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# Studies of ultrasonic dehydration efficiency*

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**Abstract:** The aim of this investigation was to define the effectiveness of non-contact drying using ultrasonic vibrations. Disk radiators were used for carrying out experiments, and a special drying chamber was designed to provide resonant amplification of ultrasonic vibrations (from 130 to 150 dB). Drying of ginseng and other vegetables demonstrated that the application of ultrasonic vibrations reduced power inputs by 20% in comparison with convective drying. It also led to a decrease of 6% in final moisture content, if the duration of drying was constant. The level of intensification of ultrasonic drying was high (up to 50 g for 1 kg of drying material), which helped to lower the temperature of the drying agent and improve the quality of the dried products.

**Key words:** Drying, Ultrasound, Vibration system, Drying chamber, Processing (treatment) of agricultural products
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## 1 Introduction

Nowadays, conventional (hot-air) driers are widely used to dehydrate different materials. These driers can be characterized by high power consumption and a high rate of defective goods because of overheating and irregular drying.

One of the most effective ways to solve these problems is to use high-intensity ultrasonic vibrations during the drying. As this does not lead to heating of the drying material (de la Fuente *et al.*, 2004; Gallego-Juarez *et al.*, 2007), ultrasonic drying is the only method suitable for materials such as heat-sensitive, thermolabile, and easily oxidable products. In addition, ultrasonic processing of raw materials positively affects the properties of such products; i.e., it can preserve their taste properties, and increase their storage life and germinability (Rozenberg, 1973; Glaznev, 1997; de la Fuente *et al.*, 2006). However, Riera-Franco de Sarabia *et al.* (2007) reported the results of experiments, which demonstrated the inefficiency of ultrasonic drying in non-contact mode (without direct contact between the radiator and the drying material). We propose that the main reasons for these problems were design imperfections in the radiators used and the absence of special drying chambers providing resonant amplification of ultrasonic vibrations.

## 2 Equipment developed for ultrasonic dehydration

To develop a drying process using ultrasonic vibrations, a compact ultrasonic drying system, with a specially formed chamber and a vibration system with a disk radiator, was designed and constructed (Khmelev *et al.*, 2007a; 2007b; Lebedev *et al.*, 2008). This equipment enables dehydration to be accomplished with the temperature of the drying agent (heated air) at no more than 40 °C.

The form of the drying chamber provides resonant amplification and equal distribution of ultrasonic vibrations radiating from both sides of the disk at the

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surface of the drying material, which is placed on trays (Khmelev *et al.*, 2008; 2009a). The directions of ultrasonic vibration propagation and air flows in the chamber are shown in Fig. 1.

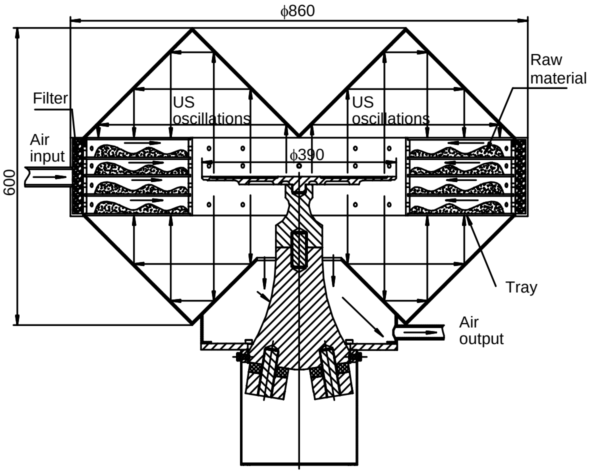
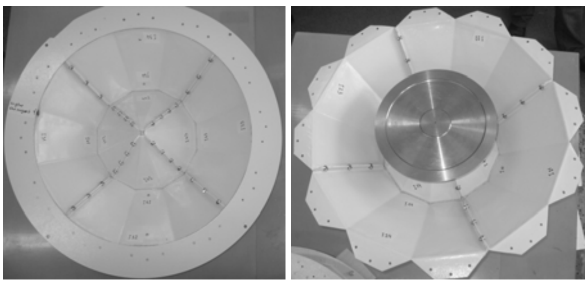



**Fig. 1 Scheme of the ultrasonic (US) dehydration system (unit: mm)**

The constructed system consists of a radiator of ultrasonic vibrations in the form of a flexural-vibrating disk connected to a piezoelectric transducer. The dimensions and the form of the transducer and disk are chosen to provide a specified frequency and radiation directivity. The piezoelectric transducer is powered by an ultrasonic power generator (not shown) (Khmelev *et al*., 2009b; 2009c).

