free fall that is normal to the tray surface;

J_n – component of acceleration of the force of inertia that is normal to the tray surface.

Thus, when moving down, the pressure of the particle on the tray will be as follows:

$$Q_2 = m(q_n - J_n). \qquad (28)$$

When the tray is moving up, the force of inertia is as follows:

$$P_1 = m(J_t - q_t), \qquad (29)$$

where q_t– component of acceleration of the free fall that is horizontal to the tray surface;

J_n –component of acceleration of the force of inertia that is horizontal to the tray surface.

The force of inertia when the tray is moving down:

$$P_1 = m(J_t - q_t). \qquad (30)$$

Since the interaction between the tray and the particle lying on it is determined by the force of friction that is equal to:

$$F = fQ, \tag{31}$$

where f – coefficient of friction

Then acceleration of the tray is transmitted to the particle until the force of inertia of the particle does not exceed the force of friction, and if $f_m(q_n + J_n) \geq m(J_t - q_t)$, the particle moves up together with the tray. Under the reverse movement of the tray, when $f_m(q_n – J_n) \leq m(J_t - q_t)$, the particle detaches from it and moves in the direction of the direct course of the tray on the parabola until a new collision with it.

Vibratory movement of grains during the working process of their drying is performed as a result of the total effect of a large number of oscillations that follow one another. A very slight movement of grain occurs during one oscillation, however, since there are 1000–3000 oscillations per minute, this process is very effective.

For the mode of operation of a monolayer dryer, when vibro-transportation of grain is carried out on a vibrating tray with continuous tossing (Bandura*et al.*, 2019), the average speed of vibro-transportation (Ganiev, Ukrainskij, 1975), can be determined by the following dependence:

$$v = A\omega\left(\cos\beta – \frac{1+R}{1–R}\cdot\frac{2–\lambda}{\lambda}\cdot sin\,\beta\cdot tg\alpha\right), \tag{32}$$

where A – amplitude of oscillations of the tray surface, m;

ω – tray oscillation frequency, s;

β – angle between the direction of oscillation and the tray surface plane, $\beta = 0…30°$;

α – angle of inclination of the tray surface to the horizon, $\alpha = 0–20°$;

λ – coefficient of instantaneous friction of grain on the tray surface when hitting, $\lambda = 0.5–0.7$;

R– recovery coefficient when the grain hits the tray surface, $R = 0.2–0.4$.

Since the dryer trays are placed horizontally, $\alpha = 0°$.

Then the required amplitude of oscillations of the tray will be equal to:

$$A = \frac{v}{\omega\left(\cos\beta – \frac{1+R}{1–R}\cdot\frac{2–\lambda}{\lambda}\cdot\sin\beta\cdot tg\alpha\right)}. \tag{33}$$

In the developed experimental-industrial sample of the vibrating machine for drying sunflower seeds, it is constructively accepted: $\beta = 30°$, $\alpha = 0–20°$, and $\omega = 99$, s, we receive:

$$A = \frac{0{,}0232}{99\left(\cos 30° – \frac{1+0{,}3}{1-0{,}3}\cdot\frac{2-0{,}6}{0{,}6}\cdot\sin 30°\cdot tg0°\right)} = 1{,}6\cdot 10^{-3},\ \mathrm{m} \tag{32}$$

Based on the generalization of these studies, it is possible to determine the main characteristics of the process of transport and technological processing of various food products depending on the mode of operation of the vibrating machine and the properties of the moving mass. The main dependences of the speed of vibro-transportation on the speed of the drive electric motors have been investigated (Table 1).

Table 1. Dependence of the speed of grain vibro-transportationon the speed of drive electric motors

n, min	900	910	930	940	950	960	970	980	990
v_1, m s^{-1}		0.0188	0.0191	0.0195	0.0202	0.0200	0.0193	0.0187	0.0183
v_2, ms^{-1}	0.0114	0.0115	0.0120	0.0127	0.0134	0.0140	0.0141	0.0132	0.0124

According to the graph of dependence of the speed of grain vibro-transportation on the speed of drive electric motors (Fig. 6), the speed of vibro-transportation increases under the growth of the engine speed. When reaching a certain value of speed, under a further increase in the engine speed of drive electric motors, the speed of grain vibro-transportation decreases. This nature of curves can be explained by the fact that at first there takes place continuous vibro-transportation of grain and therefore the speed increases under the increase in the engine speed. And at a certain value of the frequency of rotation, the particles of bulk products (grains) begin to break away from the tray and the speed of their movement along the tray begins to decrease. However, this improves the rotation of seeds during vibro-transportation, which contributes to their uniform heating at all sides.

