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Hybrid Technology of Beet Pulp Dewatering with Process Intensification in a Convection Dryer as an Element of Sustainable Processing of Agro-Industrial Waste into Bioenergy

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Abstract

In the studied process of moisture removal there is an increase in the driving force, due to centrifugation during rotor rotation, the emergence of electroosmotic pressure when creating conditions for one-sided diffusion, the filtering of the technological mass of the load through the rotor perforations, as well as the introduction of low-frequency oscillations of the dryer's actuators. Therefore, the purpose of this scientific study is to substantiate the operating modes of the vibration convective dryer by evaluating the amplitude–frequency parameters of the beet pulp dehumidification process. According to the results of the studies, the use of the angular velocity of the drive shaft of the vibrator in the range of 80...110 rad/s and the amplitude of oscillations within 2.5...3.0 mm allow the process to be carried out at maximum energy consumption of about 700...750 W. The developed technology involves the sequential implementation of vibration, filtration, and electroosmotic technological action, which allows for a reduction in the duration of beet pulp processing during dehumidification by almost two times compared to the duration when performing filtration moisture removal in a stationary layer of products. Low-frequency oscillations with force field acceleration (of the order of 2...3 g) are used to create a pseudo rapid layer of products before convective processing, and when this parameter is reduced to (0.9...1.0 g), they ensure maximum compaction of the pulp mass, which significantly increases the efficiency of electroosmotic moisture removal. Such a combination of the noted physical and mechanical factors makes it possible to reduce the specific energy consumption for the removal of 1 kg of moisture by 2.7 times compared to traditional convective drying.

Keywords: vibrocentrifugal moisture removal; electroosmotic effect; amplitude–frequency characteristics; beet pulp; pectin-containing raw materials; low-frequency oscillations

1. Introduction

The studied process of the dehumidification of beet pulp is necessary for the implementation of two promising technologies: obtaining dietary fiber and creating an effective energy carrier in the processing of sugar production waste. The sustainable transformation of agro-industrial byproduct streams is a critical component of modern food systems, particularly in the context of growing environmental pressures, energy scarcity, and the transition to a circular economy. Sugar beet processing generates large volumes of byproducts—primarily beet pulp, defecation lime, and sludge—which, if not properly managed, pose significant environmental risks due to their uncontrolled decomposition, and pollution of soil and water resources. On the other hand, beet pulp has high value as a source of dietary fiber and pectin substances. Pectin extracted from beet pulp has high water-holding capacity and low viscosity, and can be used as an additive in the production of a wide range of food products [1]. Processing beet pulp not only minimizes waste and reduces environmental impact but also creates added value, opening new directions for cross-sectoral resource utilization. In the context of transitioning to a circular economy and sustainable agri-food systems, the comprehensive use of byproducts from sugar production is strategically important and economically viable.

The dehydration process is one of the most complex and energy-intensive processes in processing and food production, significantly increasing the cost of production. Chryat et al. report that conventional dryers operate at around 3 MJ of heat per kg of water evaporated, assuming \approx 250–300 kg of water removal per tonne of wet pulp gives a range of 750–900 MJ [2]. At the same time, the degree of reduction in liquid elements or moisture in the product is proportional to its quality, shelf life, and reduction in losses and waste, which impacts the overall food security of the country [3]. Therefore, the search for innovative technological and design solutions in the development of drying systems and the improvement of food production technologies becomes relevant [4,5], particularly through the application of mechanical and physico-mechanical processing methods [6], which can reduce the energy consumption of the process.

A fundamentally new approach to the thermal processing of raw materials is the application of electrotechnologies and targeted energy supplies to specific elements of food raw materials. This has enabled the formation of hypotheses for energy-efficient processes of dehydration, extraction, and microorganism inactivation [7], such as the implementation of desalination technologies during dehydration processes [8]. The energy intensity of drying and dehydration processes has driven the search for alternative energy sources, substantiating the effectiveness of using solar and infrared energy carriers [9,10], as well as the use of vortex and oscillatory processes in the dehydration of environmental masses [11–13].