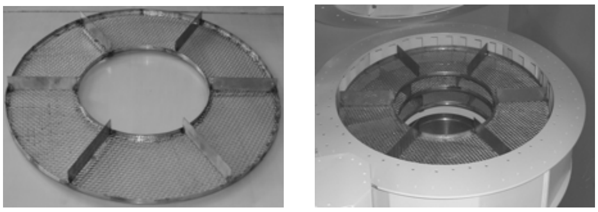
The case of the drying system has upper and lower reflectors, which are shown together with the radiator in Fig. 2. The upper reflector (cover) is removable, and is used for loading the material to be dried.



(a) (b)

**Fig. 2 Upper (a) and lower (b) reflectors of the drying chamber**

In the case of the drying system, there is a container to hold the drying material consisting of three ring-shaped trays (Fig. 3). The trays are fitted horizontally with a gap of 30 mm between each tray.



(a) (b)

**Fig. 3 Appearance of trays for drying material (a) and their placement in the drying chamber (b)**

The complete dehydration system with the ultrasonic power generator and control system is shown in Fig. 4.

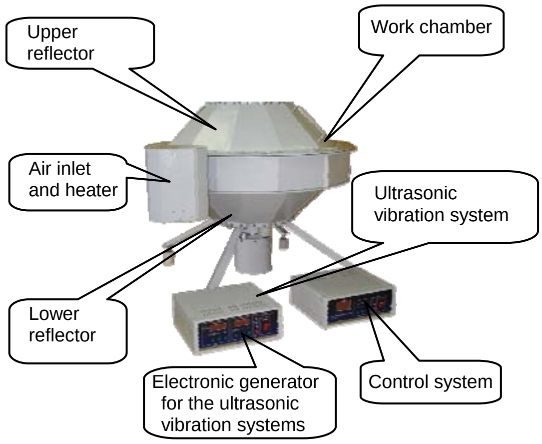



**Fig. 4 Structural diagram of the ultrasonic dehydration system**

A number of experiments were carried out to prove the efficiency of this dehydration system. First, the distribution of the intensity level of ultrasonic radiation in the drying chamber was studied. The speed and quality of drying depend on the quantity and uniformity of distribution of the ultrasonic radiation.

## 3 Determination of the intensity level of ultrasonic vibrations

To determine the intensity level of ultrasonic vibrations in the drying chamber, two types of experiments were carried out:

1. Measurement of the intensity level of vibrations was conducted with the upper reflector (cover)

of the drying chamber removed at different distances from the radiator.

2. Measurement of the intensity level of vibrations was conducted in the closed volume with the upper cover in place. Because the drying chamber was made according to calculated sizes, a standing wave mode in the volume of the drying chamber must be provided.

A specialized sound level meter (Khmelev *et al.*, 2006) with an extended frequency range (up to 30 kHz) and extended amplitude range (up to 153 dB) was used to do the measurements. Fig. 5 shows diagrams of the intensity level distribution of ultrasonic vibration in the direction of the radiator axis in the first case.

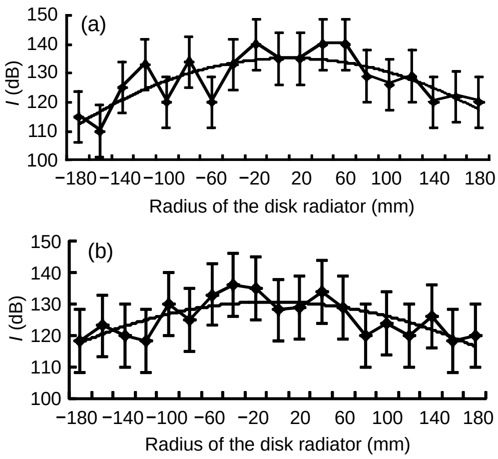



**Fig. 5 Distribution of the intensity levels (*I*) of ultrasonic vibrations over the surface of the disk radiator**
(a) At a distance of 250 mm from the radiator; (b) At a distance of 700 mm from the radiator

