Study of power consumption in vibromixing apparatus during Jerusalem artichoke drying

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Abstract. Jerusalem artichoke (JA) tubers have recently attracted interest as a functional ingredient in food products with enhanced nutritional characteristics. Dried powder of JA tubers was prepared using a developed vacuum vibromixing apparatus to prevent degradation of thermolabile substances. The critical principle of technological calculations for vibrating apparatuses is to determine the power consumption of the load circulation, depending on dynamic parameters. The paper aims to examine the effect of changes in the amplitude and frequency of apparatus vibration on the power consumption while drying the JA tubers. The results obtained experimentally in the laboratory vibromixing dryer (282 mm in diameter, 186 mm in length) show that with an increase in the amplitude, as well as the frequency of the vibration, the time of mass heating to the drying temperature and total drying time decreased. It was found that the maximum useful power is transmitted to the load at optimal vibration modes: 1.44 mm amplitude and 50 Hz frequency. Thus, under optimal dynamic parameters, the approximate time of the drying process can be determined at the moment when power value is fixed. The current results allow automatically controlling the termination of JA powder drying through power change.

1. Introduction

The Jerusalem artichoke (Helianthus tuberosus L.) is a perennial plant that consists of a stem about 1–3 m tall, small yellow flowers, hairy oval-shaped leaves, and an underground rhizome system that bears small tubers. It has numerous benefits over traditional crops, including high growth rate, inherent tolerance to frost, drought and degraded soil, strong resistance to pests, and plant diseases, with minimal needs for fertilizers. So it has excellent potential as an alternative crop in many countries. Jerusalem artichoke is useful in many ways. Conventionally, JA has been directly used for food or animal feed. But in the past two decades, alternative uses of tubers have been explored, especially as the excellent plant resource for the production of bioethanol, methane, pyrolysis gas, or biochemical materials by fermentation of microorganisms [1,2]. Besides, some bioactive ingredients extracted from its leaves and stems create an opportunity for applications in the pharmaceutical industry [3,4]. Over the last decades, consumer demand for functional foods as an opportunity to improve product quality has grown significantly. JA can be appreciated for its nutritional and medical qualities as an accessible source of protein and essential amino acids, minerals (potassium, phosphorus, magnesium, calcium, iron, selenium and others), vitamins (B complex, A, C, and β-carotene) and some functional ingredients such as inulin, oligofructose, and fructose. Inulin is a non-starch carbohydrate which is applied as a prebiotic, a source of food with a low glycaemic index, as well as a fat/sugar replacer and texturizer [5–7].
Processing of JA tubers into dry powder makes it possible to expand the field of its use in the food industry as a functional ingredient. Food powders are characterized by a small volume, mass, and high concentration of nutrients. Traditional drying technologies involve the following two steps: water removal and grinding. It should be noted that their thermolability limits the intensification of the drying process for organic materials. Higher temperature, complicated by time-exposure, leads to significant losses of biologically active substances and a decrease in the quality of the finished products due to chemical transformations of components correspondingly [8]. Therefore, there is a constant search for different ways to intensify the drying process of raw materials to preserve beneficial properties of food, including the use of vacuum, a high degree of dispersion, non-traditional types of drying (sublimation, microwave, infrare, and others) [9,10].

A new method of producing JA powder is developed by combining vacuum drying and vibration grinding in one apparatus. Vacuum helps increase moisture evaporation at low temperatures to save valuable components. Mixing due to vibration action contributes to the equalization of temperature and humidity fields in the apparatus [11–13]. An exposure of vibration on mixed material and end-effectors of the apparatus significantly reduces the power consumption and increases the rate of productivity, as well as the quality of the mixture. Thus, one of the critical principles of technological calculations for vibrating apparatuses is to determine the consumption of the load circulation, depending on dynamic parameters [14,15]. Furthermore, the value of power consumed by the vibrating apparatus is the initial data for designing the drive and strength analysis of the components.

Therefore in this research, to develop a method for primary processing and promote extensive utilization of Jerusalem artichoke tubers, the dry powder was prepared in the vacuum vibromixing apparatus and examined the effect of its dynamic parameters on the power consumption.

