ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 13(1), 39-46
Received: 20.12.2021 Revised: 15.01.2022 Accepted: 10.02.2022

UDC 664.643.1
DOI: 10.31548/animal.13(1).2022.39-46

Justification of Power Parameters of the Process of Semi-Fluidisation Freezing of Fruit and Berry Products

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Abstract. The existing semi-fluidisation devices are described by high-energy consumption during operation, heavy metal structure, and complexity of the drive mechanism. Therefore, the search for effective heat exchange schemes in low-temperature processing of fruit and vegetable products, provided that its damage and energy consumption for the process are minimised, constitutes the relevance of this study. The purpose of this study was to determine and substantiate the amplitude-frequency and power mode parameters of the vibration wave driving organ of the semi-fluidisation machine for freezing fruit and berry products, the regularities of changes in the main characteristics of low-frequency vibrations in the process under study. To perform these tasks, an experimental model of a semi-fluidisation machine with a vibration wave driving organ was developed and a set of special devices was manufactured in the form of a microcontroller system that provides measurement and automatic adjustment of the main parameters of the process under study. Intensification of heat exchange in the process of fluidisation freezing in the conditions of a pseudo-suspended state of products is described by a high heat transfer coefficient, which can exceed typical convective processes by several orders of magnitude; an increase in the active heat exchange surface up to 100% is observed; the contact surface with the energy carrier increases proportionally, which leads to a decrease in the active temperature difference; there is a 2-3 times decrease in internal friction in the mass of products and, accordingly, the technological resistance in the mass of loading is reduced, which is a potential for increasing the technical and economic characteristics of the low-temperature processing under study. The practical value of this study can be attributed to the application of vibro-slush freezing of the proposed structure with a vibration-wave product driver and a spatial elastic system for levelling out parasitic vibrations, which allows simplifying the structure, reducing power loads and, accordingly, energy costs

Keywords: wave conveyor, vibration-wave driving body, travelling wave, driving force, low-frequency oscillations, unbalanced vibration exciter

Suggested Citation:
Palamarchuk, I., Kiurchev, S., Verkholantseva, V., Borodych, B. & Lebska, T. (2022). Justification of power parameters of the process of semi-fluidisation freezing of fruit and berry products. *Animal Science and Food Technology*, 13(1), 39-46.

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Introduction

The semi-fluidisation devices presented today have as a load-carrying body a belt conveyor with a perforated surface and standard drive equipment, the operation of which is described by high-energy consumption, metal consumption of the structure, and the complexity of the drive mechanism [1]. Therefore, the development of effective schemes for creating a travelling wave on the surface of the tape upon using local mechanical vibration exciters allow implementing heat exchange in subcooling or freezing of products under the condition of minimising the force contact interaction and, accordingly, energy consumption for the process, which constitutes the relevance of this study.

As a physical phenomenon, fluidisation is interpreted as the transformation of a solid body into a powder-like state to improve its transportation or subsequent technological processing, namely low-temperature heat exchange. Semi-fluidisation can be called the process of supercooling or freezing, wherein the product layer moves on a moving belt and is simultaneously ventilated by a jet of cold air at a speed not exceeding a critical value, which is limited by the technological and design requirements of the process under study [2].

These processes combine the effect on the working organs of the machine, the mass of products or the technological environment of centrifugal forces, the period, and direction of which change with a frequency of the order of 100...200 rad/s with amplitudes of 2.0...5.0 mm [3]. The action of sign-changing centripetal and Coriolis accelerations of individual particles of the bulk product mass leads to the intensification of both the circulation and relative movement of product particles in the working chamber along the most diverse and arbitrarily complex trajectories, the creation of a pseudo-fluidised layer of products and coolant that provide optimal conditions for effective heat and mass exchange between these technological components of the process; a significant increase and intensive renewal of the interaction surfaces of technological environments, an increase in the speed of convective diffusion, a decrease in the effective density of the material, and a change in the rheological and structural-mechanical properties of raw materials during the implementation of the food production under study.