It is evident that the application of the lower reflector of the drying chamber helps to generate vibrations. As a result of reflected radiation from the backside of the disk, the diameter of the high-intensity acoustic field is more than doubled that of the disk radiator. The intensity level of the ultrasonic field formed by reflected vibrations corresponds approximately to the intensity level of the initial acoustic field which is radiated by the front side of the disk.

Fluctuations in the magnitude of the intensity level from the mean value can be explained by the location of the lower radiator near the radiation zone of the backside of the disk radiator, which is known to have a highly irregular acoustic field. This fact can be proved by obtaining measurements of the intensity level of the acoustic field at a distance of 700 mm from the disk radiator surface, which can be described as a zone of the far field. The results of the measurements indicated smaller fluctuations in the ultrasonic field (Fig. 5b).

The situation changes when the intensity levels are measured in the closed volume of the drying chamber (with the upper reflector in place). The results of measurements obtained in this case are shown in Fig. 6.

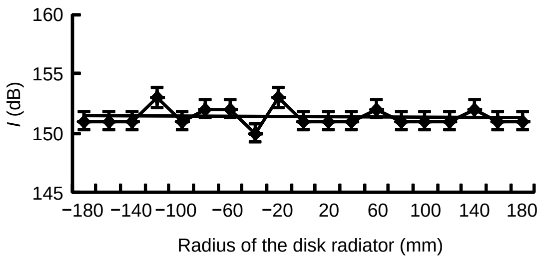



**Fig. 6 Distribution of the intensity levels (*I*) of ultrasonic vibrations in the closed volume of the drying chamber**

It is evident that in the closed volume of the drying chamber a practically uniform acoustic field was generated. Thus, the designed drying chamber provides an even distribution of ultrasonic vibrations with an intensity level of 150 dB (this is achieved due to the mode of standing wave), which is sufficient for an ultrasonic dehydration process. Electric power consumed by the electronic generator does not exceed 150 W.

Our investigations confirmed the efficiency of the developed disk radiator and the optimal design of the drying chamber. Further research was devoted to determining the optimum modes during the ultrasonic dehydration process.

## 4 Ultrasonic drying efficiency

During the experiments, the varied parameters were the feed rate of the drying agent in the chamber volume, the temperature of the drying agent, and the type (carrot, ginseng, and textile), form, and location of samples in the drying chamber.

The efficiency of the dehydration process was determined by the residual moisture content of the sample and the speed of its drying (the amount of moisture removed in g/s referred to as the sample mass).

The residual moisture content of the drying samples was defined as

$$\mu = \frac{m_{\text{cur}}}{m_{\text{ini}}} \times 100\%, \tag{1}$$

where $m_{\text{ini}}$ and $m_{\text{cur}}$ are the initial and current values of the sample mass.

The masses of the samples were measured by weighing them on laboratory scales with an accuracy of up to 0.1 g.

The speed of drying was defined as

$$\omega = \frac{m_{\text{start}} - m_{\text{after}}}{t_{\text{exp}} m_{\text{ini}}} \times 100\%, \tag{2}$$

where $m_{\text{start}}$ is the mass of the samples measured before the drying cycle, $m_{\text{after}}$ is the mass of the samples measured after the drying cycle, and $t_{\text{exp}}$ is the duration of the drying cycle.

All experiments were divided into three main stages: (1) definition of the intensification rate of the process of dehydration by ultrasonic vibration; (2) definition of the uniformity of the drying material in different parts of the drying chamber; (3) definition of the drying efficiency of different materials.

### 4.1 Intensification rate of the process of dehydration by ultrasonic vibration

First, the role of high-intensity ultrasonic vibrations during the drying process was evaluated (Shalunov *et al.*, 2009). Cotton fabric in the form of 20 mm×150 mm strips was used as a drying material. Their total initial (moist) weight was 3 kg.