The diversity of driving forces in the implementation of substance dehydration has stimulated the development of the theoretical modeling of these processes, particularly with regard to their implementation at low temperatures [14], as well as the justification of lyophilization processes, the use of thermal air pumps [15], and the application of electroosmotic pressure for removing excess moisture from beet pulp–pectin raw materials [16]. The description of these processes has led to the modeling of vacuum cooling processes for food products [17], the formation of thin layers of peppermint leaves under the influence of hot air and infrared radiation [18], the evaluation of drying kinetics [19], and the development

of mathematical models of heat and mass transfer processes for resource-saving technology in the production of bakery products from amaranth flour [20].

An analysis of desorption isotherms showed that beet pulp is easily dried and does not require significant additional energy to overcome the material's moisture-binding energy when drying to a final moisture content of 12–13%. As a result of analyzing the sorption isotherm of pulp at an ambient air temperature of 20 °C, it was proven that drying the pulp to a moisture content below 13% is impractical as during storage in warehouses at a temperature of 20 °C and a relative air humidity of 50% it will absorb moisture up to 13.2% [21].

The study of the drying process of a stationary layer of rapeseed using an electromagnetic infrared emitter allowed for the evaluation of the energy intensity of the process and the determination of the optimal thickness of the product layer [22]. Research on the drying process of apple slices using a combined radiative–convective method revealed a reduction in drying time by 1.9 times compared to the stationary mode at a heat carrier temperature of 60 °C, resulting in a product with high rehydration capacity (78–80%) and excellent organoleptic properties [23]. A two-component heat exchange model was developed between thermosiphons and a layer of bulk material, taking into account the evaporation of moisture from the product during the drying process without direct contact between flue gases and the product. This model made it possible to determine the optimal conditions for the thermal–moisture treatment of sweet potato roots, as well as the pretreatment and drying regimes, which significantly reduce processing time [24].

Based on theoretical research into the process of radiative–convective drying of oilseed materials transported by vibratory trays, it was established that the Rebinder effect, which characterizes the moisture-resistant and thermal properties of the material, decreases as moisture content decreases from 0.04 at 11% to 0.01 at 9% [25]. The evaluation of the convective drying process of sweet potato roots allowed for the determination of heat consumption during the process while ensuring maximum preservation of the raw material's natural properties. This made it possible to justify optimal conditions for thermal–moisture treatment, pretreatment regimes, and drying modes, which significantly reduce processing times [26].

The studied process of the dehydration of pulp raw materials is typically carried out in screw-type machines, which are characterized by relatively high metal consumption and significant energy requirements during operation. The performance of this process can be improved by using a low-frequency motor to move the products in the work area [27].

At the same moisture content, pectin has the highest moisture-binding energy with the material, followed by starch, cellulose, and sucrose, which has the lowest. This allows for the evaluation of parameters such as drying duration, heat consumption, and energy expenditure. Studies on the pressing processes of enriched beet pulp have made it possible to establish the dependencies of shear stress on normal stress at different moisture levels and temperatures of beet pulp, which allowed for the estimation of energy consumption for the process [28].

The aim of the work is to justify the operating modes of moisture removal with minimal energy consumption in the process of electroosmotic dehydration of beet pulp by determining the main parameters of low-frequency vibrations and evaluating the impact of vibrations on the key technological parameters of the process.

2. Materials and Methods

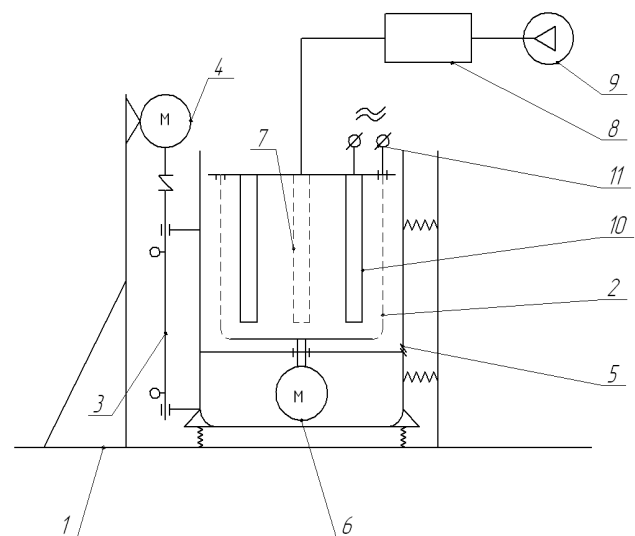
The object of processing was pulp mass as a pectin-containing raw material. Beet pulp is a byproduct of sugar production and has a structure in the form of micro-shavings no thicker than 2 mm with a moisture content of about 90%. The majority of sugar, as