Based on the analysis of Ya. Postolsky and F. Deng [4], Reynolds in 1954 described the concept of fluidisation as a process of rapid movement of gas through a layer of melt to remove certain of its constituent elements and create an oriented arrangement of them, while the outstanding chemist O. Trishyn noted in 2013 that pseudo-fluidisation and fluidisation are synonymous [5].

In the studies of S.M. Ashtiani, A.N. Chernenkova et al., unique physical and mechanical characteristics are presented, namely due to an increase in the heat transfer coefficient α, an increase in the active heat exchange surface up to 100% is observed [5; 6]. In case of an increase in the heat transfer coefficient (in comparison with convective heat exchange, an increase of up to 20 times is possible), the contact surface with the energy carrier increases proportionally, which leads to a decrease in the active temperature difference and, accordingly, creates a potential for increasing the technical and economic characteristics of the low-temperature processing under study. Furthermore, according to the researches of O. Danyliuk, V.M. Atamaniuk et al. in the conditions of a pseudo-suspended layer, there is a 2-3 times decrease in internal friction in the product mass [7; 8], which proportionally reduces the technological resistance of such an environment and, accordingly, the energy costs for its processing, namely upon sparging through the bulk mass of the gaseous coolant flow.

The process of fluidisation freezing is often equated with drying in the conditions of a suspended state of products, which is described by a very intensive heat exchange, which in terms of heat transfer coefficient can exceed typical convective processes by several orders of magnitude. In comparison with the methods of tunnel freezing with forced circulation of the coolant according to the studies of G.A. Nakov and N.I. Ivanova, fluidisation under low-temperature treatment gives a 30-40-fold increase in the intensity of heat exchange [8]. According to the study of V.I. Osypenko, the average values of heat transfer coefficients under the conditions of the fluidisation layer exceeded by 4-5 times the indicators obtained during freezing of products in tunnel apparatuses with forced air circulation at the same airflow rates [9].

Problematic aspects in these studies were that the presented processes and equipment for low-temperature processing of fruit and berry and vegetable products in modern food technologies were realised at a sufficiently high metal consumption and energy consumption, in a fluidisation chute with a perforated bottom, under the action of a variable flow of coolant, in the process of transporting products with a mesh tape, in the working area of a vibrating container. The pseudo-weighted or fluidisation layer of products in such processes is realised by sparging the mass of products with a flow of coolant from bottom to top through holes in the bottom of the chute, the walls of the oscillating container, and the mesh surfaces of the conveyor belt.

When implementing the semi-fluidisation process according to Striling's scheme [2], products are transported by a belt mesh conveyor, under which the evaporator of the refrigerating unit is located. The air supplied through the evaporator moves through the layers of products located on the mesh surface of the tape, from bottom to top. This movement ensures the transition of products to a pseudo-weighted state at a small distance from the grid. This processing is especially suitable for processing soft and fragile products, such as strawberries, raspberries, cauliflower segments, asparagus, and Brussels sprouts. To reduce the possible damage to products with full fluidisation in the process, lower values of the Froude criterion are used, for example, in the work of Savenkova for strawberries, Fg = 50...60 [10; 11].

To exclude freezing of moistened particles to the belt in some designs of freezers, a powerful jet of air is used in the entrance zone of the tunnel at 4-6 m/s, increasing the value of the Froude criterion, in particular, for strawberries to the value of Fg=100...140. Under such conditions, there is a local "boiling" of the fluidisation layer, which is close in parameters to the process of complete fluidisation. If the duration of the process is within 10-20 s, the danger of the product freezing to the grid is eliminated, and at the same time, the probability of fruit damage is considerably reduced, which is shown in the article by A.V. Shyshkin [12; 13].