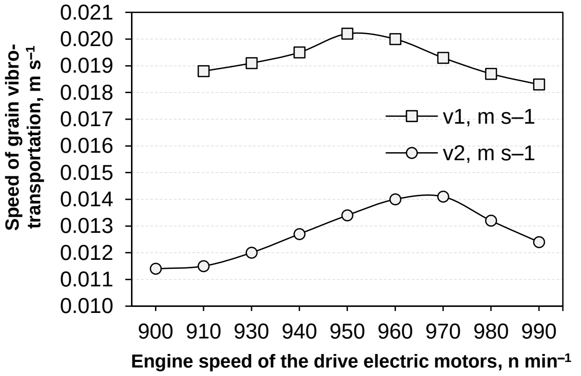


Figure 6. Dependence of the speed of grain vibro-transportation on the engine speed of the drive electric motors: 1 – speed of vibro-transportion under eccentricity of imbalances e = 0.025 m; 2 – speed of vibro-transportion under eccentricity of imbalances e = 0,015 m.

The frequency of oscillations also has a significant effect on the drying process in a vibrating tray dryer of continuous action. Several experimental studies have been conducted taking into account the following considerations:

- ensure the maximum intensity of the drying process;
- create a monolayer of the product that moves evenly and intensively, which will enable to avoid overheating of the product and achieve its uniform drying;
- application of vibration should make it possible to rotate the seeds during vibro-transportation for uniform irradiation at all sides.

Statistical analysis

The influence of oscillation frequency of the vibration tray of the dryer on the drying kinetics of sunflower seeds was studied by the influence of dispersion analysis. The Cochren's test was used to check the homogeneity of the dispersions at each level of tray oscillations. The hypothesis of homogeneity of variances was accepted in the case when the tabular value of Cochren's criterion was greater than the calculated one. The variance differences were assessed by Fisher's test at a 5% significance level. If the tabular value of Fisher's criterion exceeded the calculated one, it meant that the influence of the level of the tray oscillation frequency on the drying kinetics of sunflower seeds exceeded the level of error of the experimental data.

The results of studies on the influence of oscillation frequency of the vibrating tray on the kinetics of the process of drying sunflower seeds, which has an initial moisture content of W = 20.7, 23 and 25%, are presented in Figures 7, 8, 9.

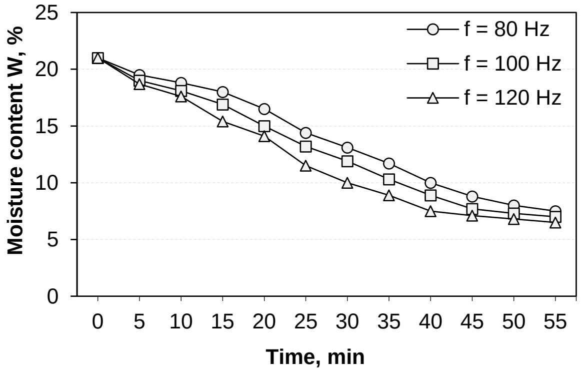


Figure 7. Influence of oscillation frequency of the vibrating tray on the kinetics of the sunflower seed drying process under initial moisture content of W = 20.7%.

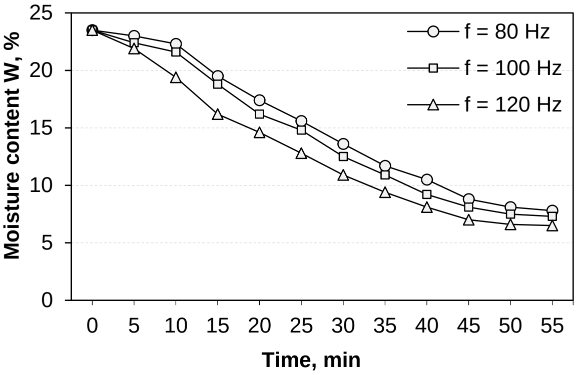


Figure 8. Influence of oscillation frequency of the vibrating tray on the kinetics of the sunflower seed drying process under initial moisture content of W =23%.

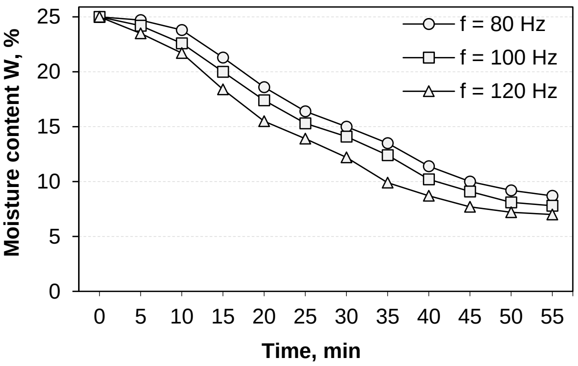


Figure 9. Influence of oscillation frequency of the vibrating tray on the kinetics of the sunflower seed drying process under initial moisture content of W = 25%.