In Fig. 7, comparative results on the speed of drying with or without the influence of ultrasonic vibrations are presented. The duration of each experiment was 30 min. The speed of drying is the average during the experiment. It can be concluded that ultrasonic vibrations speed up drying from 2 to 6 g/min for 1 kg of the drying material at 40 °C. At the same time, the drying speed and the efficiency of ultrasonic drying increase with increasing temperature and flow rate of the drying agent (from 0.25 to 0.5 m$^3$/min).

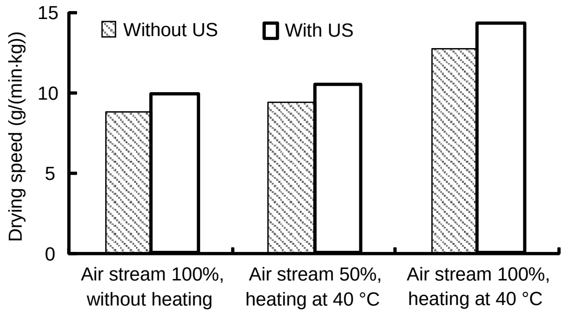



**Fig. 7 Efficiency of dehydration process by ultrasonic (US) vibrations**

This can be explained as follows. Under the influence of continuous heated air on the drying material (the duration of the experiment was 30 min), the speed of moisture removal from the material surface exceeds the speed of its supply from inner layers of the material. This promotes the formation of a layer with low moisture content on the material surface, which prevents effective moisture removal.

Under the influence of ultrasonic vibrations, moisture moves from the inner layers of the material to surface layers, which is sufficient to affect its removal. This helps to avoid the formation of a dry surface layer and considerably increases the efficiency of drying.

Thus, the results of our experiments show the appropriateness of the application of ultrasonic vibrations combined with the supply of a heated drying agent.

### 4.2 Uniformity of the material drying

The efficiency of drying was evaluated for each segment of a tray. The results were averaged and compared with those obtained from other trays. We used samples from the previous experiments as the drying material. The duration of the experiments was 30 min.

Fig. 8 shows the residual moisture of the tested samples from the segments of upper, middle, and lower trays. The drying of samples in segments within one tray is even. The value of residual moisture between the segments does not vary by more than 3%. This confirms the generation of uniform temperature and ultrasonic fields in the drying chamber.

Fig. 9a shows the comparative results of residual moisture averaged for each tray. Higher residual

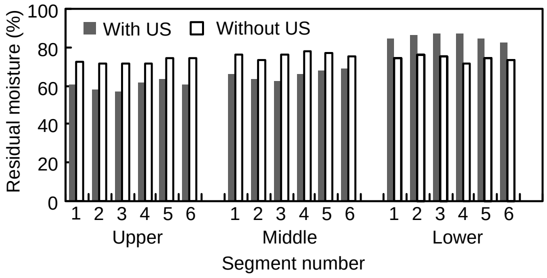



**Fig. 8  Residual moisture of sample in different segments of trays**

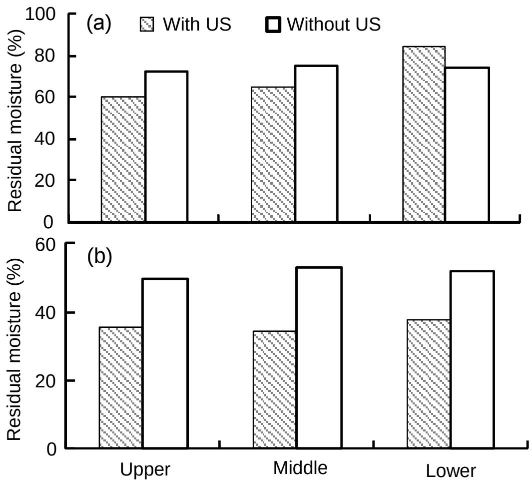



**Fig. 9  Distribution of residual moisture of samples in the trays**

(a) Drying of 30 min; (b) Drying of 60 min

moisture in the samples on the lower tray during the drying with ultrasonic vibrations can be explained by the high efficiency of ultrasonic vibrations, which leads to spraying of moisture from the surface of samples. The samples were initially very wet (more than 160% of the mass of dry material). Sprayed moisture can be carried by the supply system of the drying agent and settle on the material located in the lower tray.