Therefore, the process of fluidisation refrigerating action showed high indicators of treatment efficiency against conventional freezing in tunnels with forced air circulation [13; 14] due to a considerable increase in the intensity of heat exchange, an increase in the heat transfer coefficient and the active surface of heat exchange, which reduce the active temperature difference and increase the economic indicators of the operation of low-temperature equipment. The scientific originality of this study lies in the transformation of mechanical forced vibrations into a travelling and standing wave of a flexible load-bearing body, which creates a technological movement of products.

High results were also obtained for the use of fluidisation in low-temperature processes occurring during refrigeration, long-term storage of fruit, berry and vegetable products, the development of which is the object of research in this scientific article.

The purpose of this study was to determine and substantiate the amplitude-frequency and power mode parameters of the vibration wave driving organ of the semi-fluidisation machine for freezing fruit and berry products, the regularities of changes in the main characteristics of low-frequency vibrations in the process under study.

To achieve the purpose, the main tasks of scientific study were set as follows: to analyse the current state, innovative developments of Ukrainian and foreign scientists, to identify promising areas or the use of fluidisation action, to substantiate the structural and technological scheme of the semi-fluidisation plant; to determine the patterns of changes in the main parameters of the oscillatory process and substantiate its amplitude-frequency and power parameters.

Materials and Methods

Among the main stages of the performed study, it is possible to note the development and production of a research installation for the implementation of the semi-fluidisation process, which was carried out during 2020-2021; compilation of the necessary measurement base for evaluating electromechanical and heat exchange process parameters, in particular, ROBOTRON equipment for evaluating amplitude-frequency and kinematic characteristics directly using oscillographs and indirectly based on graphically obtained trajectories of movement of system points, wattmeter, voltmeter, and ammeter, necessary power sensors, microcontroller system; analytical determination of the main geometric, kinematic, and force parameters using methods of higher mathematics, physics, theory of fluid media in the conditions of a pseudo-liquefied layer, geometric analysis of an oscillating system, using the characteristics of the experimental model; processing and graphical interpretation of the obtained results using the MathCad mathematical environment. This technique effectively combines experimental and theoretical studies, the results of which are processed by modern information technologies.

To perform these tasks, a pilot model of a semi-fluidisation machine was developed (Fig. 1) with a vibration wave driving organ [1], which described the developed scheme of using an unbalanced vibration exciter for the development of a working wave on the surface of the tape, manufactured a complex of the above-mentioned equipment and devices in the structure of a microcontroller system, providing measurement and automatic regulation of the main parameters of the process of low-temperature processing of fruit and vegetable products in a fluidised state [15]. The presented developments allow realising the effects of increasing the surface of heat and mass transfer, soft power action on products, and reducing dynamic loads on the support units of the drive mechanism.

Tensioning device 7 (Fig. 1), equipped with a spring 11 and an adjustment nut 12 of the tensioning device, stabilises the movement of the load-bearing belt 1. Freezing of the product 13 occurs due to the mass of snow coat or finely crushed ice 14 in a fluidised layer, formed due to the horizontal and vertical movement of the load-carrying belt 1, which gently throws it up, preventing injury or damage, as in known designs of semi-fluidisation devices [16]. The mass of the snow coat or finely crushed ice 14 is removed through the tray 15 as a result of its separation in the vibrating sifter 16 from the products 13 being processed. Product 13, which has been frozen and cleared of snow, goes to the next operation. The processing cycle is then repeated to achieve the required performance, depending on the technological requirements.

Studies of the effect of low-frequency oscillations to create wave motion of the product mass, the snow coat of the coolant on the surface of the tape were implemented during the application of the accelerometer in the mode of an autonomous probe placed in the process mass.