Analysis of the presented curves has shown an almost uniform increase in the drying intensity under all considered oscillation frequencies of 80; 100; 120 oscillations per second. The increase in the frequency above f = 100 oscillation per second results in the decrease of the speed of vibro-transportation. Such speed is sufficient for the seed separation from the tray surface, which facilitates its rotation and uniform irradiation at all sides. Therefore, the rational value of vibration can be taken as f = 100 oscillations per second.

Conclusions

According to the results of experimental studies, it can be concluded that the highest speed of vibro-transportation of oilseeds is achieved under the speed of rotation of the drive electric motors within 950–970 rotations per minute. In addition, under the specified speed of rotation, there begins vibro-transportation of seeds with the separation from the tray surface, which facilitates rotation of seeds and their uniform irradiation at all sides. The conducted experimental research has allowed us to specify the design parameters of the vibrating tray of the dryer and choose rational parameters of the technological process of drying, namely the oscillation frequency of the vibrating tray, which is f = 100 oscillations per second.

Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Author contributions

VP, LF –critical analysis of the literature;
VB, LY – writing of the manuscript;
DK, YP – editing and approving of the final manuscript.

References

Bandura, V., Mazur, V., Yaroshenko, L., Rubanenko, O. 2019. Research on Sunflower Seeds Drying Process in a Monolayer Tray Vibration Dryer Based on Infrared Radiation. –INMATEH – Agricultural Engineering, 57(1):233–242.

Bulgakov, V., Bandura, V., Arak, M., Olt, J. 2018. Intensification of rapeseed drying process through the use of infrared emitters. – Agronomy Research, 16(2):349–356. DOI: 10.15159/AR.18.054.

Coradi, P.C., Fernandes, C.H.P., Helmich, J.C. 2016. Adjustment of mathematical models and quality of soybean grains in the drying with high temperatures. – Revista Brasileira de Engenharia Agricola e Ambiental, 20(4):385–392. DOI: 10.1590/1807-1929/agriambi.v20n4p385-392

Chubyk, R.V., Yaroshenko, L.V. 2011. Kerovani vibratsiini tekhnolohichni mashyny: monohrafiia [Controlled vibrating technological machines: monograph]. – Vinnytsia: VNAU, p. 355. ISBN978-966-2462-35-7.

Das, I., Das, S.K., Bal, S. 2009. Drying kinetics of high moisture paddy undergoing vibration-assisted infrared (IR) drying. – Journal of Food Engineering, 95(1): 166–171. DOI: 10.1016/j.jfoodeng.2009.04.028

Finzer, J.R.D., Limaverde, J.R., Freitas, A.O., Limaverde Junior, J.R., Sfredo, M.A. 2003. Drying of coffee berries in a vibrated tray dryer operated with solids recycle and single-stage. – Journal of Food Process Engineering, 26(2):207–222. DOI: 10.1111/j.1745-4530.2003.tb00597.x

Ganiev, R.F., Ukrainskij, L.E. 1975. Dinamika chastic privozdejstvii vibracij [Particle dynamics under the influence of vibrations]. – Kyiv: Naukova dumka, 168 p.

Nindo, C.I., Kudo, Y., Bekki, E. 1995. Test model for studying sun drying of rough rice using far-infrared radiation. – Drying Technology, 13(1–2):225–238.

Nourmohamadi-Moghadami, A., Rahmanian-Koushkaki, H., Zare, D., Karimi, G. 2017. Experimental and theoretical investigation of hot air-infrared thin layer drying of corn in a fixed and vibratory bed dryer. – Engineering in Agriculture, Environment and Food, 10(3):191–197. DOI: 10.1016/j.eaef.2017.01.004

Povidailo, V.O. 2004. Vibratsiini protsesy ta obladnannia: monohrafiia [Vibration processes and equipment: monograph]. – Lviv: Publishing House «Lviv Polytechnic National University», 248 p.

Timoshenko, S.P., Young, D.Zh., Weaver, U. 1985. Kolebaniya v inzhenernom dele [Fluctuations in engineering]. – Moscow: Mashinostroenie, p. 472.

Tripathy, P.P., Kumar, S. 2008. Neural network approach for food temperature prediction during solar drying. – International Journal of Thermal Sciences, 48(7):1452–1459. DOI: 10.1016/j.ijthermalsci.2008.11.014

Zare, D., Naderi, H., Ranjbaran, M. 2014. Energy and quality attributes of combined hot air infrared drying of paddy. – Drying Technology, 33(5):570–582. DOI: 10.1080/07373937.2014.962143