UDC 66.084.8
DOI: 10.52957/27821900_2021_02_178

LABORATORY AND SEMI-INDUSTRIAL ULTRASONIC DRYERS

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Keywords: *acoustic pressure level, drying, dispersing, ultrasonic dryer, drying curve*

The paper deals with the process of convective drying of materials using potatoes as an example at 60 °C. To intensify the drying process, non-contact ultrasound with different acoustic pressure levels in the range 130-175 dB was applied. Ultrasonic drying at175 dB reduced the drying time of potatoes by 57.1%to compare with the convection drying. We observed a step change of drying speed during the initial phase (at high moisture content) at acoustic pressure level of 150 dB. It allows to predict the activation of dehydration mechanism without a phase change, i.e., by dispersing moisture from the surface of the material to be dried. To verify the dispersion mechanism, we captured water droplets with the immersion liquid slide. The number of dispersed droplets decreased along with decreasing of material moisture content. The optimum of acoustic pressure level is 160-165 dB range in terms of reduced drying time and energy consumption. Two drum-type dryer designs have been proposed to increase the mass of material being dried at the same time. Ultrasonic drying (160-165 dB) of diced potatoes by these units was 45-47% faster than convection drying.

Introduction

Drying is an energy-intensive and time-consuming process in many industries. Therefore, the development of new technologies and apparatuses reducing energy costs and drying time is very important. Scientists are searching for ways to intensify the various materials drying processes. The issue of controlling the process temperature in order to maintain the properties of the material to be dried is a crucial one [1-5]. A promising way to reduce the temperature while increasing the drying rate is to use combined thermal and acoustic influence [6-9].

Drying time can be reduced by combining acoustic waves with convective drying with the help of the following physical mechanisms: Rayleigh - type acoustic streaming, near obstacles microstreaming, mechanical action or 'sponge effect', thermal action, near the surface pressure variation, etc. [10].

These mechanisms appear with a certain sound pressure level (at least 130 dB) [10]. The drying process is almost the same as for convection drying in the case of lower acoustic pressure level vibrations. The optimum frequency is determined by the characteristics of the material, the structure of its micropores and the size of the individual particles. In recent years, the ultrasonic frequency range (20 to 35 kHz) has been preferred because it is safer for humans (compared to audible acoustic vibrations).

Ultrasonic impact on the material to be dried can be contact (ultrasonic transducer - material to be dried) or non-contact (ultrasonic transducer - air - material to be dried).

By the contact method, the vibrating surface of the ultrasonic transducer directly affects the material to be dried, ensuring maximum transmission of acoustic energy when the contact is close. Researchers have shown decreasing of drying time in combination with convection drying compared with convection drying: in [11] 63% drying of mushrooms, in [12] - 47.7% drying of potatoes, in [2] - 80% drying of carrots.

However, according to some authors [13], the high efficiency can be attributed to the considerable thermal effect created by the mechanical friction between the material to be dried and the transducer surface, which is often an undesirable result. The main disadvantage of contact ultrasound effect is a large total area of the ultrasound transducer demand to send the ultrasonic energy directly into the material. Also, the material to be dried should have maximum contact area with the radiator. This is not technically possible when implementing the drying process on an industrial scale.

These disadvantages require the use of ultras through an intermediate gas medium. [2, 14] show that non-contact ultrasound intensifies the drying process; however, the results are not as good as contact exposure. The main reasons are the low ultrasonic transducer efficiency and the reflection of vibrations at the "transducer - air - drying material".

Effective transducers by the authors in the form of flexibly vibrating plates or disks [15-17] can reduce the drying time of pasta products by 24-26% [18], cypress-tea and textile materials by 30% [19-20]. However, these results were obtained at a sound exposure level of 150 dB or less. The ultrasonic drying process up to 175 dB has practically not been studied. The various authors have chosen the material to be dried and its size randomly, which makes it impossible to compare the results objectively.

By Dalton's law, the process of evaporation of moisture from a free surface is under isothermal conditions:

$$\frac{dm}{d\tau} = KS\frac{P_0 - P_\infty}{P_б}, \tag{1}$$

where m is mass of liquid evaporated; τ - time; K is coefficient taking into account hydrodynamic conditions at surface; S is surface area of material evaporation; P_0 is saturated vapor pressure at material surface (at surface temperature); P_∞ is partial pressure of vapor in ambient; P_b is barometric pressure in ambient.