well as some mineral and organic substances, is removed from it through a diffusion process. To evaluate the kinematic and energy parameters, a wireless sensor for recording amplitude–frequency characteristics with independent power supply, based on the LIS3DH accelerometer by the company STMicroelectronics, Geneva, Switzerland was used. It had the following characteristics: ultra-low power consumption— $2\ \mu\text{A}$; an operating voltage from 1.71 to 3.6 V; an adjustable acceleration measurement range of $\pm 4\ \text{g}$, $\pm 8\ \text{g}$, and $\pm 16\ \text{g}$; an SPI/I2C interface for data reading; and a built-in self-test module. After stopping the equipment, amplitude–frequency characteristics were obtained using software and an adaptive cable. These characteristics are interpreted as graphical dependencies and a digital data matrix. The software allows for the analysis of the vibration acceleration, vibration velocity, vibration displacement, and the frequency of generated oscillations. To register the rotational speed of the drive shaft, the wireless tachometer UNI-T UT372, Honkong, China was used. To control and adjust the rotational speed of the motor shaft, the autotransformer AOSN-20-220-75, Lviv, Ukraine was employed, which is designed for operation with an alternating current. It contains a movable current-collecting contact in the form of a graphite roller, allowing for smooth voltage adjustment from zero to maximum. Additionally, the winding of the mentioned autotransformer has several terminals, enabling different current characteristics at the output. The device can also be used as a stabilizer as its connection to the setup prevents voltage surges in the network.

The operational characteristics of the laboratory autotransformer AOSN-20-220-75 allow for real-time data collection, an analysis of power consumption, and the rotational frequency of the motor in the developed experimental dryer model (Figure 1a). The study of the main parameters of the beet pulp dehydration process was conducted using an experimental vibrocentrifugal electroosmotic dehydrator (in house design). The setup consists of a centrifuge 5 (Figure 1b), which is mounted on frame 1 via elastic elements. Vibrational oscillations are induced in the centrifuge using an unbalanced vibrator drive 3, which is powered by an electric motor 4. The centrifuge rotor 2 is rotated by motor 6. Electroosmosis electrodes 10 are arranged on the periphery of the rotor. To supply the heat agent, which is pressurized by the compressor 9 and heated in the heat generator 8, the centrifuge body includes a perforated pipe 7.



(a)



(b)

Figure 1. Vibrocentrifugal electroosmotic dehydrator. Photograph of the setup (a). Schematic diagram of the machine (b): 1—frame; 2—perforated centrifuge rotor; 3—vibration exciter; 4—vibrator drive motor; 5—working body; 6—centrifuge motor; 7—pipe; 8—heat generator; 9—compressor; 10—electrodes; and 11—voltage converter.

The set temperature of the drying agent was maintained automatically, and it was also possible to adjust it quickly using a power regulator. The set frequency and amplitude of vibrations were set independently using an electronic device and by changing the angle of installation of the vibration exciter imbalances.

3. Results

The studied dehumidification process allowed us to develop a technology for processing beet pulp, which ensures the sequential implementation of three-stage filtration-convective dehumidification of high-moisture raw materials by changing technological influences and parameters. The developed process for dehydrating pectin-containing raw materials in the form of beet pulp includes sequence of several operations. The sequential implementation of a three-stage filtration-convective dehydration process for high-moisture raw materials was ensured by using the vibrocentrifugal electroosmotic experimental dehydrator (in house design) with varying technological impacts and parameters. At first, the process of filtration-convective drying occurred in a stationary layer. At the second stage, a mechanical vibration exciter connected to the drying chamber induced low-frequency oscillations in the mass of the processed product. Finally, a set of measures was implemented to form, set, and automatically regulate the current density of the electrodes by adjusting the frequency, asymmetry, and density of the currents. This allowed for the tracking of their impact on the dehydration time while minimizing energy consumption for the process. In order to determine the necessary kinematic, force, and energy characteristics of the studied system, the trajectories of the actuators were determined using Lagrangian modeling [29].

