Influence of ultrasonic vibrations on the temperature of the dried material

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Abstract. The article presents studies on ultrasonic drying of agglomerated cork plug samples. It was revealed that the ultrasonic standing wave mode provides an increase in the drying speed compared to the traveling wave mode. It has also been shown that the energy of ultrasonic vibrations is absorbed in the cork material. In this case, the temperature inside the sample is 10 °C higher than on its surface. This helps to increase the rate of moisture release from the internal layers to the surface of the sample due to thermal diffusion.

1 Introduction

Drying is the most important stage of many chemical technological processes. In traditional (convective) drying, after moisture evaporates from the surface, the drying speed slows down, since the remaining moisture has to overcome the resistance of the material structure when moving to the surface.

The total moisture flow inside material j can be found using the formula [1]:

$$j=\alpha_m\rho_0\,\nabla U-\alpha_m^T\rho_0\,\nabla T-K_p\,\nabla P \quad (1)$$

where α_m is the moisture diffusion coefficient; ∇U is humidity gradient; α_m^T is thermal diffusion coefficient; ρ_0 is dry body density; ∇T is temperature gradient; K_p is molar transfer coefficient under the influence of pressure gradient; ∇P is pressure gradient.

The main driving force ensuring the movement of moisture to the surface is the first term, which takes into account the moisture gradient. The second term of the equation in convective drying prevents the release of moisture, since the temperature on the surface is higher than inside the material. The third term of the equation at temperatures less than 100 °C and atmospheric pressure is practically equal to zero.

Intensification of the drying process, in particular, can be achieved by changing the direction of the temperature gradient. This can be achieved, for example, by microwave drying [2, 3]. However, thermolabile materials (many food products, medicines, etc.) do not allow overheating in general, as well as local extreme temperature increases.

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Therefore, there is a need to develop combined drying methods based on “soft” energy effects. This effect can be caused by ultrasonic (US) vibrations [4, 5] with a sound pressure level of at least 150 dB.

According to researchers [6, 7], ultrasonic exposure of dried materials does not lead to significant heating. However, the search for ultrasonic exposure modes and materials for drying can change the thermal effect of ultrasonic drying. As part of this work, a study was carried out on the influence of the standing wave mode during ultrasonic drying on the drying kinetics.

2 Materials and methods

To conduct research to determine the temperature of the dried material during ultrasonic drying, a drying stand for small volumes was developed (Fig. 1).

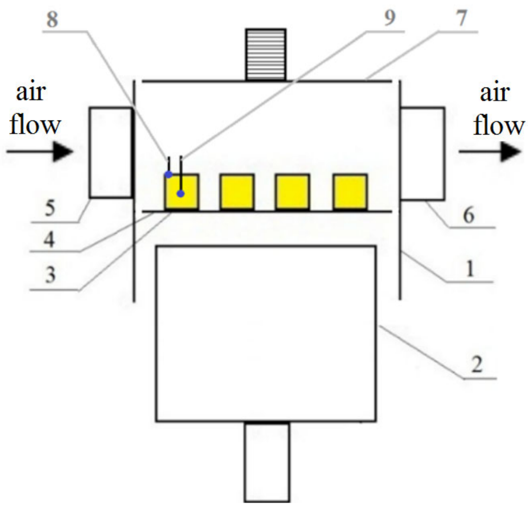

Fig. 1. Structure of the ultrasonic drying bench. 1 - drying stand body; 2 - ultrasonic radiator; 3 - mesh tray; 4 - dried material; 5 - inlet pipe; 6 - outlet pipe; 7 - upper movable plane of the stand; 8 - thermocouple on the sample surface; 9 - thermocouple in the sample center.

The experimental stand consists of a housing 1, an ultrasonic emitter 2, a mesh tray 3 with samples of the dried material 4, an upper plane 7, which can move parallel to the walls of the housing. Through the inlet 5 and outlet 6 nozzles, air flow through the drying chamber is ensured. Thermocouples 8 and 9 provide temperature measurements on the surface and in the center of the sample.

By moving the upper movable plane of the drying stand, it is possible to obtain different modes of ultrasonic vibrations. The standing wave mode can be obtained by ensuring the distance between the emitter and the upper plane of the drying stand is a multiple of half the wavelength of ultrasonic vibrations in the air, i.e. resonant size. The mode was set experimentally using a steam generator. For example, a standing ultrasonic wave forms stationary layers of water vapor, which are easily determined visually (Fig. 2).

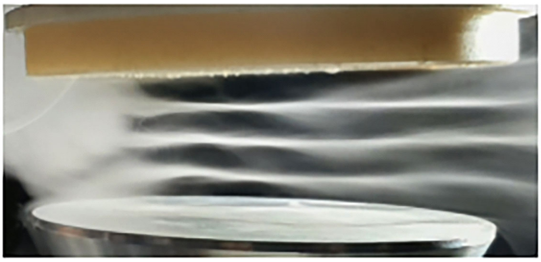

Fig. 2. Ultrasonic standing wave visualized by water vapor.

Ultrasonic vibrations with a frequency of 22 kHz are generated by the ZAGS-0.1/22-O "Nightingale" device [8] (Fig. 3).