Reducing the size of the material leads to increasing of the evaporation surface area and the drying speed. The size of the material to be dried was chosen to be a multiple of the wavelength of the ultrasonic exposure in air to provide better conditions for the vibrations to penetrate the material and excite its vibrations at the ultrasonic frequency.

Study

Ultrasonic drying was combined with convection drying in a SHINI SHD25 drying plant with integrating ultrasonic disk radiator [21] (Fig. 1).

Fig. 1. The exterior of a drying unit with ultrasonic dryer

To determine the acoustic pressure level on the pallet with the material to be dried we use the Ecophysics-110A/Engineer-110A noise level meter. Measurements were taken at the acoustic axis of the transmitter and at a distance of 70 mm from the axis at different generator settings (Table 1).

Table 1. Acoustic pressure levels at 180 mm from the disc radiator

Distance from disc axis, mm	Electronic generator installation level from maximum power, %						
	40	50	60	70	80	90	100
	Acoustic pressure level *L*, dB						
0	132	141	152	162	166	171	176
70	128	140	149	159	164	168	174
Average value	**130**	**140.5**	**150.5**	**160.5**	**165**	**169.5**	**175**

We chose potatoes as the most common vegetable in the Russian Federation. During the experiments the weight of potatoes was (250±0.1) g, with a cube size of 15×15×15±1 mm. Drying agent temperature t = (60±1) °C. Speed of the drying agent is (0,5±0,03) m/s. The air humidity is (55±5)%.

The moisture content of the potatoes during the drying process was determined by the formula

$$w^0 = \frac{W}{G_c}, \tag{2}$$

where W is the mass of moisture, G_c is the mass of dry potatoes.

The drying speed was determined by numerical differentiation:

$$\frac{dw^0}{d\tau} = -\frac{w_{i+1}^0 - w_i^0}{\tau_{i+1} - \tau_i}, \tag{3}$$

where w_i^0 - the moisture content of the potatoes at time τ_i; w_{i+1}^0 - the moisture content at time τ_{i+1}.

The potatoes were weighed every 15 minutes with an accuracy of ±0.1 g. During the drying process the weight of potatoes was reduced by 4 times, i.e., until a moisture content of (0.14±0.01) kg/kg was reached.

The drying curves for potatoes are shown in Fig. 2.

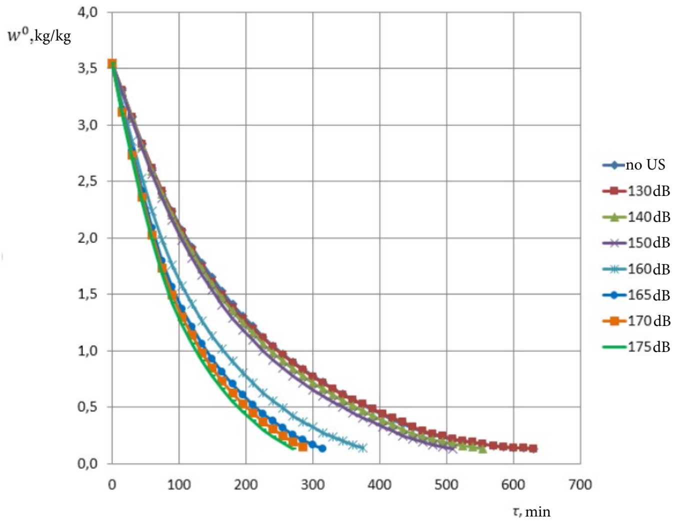


Fig. 2. Potato drying curves at different acoustic pressure levels

The drying time of the control (convection drying) experiment was 630 min. The combined effect of heated air and 175 dB ultrasonic vibrations resulted in a drying time reduction of 57.1%. (Table 2).

Table 2. Drying time for potatoes to a moisture content of 0.14 kg/kg at different acoustic pressure levels

	Acoustic pressure level L, dB							
	0	130	140	150	160	165	170	175
Drying time, min	630	630	555	510	375	315	285	270
Drying efficiency, %	0	0	12.7	19	40.5	50	54.8	57.1

The drying efficiency was determined by the reduction in process time as compared to the control experiment. There is no increase in drying efficiency at a acoustic pressure level of 130 dB. It confirms that low-intensity ultrasound has no effect. A further increase in acoustic pressure level up to 150 dB leads to a proportional reduction of drying time. There is a jump in drying efficiency at acoustic pressure levels above 150 dB.