$$\begin{cases} x_1 = \frac{m_g \cdot e \cdot \omega_2^2 \left(\frac{C_x}{m} - \omega_2^2 \right)}{m \cdot \left[\left(\frac{C_x}{m} - \omega_2^2 \right)^2 + \alpha_x^2 \cdot \omega_2^2 \right]} \sin \omega_2 t + \frac{m_g \cdot e \cdot \omega_2^3 \alpha_x}{m \cdot \left[\left(\frac{C_x}{m} - \omega_2^2 \right)^2 + \alpha_x^2 \cdot \omega_2^2 \right]} \sin \omega_2 t \\ \gamma_1 = \frac{m_g \cdot e \cdot \alpha_y \omega_2^3}{m \cdot \left[\left(\frac{C_y}{m} - \omega_2^2 \right)^2 + \alpha_y^2 \cdot \omega_2^2 \right]} \cos \omega_2 t + \frac{m_g \cdot e \cdot \omega_2^2 \left(\frac{C_y}{m} - \omega_2^2 \right)}{m \cdot \left[\left(\frac{C_y}{m} - \omega_2^2 \right)^2 + \alpha_y^2 \cdot \omega_2^2 \right]} \sin \omega_2 t \end{cases}$$

where m_g is the oscillating mass of the drive; C_x and C_y are the stiffness of the elastic elements in directions x and y ; α_x and α_y are the dissipation coefficients in the directions x and y ; m is the mass of the moving parts of the drive; e is the eccentricity of the drive shaft; ω_2 is the angular velocity of the drive shaft; and x_1 and y_1 are the linear coordinates of free motion in the respective directions.

Based on the derived system of motion equations, and using the MathCAD mathematical environment, graphical dependencies for the main kinematic characteristics of this oscillatory system were obtained (Figures 2 and 3).

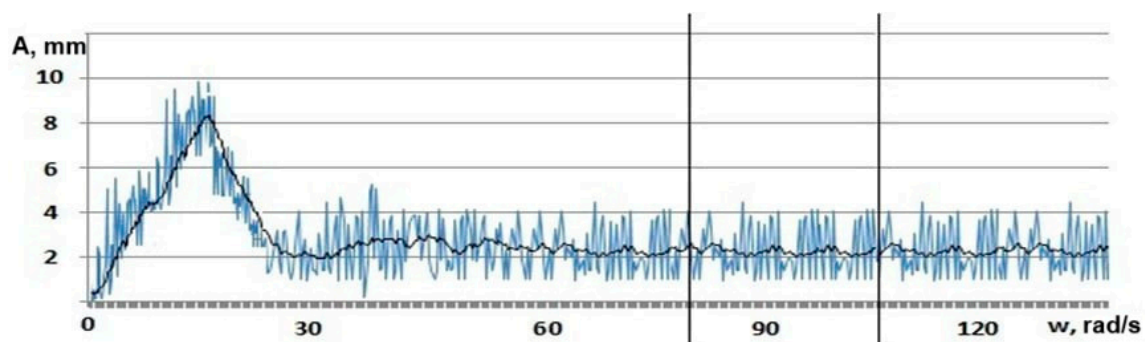


Figure 2. Amplitude–frequency characteristics: A—amplitude of oscillations, mm; ω —angular velocity of the drive shaft, rad/s; 1—theoretical amplitude–frequency characteristic; and 2—experimental amplitude–frequency characteristic.

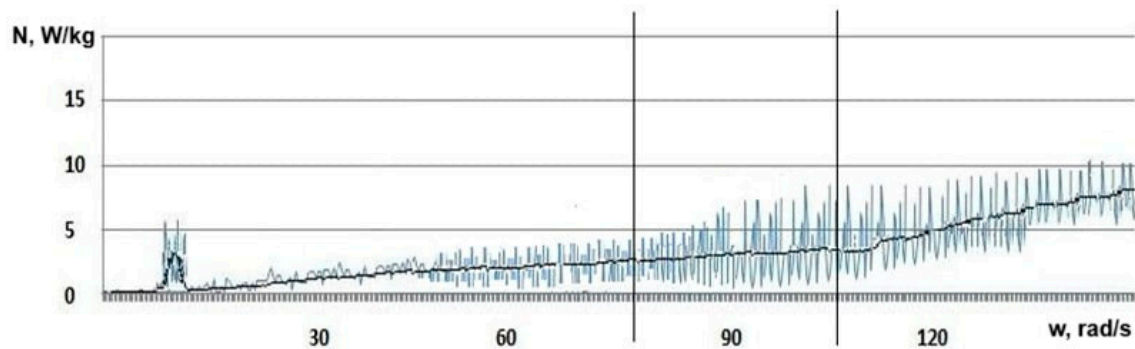


Figure 3. Vibration intensity of the oscillatory motion of the dryer's actuators: N —intensity of oscillatory motion (specific energy consumption).