2. Materials and methods

2.1. Sample preparation
Jerusalem artichoke tubers, Skorospelka variety, were grown in Tatarstan local farm and harvested ten months after planting. Five days after the harvest, the tubers were washed and brushed manually to eliminate soil residues. Clean and dry tubers were packed in plastic bags and stored in a chamber at 4±2 °C and > 98% relative humidity until use (maximum one week). The JA tubes of mass 10±0.5 g were hand peeled and diced into 10 mm ×10 mm × 10 mm. Then cubes were stored at room temperature before the test that performed about 20±1 min later.

2.2. An experimental set-up
The vibromixing dryer has a horizontal body of diameter 282 mm and length 186 mm with an inner central pipe. The dryer set up on flexible supports, being an end-effector with mass \( M \). A vibrator shaft is placed inside the central pipe on bearing supports. Plates with debalances \( m \) and eccentricity \( r \) are fixed at both ends of the shaft. Shaft rotation is driven by an electric motor (4.5 kW and 2880 rpm) through a system of a flexible connector, a V-belt transmission, and a speed variator. The vibration amplitude \( A \) of the apparatus body depends on the number of the withdrawable debalances. The amplitude value is measured by the vibrograph (VR-1, Vibropribor, Russia). The study of the influence of the vibration amplitude on the power consumption during the process was performed at a constant vibration frequency \( \nu = 60 \) Hz and amplitudes \( A \) of 0.64; 1.03; 1.44; 1.83 mm. The turning number of the shaft determines the frequency of vibrations in the range from 25 to 75 Hz (at constant \( A = 1.44 \) mm) and is recorded using the stroboscopic tachometer (ST-5, Analypribor, Georgia). The laboratory set-up is equipped with the wattmeter (CL8516, Mir, Russia) in order to measure the power consumption. The body of the vibrating apparatus has a heating jacket with hot water, which comes from the boiler with a built-in thermostat (Ariston, Italy) using the circulation pump (WILO, Germany). The temperature mode is controlled by the digital thermometer (IT-17-S, Eksis, Russia) with the thermocouple (TSP-100, Novatek, Russia) mounted inside the apparatus. The vacuum line consists of pump 12 (Stegler 2VP-1, China), tube condenser with a tank.
Figure 1. The laboratory set-up of the vacuum vibromixing dryer: 1 – mixer body; 2 – central pipe; 3 – vibrator shaft; 4 – debalance; 5 – flexible support; 6 – bearing support; 7 – flexible connector; 8 – intermediate support; 9 – V-belt transmission; 10 – variator; 11 – motor; 12 – vacuum pump; 13 – condenser; 14 – condenser tank.

2.3. Power consumption

The power consumption of the vibromixing apparatus is substantially determined by the vibration of the loaded body. The most reliable equation for calculating the shaft power $N$ (kW) in terms of the dynamic parameters of the vibrating apparatus may be approximated as:

$$
N = 4qr^2m\omega^2 \sin 2\gamma \frac{m\omega^2 (r - A) f_{mp}d}{204 (p^2 - \omega^2)} + \frac{m\omega^2 (r - A) f_{mp}d}{204 (p^2 - \omega^2)}.
$$

where $q = m/(m + M)$; $m$ is debalance weight, kg·s²/m; $M$ is loaded dryer weight; $r$ is eccentricity of the debalance, m; $p$ is natural frequency, 1/s; $\omega$ is angular velocity of vibrating shaft rotation, 1/s; $\gamma$ is phase-shift angle between forced vibrations and driving force; $A$ is the vibration amplitude of the apparatus body, m; $f_{mp}$ is a reduced coefficient of friction in a rolling bearing; $d$ is a bore diameter of a bearing cup, m.

It can be seen from equation (1) that the power consumption is proportional to the amplitude in the first degree and the frequency in the third degree. For purposes of clarity, in the first term of equation (1), one can introduce the amplitude for the case of forced vibrations in the form:

$$
A = \frac{4qr^2 \omega^2}{p^2 - \omega^2}.
$$

3. Results and Discussion

The power consumption curves depending on the different amplitudes when drying JA tubers in the vacuum vibromixing apparatus until the establishment of the final water content of 5–6 % are illustrated in figure 2. It was found that with increasing the amplitudes, the heating time of mass to drying temperature and drying time are decreased. The reason is that the intensity of the mass motion rises as amplitude goes higher, which leads to the increase in heat transfer between the apparatus body and the load, as well heating the mass due to friction goes higher. However, intensification of this motion accordingly requires the additional energy consumption.
Figure 2. Variation of the power consumption \( N \) of the vibration amplitude \( A \), mm:
1 – 0.64; 2 – 1.03; 3 – 1.44; 4 – 1.83 (\( \nu = 50 \text{ Hz} \))