A constant drying speed can be detected in the drying curves up to 150 dB (Fig. 3). There is no period of constant drying speed at levels of 160 dB and above.

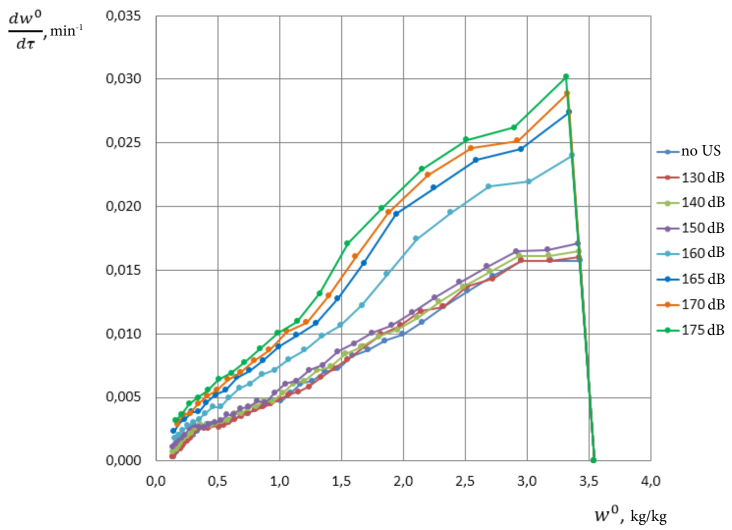


Fig. 3. Drying speed curves for potatoes at different acoustic pressure levels

For a more thorough analysis of the effect of acoustic pressure level on process efficiency, the drying rate was averaged for two equal periods of high moisture content (moisture content greater than 1.78 average) and low moisture content (<1.78). The resulting dependencies of the average drying speed on the acoustic pressure level are shown in Fig. 4.

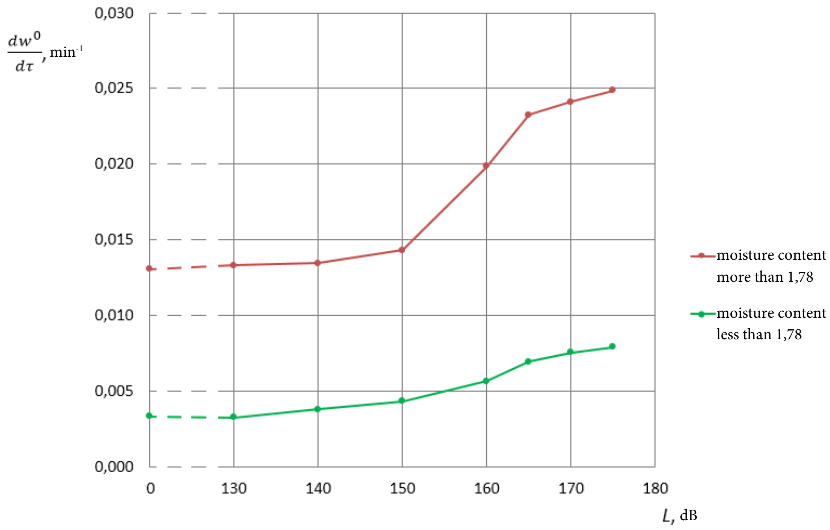
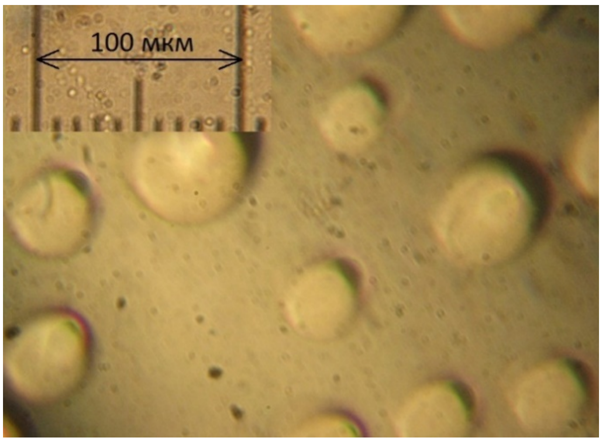