These include the trajectory of motion of the machine's actuators and the corresponding amplitude–frequency characteristics (Figure 2), as well as the vibration intensity (Figure 3). The vibration intensity can be determined using kinematic parameters, namely $N = A^2 \omega^3 = a v = N_p/m_g$, where $a = A \omega^2$ is the vibrational acceleration, $v = A \omega$ is the vibrational velocity, N_p is the power generated by low-frequency oscillations, and m_g is the mass of the oscillating parts of the drive.

These dependencies allow for the justification of the stable operating range of the vibration exciter in the super-resonance mode (at $\omega > 50$ rad/s) and the region of sharp energy consumption increase for the drive (at $\omega > 100$ rad/s), thereby substantiating the effective operating parameters of the studied mechanical vibration exciter.

The constructed amplitude–frequency characteristic (Figure 2) contains three main sections. In the first pre-resonance section ($\omega = 0 \dots 20$ rad/s), there is a rapid increase in the amplitude of oscillations, followed by a decrease after reaching the maximum. Under such conditions, difficulties are observed in maintaining and regulating a certain stable range, although the energy consumption to achieve high amplitudes is minimal. The second section ($\omega = 20 \dots 80$ rad/s) represents the transition area, which is characterized by instability with regard to the changes in frequency and amplitude of oscillations. The third post-resonance section ($\omega = 80 \dots 110$ rad/s) is marked by the stabilization of the working amplitude levels and ease of regulating possible changes. However, as the angular velocity increases, energy consumption for vibration excitation also rises (Figure 3). Thus, the operating modes are limited to a specific frequency range, as shown by the vertical lines in Figures 2 and 3. Practically the same conclusions regarding the justification of the operating modes of the developed dryer can also be drawn from the theoretical dependencies [30].

The conducted studies allowed for a comparative analysis of the impact of various physical–mechanical measures (Figure 4) and demonstrated the effectiveness of vibro-centrifugal removal of free moisture at the first stage of processing. At the second stage, the continuous product layer was disrupted under the influence of the vibrational field, followed by diffusion, with electroosmotic intensification of the moisture removal process at the third stage of processing. The experiments revealed that the processing time using vibrational filtration drying with the application of the electroosmotic effect was reduced by 38%.

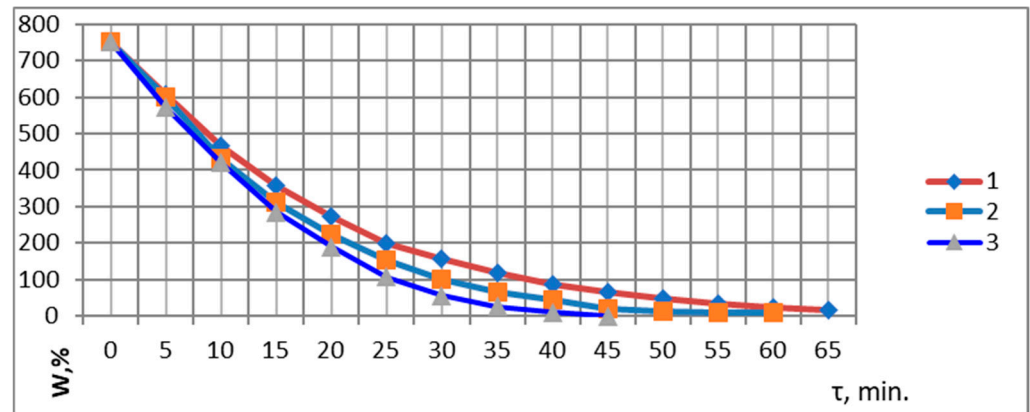


Figure 4. Drying kinetics of pectin-containing raw materials under different moisture removal methods: 1—filtration drying in a stationary layer at $W_{II} = 720\%$, $V = 3$ m/s; 2—vibrational filtration drying at $W_{II} = 720\%$, $V = 3$ m/s., $A = 4$ mm; and 3—vibrational filtration drying with the application of the electroosmotic effect at $W_{II} = 720\%$, $V = 3$ m/s., $A = 4$ mm, $E = 80$ V/cm, $F = 200$ Hz, $Q = 3$, $\Pi = 0.75$.