This is confirmed by results of drying of 60 min as shown in Fig. 9b, which demonstrates the high uniformity of drying in the chamber if there is no cavity spraying of moisture from the surface. It allows evaluation of the efficiency of ultrasonic drying of samples located on single trays and of the total mass of the drying material.

## 4.3  Drying efficiency of different materials

Finally, we determined the drying efficiency of products with different types, shapes, and sizes. Carrots cut into disks (28 mm×5 mm) and into bars (35 mm×5 mm×3 mm), whole ginseng root, and ginseng roots cut into disks (5 mm) were used as experimental samples. The total weight of all dryable samples of each type was 3 kg. Each sample was exposed to four combinations of energy deposition (Table 1). The appearance of experimental samples before drying is shown in Fig. 10.

**Table 1  Scheme of the experiment**

| Exp. No. | Supply of drying agent (0.5 $m^3$/min) | Heat of drying agent (40 ºC, 1000 W) | Ultrasonic influence (150 W) |
|---|---|---|---|
| 1 | + | − | − |
| 2 | + | − | + |
| 3 | + | + | − |
| 4 | + | + | + |

+: the type of energy deposition was used; −: the type of energy deposition wasn't used

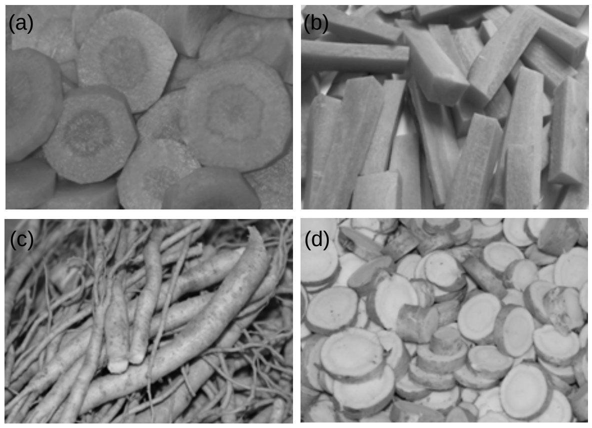



**Fig. 10  Photos of materials before drying**

(a) Carrots cut into disks; (b) Carrots cut into bars; (c) Whole ginseng root; (d) Ginseng root cut into disks

Fig. 11 shows the dependence of the residual moisture content of carrot on the duration of drying. As in the case of cotton fabric, the data showed that in both cases an effect from ultrasonic vibrations was apparent only when heated drying air was supplied. This effect can remove as much as 50 g of moisture from 1 kg of mass of dryable material. The effect of ultrasonic radiation increases with the duration of drying. This means that during the drying of samples by heated air alone, there is a layer with low moisture content, which prevents effective moisture removal from the surface. The thickness of the layer with low moisture content increases over time, making further

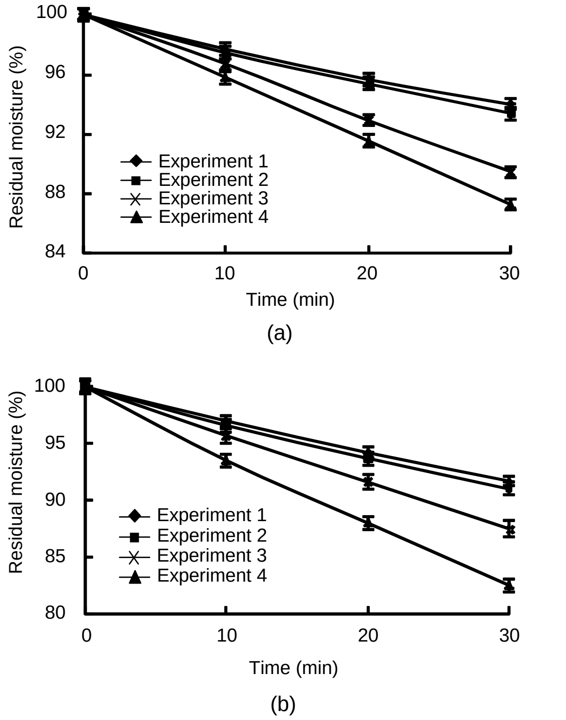



**Fig. 11 Dependence of residual moisture content of carrot on the duration of drying**
(a) Carrots cut into disks; (b) Carrots cut into bars