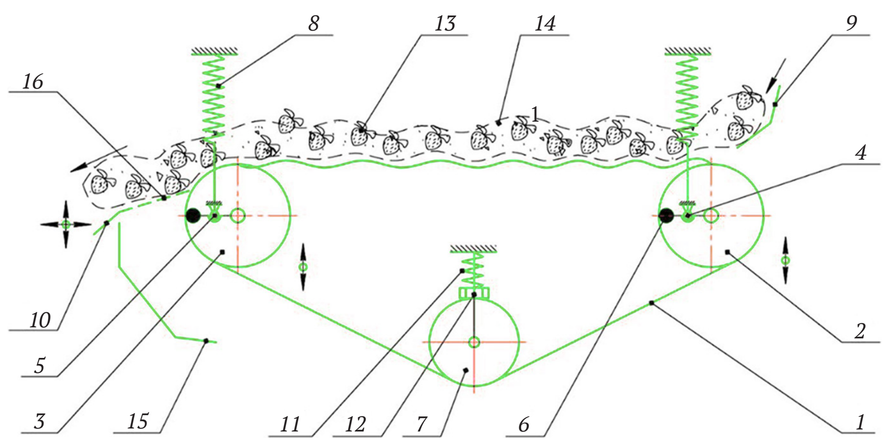


Figure 1. Diagram of the developed fluidisation device for vibro-slush freezing

The real-time microcontroller system allowed obtaining the information on the main parameters of the process on the display of a personal computer, which enabled the optimisation of the modes of heat exchange processing, observed in the dynamics of product cooling to the values specified by the technology. The set temperature of the refrigerant was maintained automatically if it could be quickly adjusted using the power regulator. The specified frequency and amplitude of vibrations were set independently by an electronic device and by changing the angle of the imbalance setting of the vibrator located inside the support rollers of the tape.

Results and Discussion

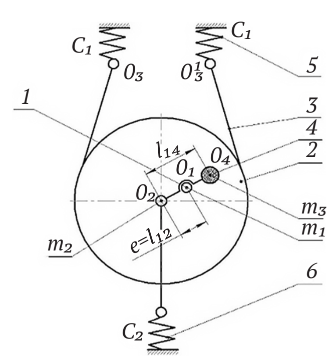
In the developed semi-fluidisation technological machine, the process of heat removal is realised in the case of contact of fruits and berries, which are prone to damage during transportation in the working area, and the mass of the snow coat in the conditions of their fluidised layer. As a result of this movement, gravitational and centrifugal forces, and the influence of aerodynamic drag of the elements of this technological environment are counteracted. Modern schemes of these devices make provision for the creation of a fluidised bed exclusively due to aeration through a perforated transport belt [17], which creates sufficiently large technological supports and, accordingly, high-energy consumption. The load-carrying body of the fluidisation-tunnel apparatus performs a longitu-dinal movement together with the products, which makes it difficult to supply the fluidised bed with a coolant flow [18]. The mechanisms for tensioning the tape and motoring the drive drum are complex enough for the considerable length of the working chamber [5]. Under such conditions, heat transfer is carried out only by convection, which helps press the products to the conveyor belt and leads to a decrease in the free contact surface in the process mass [19]. Furthermore, a common disadvantage of existing semi-fluidisation machines is their high metal and energy consumption [5].

The application of the device for vibro-slush freezing of the proposed design (Fig. 1), thanks to the installation of an unbalanced vibration exciter, moving shafts, a tensioning device, spring sup-ports, an elastic element of a tensioning device, an adjusting nut of a tensioning device, a mass of snow coat or finely crushed ice, a tray for removing snow fur particles or of finely crushed ice, a vi-brating sifter for separating particles of a snow coat or finely crushed ice from products, allows sim-plifying the design, reducing energy consumption by 2.5-3.0 times, improving the vertical movement of the product for the possibility of its longitudinal movement to ensure sufficient freezing in one pass, increasing the intensity of heat exchange in the fluidised bed with the possibility of bringing the area of contact interaction up to 100%, which determines the potential for increasing the produc-tivity of the freezing process in general. The developed scheme also makes provision for heat ex-change by conduction, which is known to substantially improve the contact interaction conditions of the coolant and products [2].