The studies were conducted at a constant oscillation frequency of 16 Hz, with amplitude values of 2, 4, and 6 mm, at which the duration of the filtration-convective drying process was recorded (Figure 5). The working temperature inside the mass of pectin-containing raw materials at 50 °C was achieved twice as fast when using vibrational technological action with an oscillation amplitude of 4 mm compared to traditional convective drying. This is explained by the creation of a fluidized layer of the product and the improvement in conditions for the penetration of the heat carrier flow.

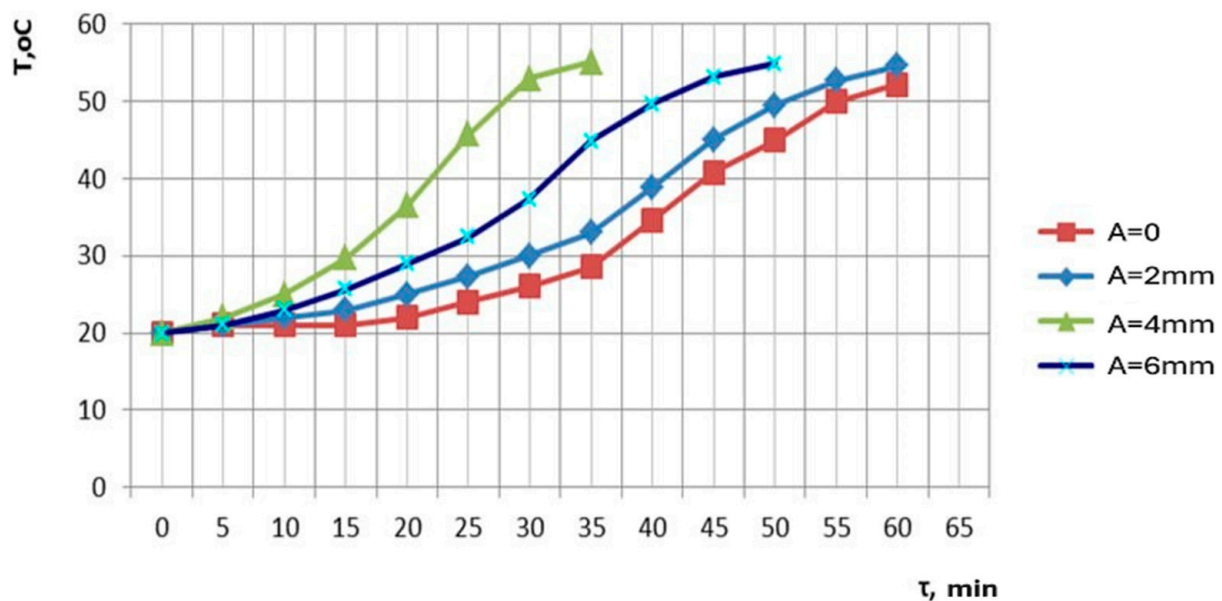


Figure 5. Dependence of the temperature of pectin-containing raw materials on the dehydration time at different oscillation amplitudes: T —temperature of beet pulp, °C; τ —duration of drying at corresponding oscillation amplitude values $A = 0, 2, 4,$ and 6 mm.

The minimal processing time was achieved during convective drying with the creation of a vibrationally fluidized layer at an oscillation amplitude of 4 mm (Figure 6), which reduced the processing time by 43% compared to traditional convective moisture removal. Increasing the oscillation amplitude to 6 mm did not provide a technological effect, despite the increase in energy consumption for the process.