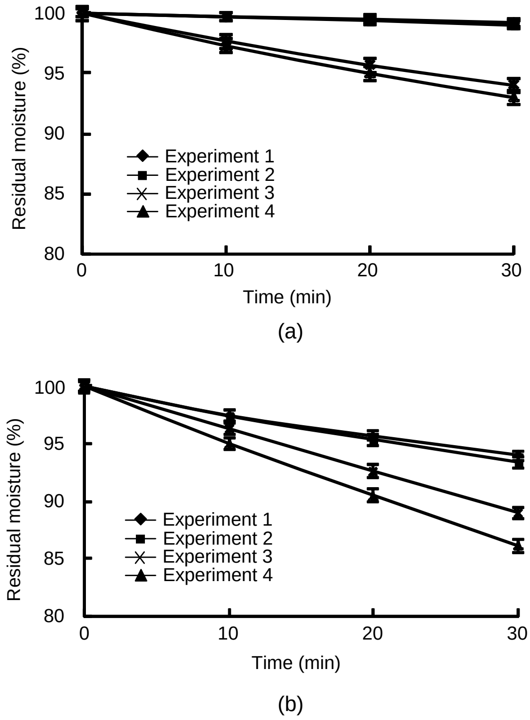



**Fig. 12 Dependence of residual moisture content of ginseng on the duration of drying**
(a) Whole ginseng root; (b) Ginseng root cut into disks

moisture removal difficult. With ultrasonic vibrations, this does not occur. During the drying of samples with a capillary-porous structure, ultrasonic vibrations help to transfer moisture from the inner layers of the drying material to the surface, where it can be removed with the help of the drying agent. The effect obtained from the application of ultrasonic vibrations is very noticeable (Fig. 11b).

Fig. 12 shows the dependence of residual moisture content of ginseng on the duration of drying. Fig. 12a indicates the low efficiency of drying of whole ginseng root. The increase in drying process efficiency made by ultrasonic vibrations is negligible. Heated air does not change the situation. The results can be explained by the presence of peel on the ginseng root surface, which blocks moisture evaporation and prevents moisture emission from the inner layers of the root to the surface under the influence of ultrasonic vibrations. It minimizes the effect of the use of ultrasound. In contrast, with ginseng root cut into disks, ultrasonic vibrations have a substantial influence on the effectiveness of the drying process, achieving additional moisture removal of up to 29 g from 1 kg of sample mass (Fig. 12b).

These results demonstrate that the main factor influencing ultrasonic drying is the effect of moisture moving through capillaries to the surface, which is made possible by the acoustic field.

To summarize all the results and to compare the effectiveness of ultrasonic drying, the residual moisture content of all samples is shown in Fig. 13.

Fig. 13 shows that the influence of ultrasonic vibrations is the most effective when the air supply is heated up to 40 °C. An effect of ultrasonic vibrations without a supply of heated air is not rational. A decrease of 30% in residual moisture content claimed by Gallego-Juarez *et al.* (2007) and de la Fuente *et al.* (2004) from the contact effect of ultrasonic vibrations without heated air can be explained by cavity removal in the form of liquid. Moreover, the technology of contact ultrasonic drying cannot be used in cases where it is necessary to dry different enzymes, proteins, and other materials, which cannot be influenced by mechanical contact.