The power parameters of vibration determine the regularities of the mechanical impact on the machine elements and the object of processing, among which it is possible to note the magnitude of the driving force, which directly creates the working movement of the executive bodies of the ma-chine in the event of their removal from the equilibrium position; forces that arise in the event of de-formation of the elements of the elastic system, returning the executive bodies to the equilibrium po-sition; tension forces of elastic band branches; unbalanced forces that arise in the system in the event of parasitic and working forces and reduce the reliability of the support unit and the vibration exciter in general.

To generate vibrations during interoperational transportation of fruit and berry products, name-ly strawberries, cherries, and snow coat, the machine under study made provision for the use of two mechanical vibration exciters mounted in the support rollers of the belt mechanism. The speed of ro-tation was registered from the drive shaft with an accelerometer, and the power – with a wattmeter. The presented mechanism allows reducing the energy consumption by 2.5-3.0 times while maintain-ing an intensive vibration-impulse mode of movement of technological masses and ensuring suffi-ciently comfortable operating conditions of the bearing supports of the drive shaft from the stand-point of levelling dynamic loads under the spatial elastic system, since the proposed elastic system of the vibration exciter allowed levelling the transfer of parasitic vibrations to the supporting structure. The dynamic load on the latter is reduced by 4.5 times also due to the presence of a spring-loaded suspension of the guide belt of the developed semi-fluidisation machine, which was estimated by the corresponding decrease in the amplitude of oscillations of the drive shaft up to 5 times for the reso-nant mode [20].

To identify the desired amplitude-frequency and force parameters when using analytical geometry methods, a calculation scheme was developed that illustrates the initial (Fig. 2, a) and current (Fig. 2, b) position of the drive mechanism, its main geometric parameters.



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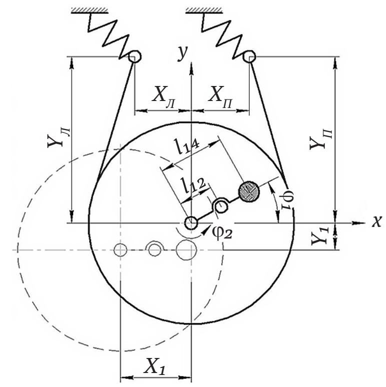


b

Figure 2. Design scheme of the vibrational system of vibration wave transport in case of deviation from the equilibrium position: 1 – roller; 2 – tape; 3 – drive shaft of the vibrator; 4 – counterweight; 5 – elastic suspension; 6 – vibration resistance; m_1 – the mass of the drive shaft with the support assembly; m_2 – mass of roll, tape, and products; m_3 – counterweight mass; C_1 – stiffness of the elastic suspension; C_2 – stiffness of vibration support; X_1 – linear horizontal deviation of the centre of mass of the cylinder; Y_1 – linear vertical deviation of the centre of mass of the roller; φ_1 – angular deviation of the roller; φ_2 – angular deviation of the centre of mass of the drive shaft of the vibration exciter

The developed oscillating system is characterised by 4 degrees of freedom, namely, the angle of rotation of the drive shaft φ_1, the angle of rotation of rollers or working and at the same time support rollers φ_2, linear displacements of the centre of mass of the drive shaft relative to the coordinate axes: *X1* and *Y1*. The system is three-mass, for which $m_0=m_1+m_2+m_3$ is the total mass of moving parts of the system, kg; m_1 – mass of the drive shaft; m_2 – mass of the working container; m_3 – mass of the counterweight.