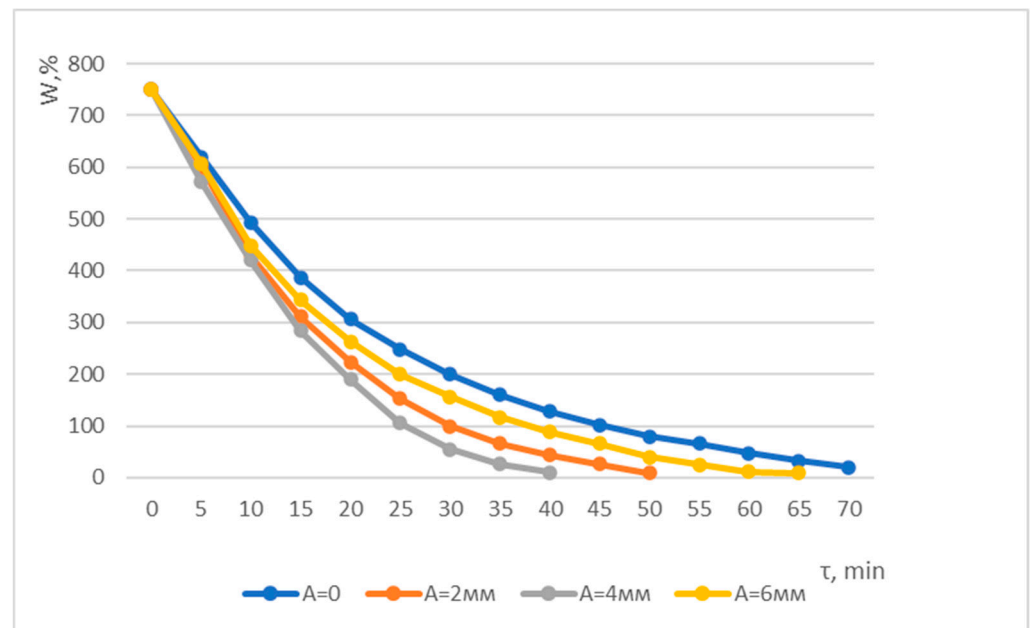


Figure 6. Dependence of the moisture content of pectin-containing raw materials on the dehydration time (τ) at different oscillation amplitudes ($A = 0, 2, 4,$ and 6 mm). Main parameters of dehydration: W —moisture content of beet pulp, %; $V = 3$ m/s—velocity of the heat carrier flow; $E = 80$ V/cm—intensity of the electromagnetic field; $F = 200$ Hz—frequency of the electromotive force; and $\Pi = 0.75$ —degree of equipment loading.

4. Discussion

In light of global trends toward a circular economy, waste from the sugar industry—especially sugar beet pulp—is gaining importance as a versatile raw material. In the study by [31,32], the authors indicate that this waste can serve as a source of a platform chemical—furfural—obtained through acid hydrolysis. Furfural provides the basis for the synthesis of derivatives such as furfuryl alcohol (useful as a fuel additive in sugar factories) and tetrahydrofurfuryl alcohol (applied in fertilizers that contribute to increased sugar beet yields). The economic and environmental models presented in this work demonstrated that furfural recovery reduces the amount of waste and improves the ecological balance of the sugar industry, aligning with the concept of circularity in raw material processing [33,34].

The publication by [35,36] represents a compelling case study supporting material cycle closure in sugar production. It shows that lignocellulosic waste can be a valuable feedstock for the production of platform chemicals (furfural and its derivatives), and that proper technological direction, energy optimization, and the use of waste heat can significantly improve both the economic efficiency and ecological performance of the process.

A complementary perspective is provided [31,32] by the review of [37–40], which emphasizes the wide spectrum of possible bioproducts from sugar beet pulp, from biogas and bioethanol to pectins, biorefinery products, and industrial compounds. The authors highlight that proper pretreatment and utilization of this biomass as a valuable substrate are crucial for advancing the bioeconomy. In Poland, other researchers are working on different solutions for waste and food residues, and for the drying process of food, itself [41,42].

In modern drying and dehydration processes, the use of vibrational and wave effects is quite common. Theoretical justification for the efficiency of mechanical and vibrocentrifugal processes has been applied in technologies for pressing pulp [43]. Mathematical models have been developed for creating a fluidized bed under the influence of low-frequency oscillations [44], and studies on the characteristics of nonlinear dynamics and energy transfer in a vibrational gas–solid fluidized bed were made using the Hilbert–Huang

transform [45]. The propagation of pressure oscillations in two orthogonal directions using a fluidized bed with internal circulation was studied experimentally [46], and, additionally, the influence of standing wave parameters on the hydrodynamic behavior during the fluidization of powdery masses using sound energy was evaluated [47]. These studies have demonstrated the effectiveness of using vibrations to improve heat and mass transfer conditions during the dehydration of bulk technological media in a fluidized bed.