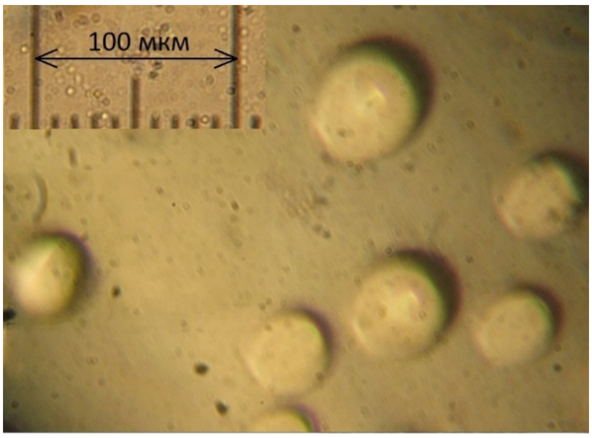
Fig. 4. Dependence of average potato drying speed on acoustic pressure level at t = 60° C

At high moisture content (> 1.78) in the 150-165 dB range, the drying acceleration is $600 \cdot 10^{-6}$ (m·dB)$^{-1}$. When the acoustic pressure level is further increased, the acceleration is less and is $160 \cdot 10^{-6}$ (min·dB)$^{-1}$. An increase in the drying speed in the range 150–165 dB may be caused by moisture dispersion from the outer surface of the material.

Dispersing mechanism was carried out as follows. A slide with immersion liquid was placed under the mesh tray with the material to be dried, the dispersed water particles were deposited on it. The slide was then photographed through a Mikmed-6 (Lomo) microscope at 400x magnification (Fig. 5). The drying was carried out at a acoustic pressure level of 160 dB.



a



b

Fig. 5. Photos of the dispersed liquid at different potato moisture contents: *a* - 3.5 kg/kg; *b* - 2.2 kg/kg

There is separating and precipitating on the slide with a high moisture content (the presence of moisture on the surface) of the dried potato. As the moisture content decreases, the number of droplets decreases. There are no droplets if the moisture content is less than 1 kg/kg.

The dispersed droplets are evaporated in the volume of the drying unit if the temperature of the drying agent is high enough. However, at room temperature and sufficient drying agent rate, moisture can be carried away as droplets from the plant. It will reduce the energy consumed by the drying plant.

The proportional increase of acoustic pressure level is accompanied by a non-linear increase of the ultrasound machine power consumption. A non-contact ultrasonic level of 160-165 dB should be used for energy-efficient use of ultrasonic vibrations of the drying process.

Two drum-type dryers have been developed in combination with convection drying for semi-industrial applications of ultrasonic drying.

The horizontal drum-type dryer consists of a cylindrical body 1 and cylindrical surfaces 2 and 3, arranged coaxially with the body. There are axial perforations 5 and blades 4 in each surface, on the inner part of the body there are also blades (Fig. 6). An ultrasonic disc emitter is in front of the end wall of the dryer. Drying is by convection with ultrasonic impact of 160-165 dB. The drum rotates, draws the material to be dried 6 by the blades and transfers it from one volume of the dryer to the other through the axial perforations. This way the bulk material is always in thin layers, providing effective exposure to the drying agent and ultrasonic vibrations.

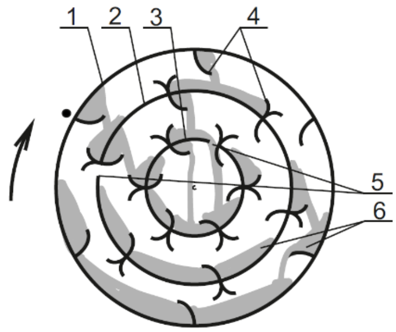


Fig. 6. Horizontal dryer cross-section

The drying speed curves for potatoes are shown in Fig. 7. Drying was carried out with the same drying agent parameters as in the laboratory setting at a sound pressure level of 160–165 dB. The mass of the potatoes was 6 kg.