The driving or exciting force arising from the rotation of the drive shaft of the vibration exciter can be represented as the product of its two projections on the coordinate axis:

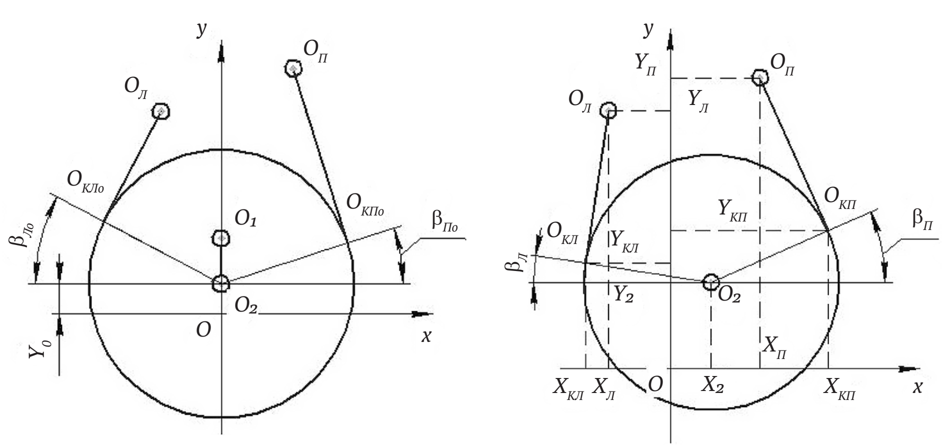
$$F_x = m_1 l_{12} \omega_1^2 \sin \omega_1 t,\ F_x = m_1 l_{12} \omega_1^2 \cos \omega_1 t,\ F_B = \sqrt{F_x^2 \quad F_y^2} \tag{1}$$

Restorative or internal elastic resistance forces of the system reveal elastic elements and vibration supports, which characterise the occurrence of a double elastic connection between the flexible load-bearing body and the body of the installation, as well as between the elastic rollers of the guide part of the machine and its base.

The first elastic connection determines the tension force of the guide tape *T*, which depends on the total deformation of the flexible connection Δl and its stiffness C_{pr}:

$$T = \Delta l \cdot C_{pr} \tag{2}$$

These characteristics are found based on geometric analysis of the oscillatory system under study. The points of suspension of the O_3 tape and its contact with the support rollers on the left and right sides are respectively denoted by $O_л$, $O_{кло}$, $O_п$, $O_{кпо}$ (Fig. 3).



a b

Figure 3. Geometric parameters of the roller coupling with the tape: *a*) the system in the initial position; *b*) the system in the current state

Then the distance between them is as follows:

$$O_{П}\ O_{КПО} = \sqrt{X_{П}^2 + Y_G^2 + R^2} \tag{3}$$

Similarly, at the current moment of time, these distances will be equal:

$$\begin{aligned} O_{Л}\ O_{КЛ} &= \sqrt{(X_1 + X_{Л} + l_{12}\sin\varphi_1)^2 + (Y_{Л} - X_1 + l_{12}\cos\varphi_1)^2 + R^2} \\ O_{П}\ O_{КП} &= \sqrt{(X_{П} - X_1 + l_{12}\sin\varphi_1)^2 + (Y_{П} - X_1 - l_{12}\cos\varphi_1)^2 + R^2} \end{aligned} \tag{4}$$

For the vibration drive under study, the total deformation of the tape and the elastic element of the spring-loaded suspension at the current moment of time for the left and right branches will be as follows:

$$\begin{gathered} \Delta l_{Л} = \sqrt{(X_1 - X_{Л} - l_{12}\sin\varphi_1)^2 + (Y_{Л} - Y_1 + l_{12}\cos\varphi_1)^2 - R^2} - \sqrt{X_{Л}^2 + Y_{Л}^2 - R^2 + R\varphi_1} \\ \Delta l_{П} = |O_{П}\ O_{КП}| - |O_{П}\ O_{КПО}| - R\varphi_2 = \\ = \sqrt{(X_{П} - X_1 + l_{12}\sin\varphi_1)^2 + (Y_{П} - Y_1 - l_{12}\cos\varphi_1)^2 + R^2} - \sqrt{X_{П}^2 + Y_{П}^2 - R^2 - R\varphi_2} \end{gathered} \tag{5}$$