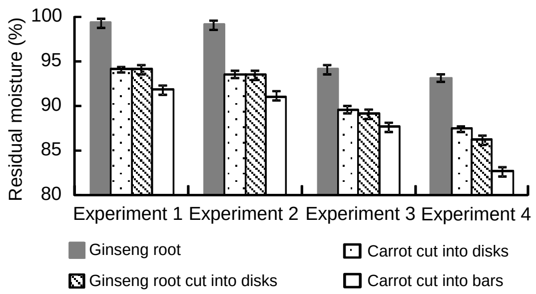



**Fig. 13 Residual moisture of different samples**

In this study, an increase of 4% in the effectiveness resulting from the use of ultrasonic vibrations and heated air in comparison with drying by heated air alone is lower than the increase of 12% reported by de la Fuente *et al.* (2004) and Gallego-Juarez *et al.* (2007). This can be explained that Gallego-Juarez *et al.* (2007) used ultrasonic drying in contact mode under static pressure. Influence of ultrasonic vibrations reported by Gallego-Juarez *et al.* (2007) led to not only drying samples but also to an increase in the effectiveness of compression, i.e., pressing of moisture from drying samples. It is evident that this factor is of great importance in this case.

## 5 Estimation of the energy efficiency of the ultrasonic drying system

On the basis of the results obtained, the energy efficiency of the ultrasonic drying was estimated, and the consumed electric power was analyzed. The source data were as follows: electric power consumed by the electronic generator was 150 W, the electric power consumed by the electric heater of the drying agent was 1000 W, the duration of the drying cycle was 30 min, and the cost of the supply of drying agent was not taken into account. The process efficiency $\xi$ was estimated as

$$\xi = \frac{P \cdot t}{m}, \quad (3)$$

where $P$ is the consumed electric power, $t$ is the duration of the drying cycle, and $m$ is the mass of moisture removed.

Table 2 confirms the high efficiency of the application of ultrasonic vibration to the drying of different products. It helps to reduce power inputs by 20% while the duration of drying remains unchanged and the residual moisture content of the product decreases. Obtained values of energy efficiency demonstrate the need for further improvement of radiators in order to increase the power of generated vibrations. This will speed up the drying process and allow lower power inputs to be used for drying. The developed ultrasonic dehydration system has the performance specifications given in Table 3.

**Table 3 Performance specifications of ultrasonic dehydration system**

| Parameter | Value |
|---|---|
| Power supply (V) | 220 |
| Maximum load of the drying chamber (kg) | 10 |
| Power consumed by the ultrasonic generator (W) | 150 |
| Power consumed by the heater (W) | 1000 |
| Dimensions of the drying chamber, diameter, height (mm) | 860×600 |
| Maximum heating temperature of drying agent (°C) | 40 |
| Consumption of drying agent ($m^3$/min) | 0.5 |
| Frequency of ultrasonic vibrations (kHz) | 24 |

## 6 Conclusions

In this study, an ultrasonic dehydration system was developed, providing effective drying of thermolabile materials and products at a temperature of the drying agent of no more than 40 °C with the

**Table 2 Comparison of energy efficiency**

| Type of influence | Mass of removed moisture (g) | | | | | MRE (%) | Type of influence | Energy efficiency (W·min/g) | | | | | MRE (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | | 1 | 2 | 3 | 4 | 5 | |
| SDA | 750 | 315 | 375 | 180 | 330 | 1.1 | SDA | 40 | 95 | 80 | 167 | 90 | 1.5 |
| SDA-US | 1050 | 381 | 525 | 210 | 417 | 1.2 | SDA-US | 33 | 90 | 66 | 164 | 83 | 1.5 |
| US | 300 | 66 | 150 | 30 | 87 | 0.9 | US | 15 | 68 | 30 | 150 | 51 | 1.5 |

1: Cotton fabric; 2: Carrot cut into disks; 3: Carrot cut into bars; 4: Whole ginseng root; 5: Ginseng root cut into disks. SDA: supply of heated drying agent; US: ultrasonic influence; SDA-US: supply of heated drying agent and ultrasonic influence; MRE: relative error simultaneous application of high-intensity ultrasonic vibrations. High intensification of the drying process by ultrasonic vibrations (an increase of up to 50 g for 1 kg of drying material) helps to lower the temperature of the drying agent without loss of quality or speed. This is especially important for industries in which heating of drying material is prohibited or undesirable.

The high efficiency of the drying process is due to the use of a disk radiator in the construction of the dehydration system, which forms an ultrasonic field with an intensity level of no less than 130 dB, and due to the resonant volume of the drying chamber amplifying the intensity level up to 150 dB.

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