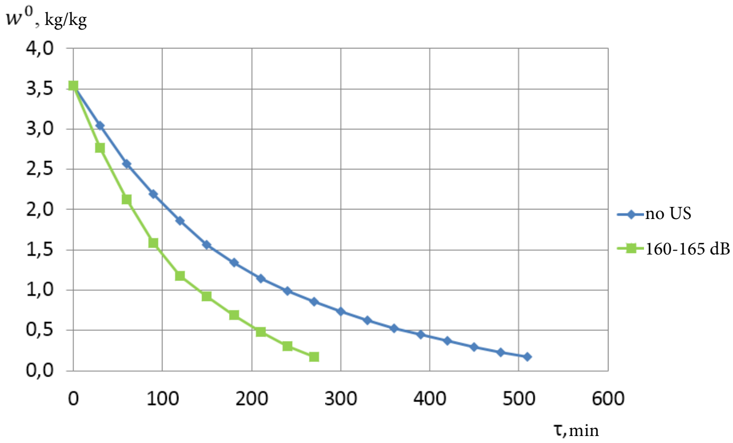


Fig. 7. Horizontal dryer drying curves

The convection drying time was 510 min, by the additional ultrasonic effect was 270 min.

The vertical drum dryer (Fig. 8) consists of a cylindrical drum 2 with a diameter *D*. There is inside spiral tray 3 with a decreasing inner diameter towards the top of the dryer. The dried material 1 is transferred from bottom to top by tilting and vibrating the drum by vibration drive 4, after the product is dumped down into tray 7. The ultrasonic transducer 5 affects the material by direct action (during material dumping) or by reflection from the reflectors 6 and the dryer body (when the material is on the spiral tray).

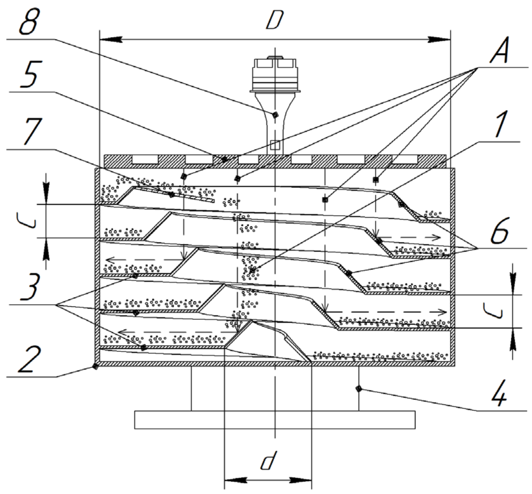


Fig. 8. Vertical-type ultrasonic drum dryer design

The convection drying time was 540 min, by the additional ultrasonic effect was 300 min (Fig. 9). The mass of the potatoes was 6 kg.

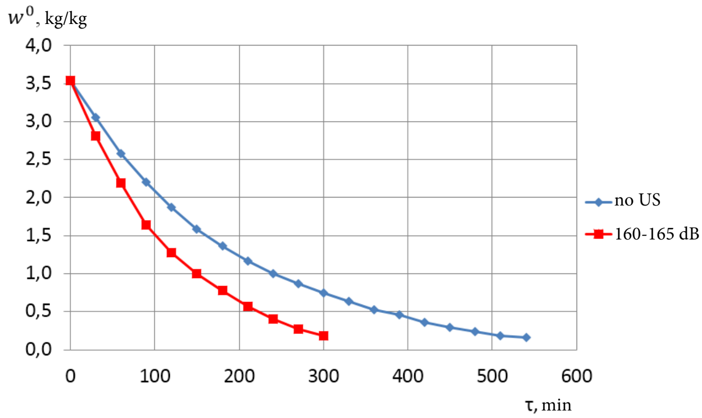


Fig. 9. Vertical drum potato drying curves

The developed drum-type dryers have reduced the drying time by 44-47% compared to convection drying.

Conclusions

The research shows the efficiency of ultrasonic non-contact influence application for intensification of materials drying on the example of potatoes. It is shown:

the maximum reduction in drying time is 57.1% at acoustic pressure level of 175 dB;

the optimum effect of ultrasound on the drying process of materials in a stationary thin layer is achieved at an acoustic affect level 160–165 dB;

for practical application of ultrasonic drying in identified optimum levels of ultrasonic pressure conditions, the designs of drying plants implementing continuous transferring (pouring) of the dried material in horizontal and vertical drums have been proposed and developed;

the drying time in the developed dryers is reduced by 44–47% to compare with the convection drying;

This makes the use of ultrasound for drying thermolabile materials extremely promising.

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Received 04.05.2021
Accepted 08.06.2021