Component $R\varphi_2$ considers the rotation of the support roller of the belt with the mounted vibration exciter by an angle φ_2. Then the tension forces of the tape for the left and right branches are expressed as dependencies:

$$T_{Л} = C_{пр}\left(\sqrt{(X_1 - X_{Л} - l_{12}\sin\varphi_1)^2 + (Y_{Л} - Y_1 - l_{12}\cos\varphi_1)^2 - R^2} - \sqrt{X_{Л}^2 + Y_{Л}^2 - R^2 + R\varphi_2}\right) \tag{6}$$

$$T_{П} = C_{np} = \left(\sqrt{(X_n - X_1 + l_{12}\sin\varphi_1)^2 + (Y_n - Y_1 - l_{12}\cos\varphi_1)^2 - R^2} - \sqrt{X_n^2 + Y_n^2 - R^2 + R\varphi_2}\right) \tag{7}$$

The presented dependencies are built using the MathCad mathematical environment (Figs. 4; 5).

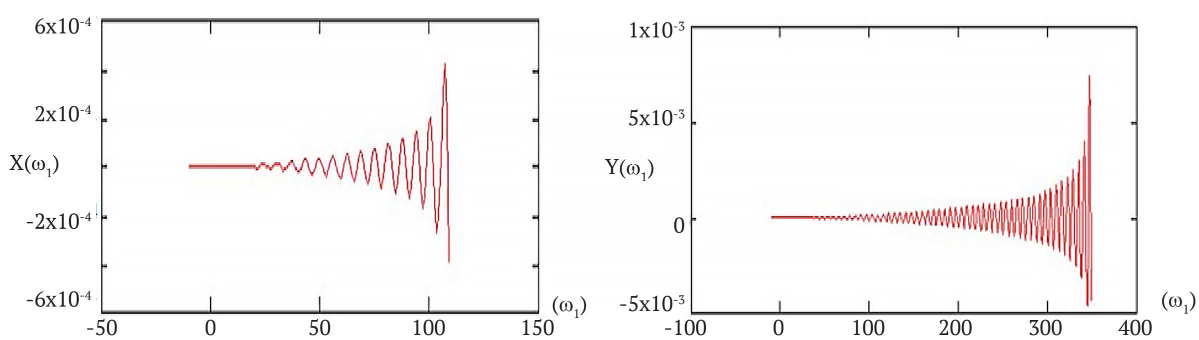


Figure 4. Trajectories of the centre of mass of the working roller along the axes of the plane coordinate system X_r and Y_r (m) from the angular velocity of the drive shaft of the vibration exciter ω1 (rad/s)

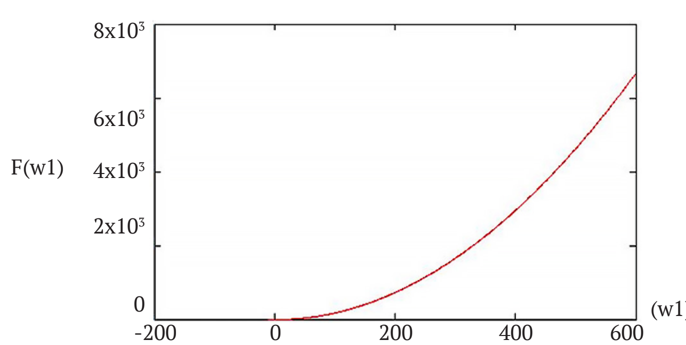


Figure 5. The absolute value of the driving force F_r (H) from the angular velocityof the drive shaft of the vibration exciter ω1 (rad/s)

Graphical dependencies of the trajectory of the centre of mass of the working roller along the axes of the plane coordinate system X_r and Y_r (Fig. 4) indicate a stable wave mode of motion within the angular velocity of the drive shaft of the vibrator $\omega_1=50\text{-}80\ rad/s$, which corresponds to the value of the vibration speed $\upsilon_r= 0.10\text{-}0.18\ cm/s$ (Fig. 5). The absolute value of the driving force begins to increase substantially at $F_r=1\text{-}1.5\ kN$ at values of $\omega_1=100\text{-}120\ rad/s$ (Fig. 5).