The operational characteristics of this process can be improved by using a low-frequency drive to move the product in the working zone [48]. Vibrations of the working container cause both general circulation of the loaded mass and relative chaotic movement of the mixture's components. This leads to a weakening of the cohesive forces between the particles of the technological medium, the destruction of formed conglomerates, and changes in the rheological properties of the material, such as viscosity, shear modulus, effective friction coefficient, and adhesive bonding forces. Collectively, this creates an effect which loosens the product mass, reduces structural resistance, and increases the surface area for heat and mass transfer [49].

The use of low-frequency vibrations in the processes of moisture removal from beet pulp has traditionally not been employed due to the difficulty of vibration penetration into the moist mass [45]. The effectiveness of vibrations in the studied process is based on the hypothesis of their multi-purpose application to various tasks, as follows: loosening to reduce technological resistance, and pressing to create a denser electrostatic layer and enhance the electroosmotic effect. Electroosmotic processes in a high-moisture raw material layer, when creating a pressure difference in the working volume, allow for an increase in the driving force of filtration and dehydration processes.

Thus, the main factors of the studied process are the following elements and design-technical measures. The increase in the driving force of the dehydration process is achieved through centrifugation during rotor rotation, vibrational pressing with the creation of a compacted product layer, which enhances the subsequent use of the electroosmotic effect under conditions of one-sided diffusion, and the filtration process of the medium through the perforations of the rotor. However, the latter process leads to an increase in technological resistance, which worsens the conditions for intensifying the processing. This drawback can be mitigated by creating a fluidized layer of the product due to the oscillatory motion of the working chamber, which significantly reduces the internal friction forces within the loaded mass. Under the influence of such factors, the dehydration process time decreases, which intensifies the moisture removal process and indirectly reduces energy consumption.

The evaluation of the technological application of a combination of physical-mechanical factors for intensifying the dehydration process of pectin-containing raw materials revealed that the use of vibrational electroosmotic drying with an oscillation amplitude of 6 mm allows for a 1.44-fold reduction in moisture removal time compared to convective filtration drying in a stationary product layer.

Using the Lagrange equations of the second degree, a mathematical model of the motion of the actuators of the developed dryer was created. Considering that the dynamic characteristic component of the derived equations dampens under the action of natural oscillations in the super-resonance mode, it became possible to use the Cauchy method to solve the obtained system of linear inhomogeneous differential equations of motion. Using this system of equations, graphical dependencies were obtained for the trajectory of motion, oscillation amplitude, vibration velocity, and vibration acceleration of the actuators of the studied oscillatory system, as well as for energy consumption for the drive and the energy intensity of the oscillatory motion. This allowed for the justification of the operating modes of the working container's motion in the studied dryer.

5. Conclusions

The processing time required to achieve the desired moisture content using the vibrational, filtration, and electroosmotic effects was 1.44 times shorter than for convective filtration drying in a stationary product layer, which allowed for a reduction in the energy consumption of the process accordingly.

The minimum processing time was achieved during convective drying with the creation of a vibrationally fluidized layer at an oscillation amplitude of 4 mm, which reduced the processing time by 43%, reducing the energy costs compared to traditional convective filtration moisture removal.

The developed technological scheme of vibrational electroosmotic dehumidification facilities a reduction in energy consumption for the removal of 1 kg of moisture by 2.7 times compared to traditional convective drying. In addition, the latter process is quite destructive for thermolabile disperse systems.

The obtained patterns of changes in the main parameters of the machine's vibratory exciter allowed us to substantiate its effective operating modes, including the angular velocity of the vibratory exciter drive shaft within 80. . .110 rad/s and the amplitude of oscillations within 2.5. . .3.0 mm, which allows the process to be carried out at maximum energy consumption of about 700. . .750 W.

Author Contributions: Conceptualization, I.P., T.H. and O.P.; methodology, O.Z., T.H. and L.K.; software, O.V. and S.S.; validation, K.D., S.S. and Z.R.-D. formal analysis, O.V. and S.S.; resources, I.P. and A.O.; data curation O.P. and A.O.; visualization, O.Z. and Z.R.-D.; project administration, I.P.; funding acquisition, S.S.; supervision, T.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare that they have no conflicts of interest.

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