Figure 3 shows power changes while drying at different vibration frequencies. The same trend was demonstrated as in figure 2 – as the vibration frequency increases, the drying time is reduced. Moreover, at the frequency of 25 Hz, there is some constant area after the maximum peak. The beginning of this section coincides with the water content of 61 \%. At this frequency there is no mass circulation, only vibrating of its particles occurs. Heat transfer is slow and is mainly governed by the heat conductivity of the mass. The drop in power to complete moisture removal can be explained by decreasing the amount of liquid phase sufficient to reduce the mass resistance to vibration to a constant value.

Figure 3. Variation of the power consumption \( N \) from the vibration frequency \( \nu \), Hz: 1 – 72; 2 – 62; 3 – 50; 4 – 38; 5 – 25 (\( A = 1.44 \text{ mm} \))
It can be supposed that the alignment of the maximum power at 72 Hz and the start of drying (ordinate axis) stems from the following fact. There are both high circulation of the mass and a large number of collisions between particles and walls per unit time reasons for heating of the mass to drying temperature in a short moment. This period is commensurate with the instrument time error, and it is small compared to the total drying time.

So, as shown in figure 3, the optimum drying time decreases with increasing the frequency, since more power is transmitted to the load, the faster the minimum water content is reached. However, the drying time gain at frequencies higher than 50 Hz is small in comparison with frequencies up to 50 Hz. But significant growth in both vibration strain and total power consumption is observed at > 50 Hz. Therefore, there is no point in drying at frequencies exceeding 50 Hz in the vibromixing apparatus of this size.

The experimental value of the power consumption in the loaded vibromixing apparatus may be considered under two parts. The first one is the power transmitted directly to the mass to overcome the resistance caused by the material, and the second one is the power consumed to vibrate the unloaded mixer. The value of power transmitted to the load can be considered useful, going directly to the intensification of mixing, since this part of power goes to the circulating motion and vibrations of the mass in the mixer. Besides, the power for vibrating the unloaded mixer at the different vibration modes is obtained by the experimental approach too. So based on experimental data, the relations the maximum $N_{\text{max}}$, initial $N_i$, final $N_f$ useful powers concerning dynamic parameters of apparatus are depicted (figure 4).

![Figure 4. Dependence of the power consumption on dynamic parameters of vibrating apparatus: 1, 2, 3 – $N_{\text{max}}$, $N_i$, $N_f$ at various amplitudes ($\nu = 50$ Hz); 4, 5, 6 – $N_{\text{max}}$, $N_i$, $N_f$ at various frequencies ($A = 1.44$ mm).](image)

According to the graphs in figure 4, the maximum power is transmitted to the load at an optimum amplitude of $A = 1.44$ mm, whereby the necessary water content of the material is achieved in the shortest possible time. The optimum frequency of 50 Hz is observed only for final power values (curve 6). For other useful power values, this is not occurred due to likely the increased number of
collisions of material particles with the apparatus body when the frequency increases. This fact leads to
an increase in resistance proportional to the number of collisions. Besides, the magnitude of these
resistances is much higher for dry friction than with liquid one.

It should be noted that for a given size of the vibromixing dryer with optimum vibration parameters,
the time when the power becomes constant coincides with the time when the minimum water content is
established, as can be seen in figure 5.

![Figure 5. Cross-plot between useful power $N_1$ of the apparatus and water content $W$ during JA drying](image)

4. Conclusion

The results obtained experimentally in the laboratory set-up (diameter of 282 mm, length of 186 mm)
while drying the tubers of Jerusalem artichoke show that with the increase in the amplitude, as well as
the frequency of the vibration, the heating time of mass to drying temperature and drying time are
decreased. It was found that the maximum useful power is transmitted to the load at optimal vibration
modes: 1.44 mm amplitude and 50 Hz frequency. Thus, under the optimal dynamic parameters, the
approximate time of the drying process can be determined at the moment when power value is fixed.
The current results allow automatically controlling the termination of JA powder drying through power
change.

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