Conclusions

Considering the above directions for improving the process of fluidisation freezing of fruit and berry products, a semi-fluidisation machine with a vibration-wave driving body for the movement of the belt mechanism was developed; a set of measuring devices for evaluating and determining the amplitude-frequency and power parameters of the researched cooling process.

The developed method allows increasing the intensification of heat and mass transfer due to the use of a fluidised bed of products, the use of vibration and wave effects and the current scheme of the developed conveyor installation, which not only reduces the forces of internal friction during transportation, but also forms a dynamic wave to ensure the forced movement of products along a flexible load-carrying body in conditions of continuous renewal of product layers in case of their mixing.

A stable wave mode of movement of the developed installation is observed up to the value of the angular velocity of the drive shaft of the vibration exciter $\omega_1=100–120\ rad/s$. Graphical presentation of amplitude-force dependences allowed justifying the theoretical range of angular velocity of the drive shaft of the vibration exciter in the range of *50-80 rad/s* and the magnitude of the driving force to create a given oscillatory mode in the interval of *0.5-1.0 kN* for the specified frequency interval.

This paper established that it is promising to use vibration wave schemes for an organic combination of transportation processes and low-temperature processing of granular products, improvement of heat exchange conditions through the combined use of convective and conductive heat transfer, substantial reduction of product damage, namely of fruits and vegetables.

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Обґрунтування силових параметрів процесу семіфлюїдизаційного підморожування плодово-ягідної продукції

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Анотація. Існуючі семіфлюїдизаційні апарати характеризуються порівняно високими енерговитратами при експлуатації, металоємкістю конструкції, складністю приводного механізму. Тому пошук ефективних схем теплообміну у процесах низько-температурної обробки плодоовочевої продукції за умови мінімізації її пошкоджуваності та енерговитрат на процес становить актуальність проведених досліджень. Метою роботи є визначення та обґрунтування амплітудно-частотних та силових режимних параметрів віброхвильового рушійного органу семіфлюїдизаційної машини для підморожування плодово-ягідної продукції, закономірностей зміни основних характеристик низькочастотних коливань у досліджуваному процесі. Для виконання приведених завдань була розроблена дослідна модель семіфлюїдизаційної машини з віброхвильовим рушійним органом та виготовлений комплекс спеціальних приладів у вигляді мікроконтролерної системи, що забезпечують вимірювання та автоматичне регулювання основних параметрів досліджуваного процесу. Інтенсифікація теплообміну в процесі флюїдизаційного заморожування в умовах псевдозваженого стану продукції характеризується високим коефіцієнтом теплопередачі, який може перевищувати типові конвективні процеси на декілька порядків; спостерігається підвищення активної поверхні теплообміну до 100 %; пропорційно зростає контактна поверхня з енергоносієм, що призводить до зниження активної різниці температур; відбувається зменшення у 2–3 рази внутрішнього тертя в масі продукції та відповідно знижується технологічний опір у масі завантаження, що становить потенціал для підвищення техніко-економічних характеристик досліджуваного процесу низькотемпературної обробки. До практичної цінності проведеної роботи можна віднести застосування віброшугового підморожування запропонованої конструкції із віброхвильовим рушієм продукції та просторової пружної системи для нівелювання паразитних коливань, що дає можливість спростити конструкцію, зменшити силові навантаження та відповідно енерговитрати

Ключові слова: хвильовий конвеєр, віброхвильовий рушійний орган, біжуча хвиля, змушуюча сила, низькочастотні коливання, дебалансний віброзбуджувач