Fig. 3. Photo of the ultrasound device "Nightingale".

A photograph of the experimental stand is shown in Fig. 4.

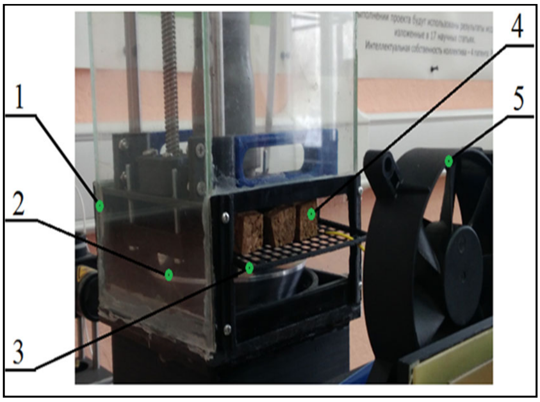

Fig. 4. Photo of ultrasonic drying stand. 1 – body; 2 – ultrasonic emitter; 3 – mesh tray; 4 – cortical plug; 5 – fan.

An agglomerated cork plug was chosen as the dried capillary-porous material. Cork cork can be easily moistened and dried dozens of times without changing its properties.

The work [9] presents studies showing that it is advisable to carry out ultrasonic drying for samples with dimensions equal to the wavelength of ultrasonic vibrations in air, therefore the cubes of cork material had a size of 15x15x15 mm. The mass of the cork plug samples was measured on a Pocket scale MH-100 scale (China) with an accuracy of 0.01 g. The air flow velocity was measured with a digital anemometer UT363S from UNI-T. The temperature of the cork samples was measured using two APPA 99ll multimeters (APPA Technology Corporation, Taiwan). To measure the temperature on the surface of the sample, the hot junction of a K-type thermocouple was placed into the cork material at a depth of 1 mm; to measure the temperature inside the sample, the second thermocouple was buried 7 mm into the cork material.

To perform the drying experiments, the cork samples were first hydrated by complete immersion in water for 24 h. In this case, the samples reached a moisture content value of 0.2±0.005 kg/kg. Then a series of three experiments was carried out:

1) convective drying at temperature T = 25 °C and air flow speed 1.5 m/s;
2) Ultrasonic exposure with a non-resonant height dimension of the drying chamber together with convective drying at a temperature of T = 25 °C and an air flow speed of 1.5 m/s;
3) Ultrasonic influence with a resonant size of the height of the drying chamber together with convective drying at a temperature of T = 25 °C and an air flow speed of 1.5 m/s.

All experiments lasted 70 minutes, with samples weighed and temperatures monitored every 10 minutes.

3 Results and discussion

Drying curves and temperature dependences on the surface and inside the cork material under different ultrasonic drying modes are shown in Fig. 5. The moisture content of the cork material is shown on the left axis, and the temperature of the cork material under different drying modes is shown on the right axis.

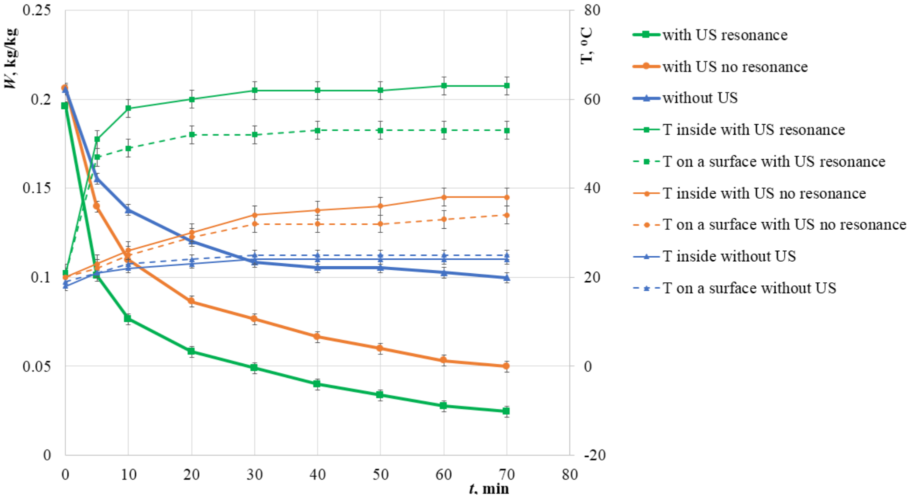

Fig. 5. Drying curves and temperature dependences for different drying modes.

From the drying curves of the cork plug to a moisture content of 0.1 kg/kg, the duration of the process can be determined: convective drying - 70 minutes, ultrasound with a non-resonant size - 14 minutes, ultrasound with a resonant size - 5 minutes.

During convective drying, the temperature on the surface of the sample after 20 minutes reached the temperature of the drying agent T = 25 °C; inside the sample, the temperature was approximately 1 °C less throughout the entire drying process. In the traveling wave mode (non-resonant distance), the temperature on the surface of the cork sample first increases rapidly, then gradually approaches a value of 34 °C. However, the temperature inside the material is on average 4 °C higher starting from the 30th minute of the drying process. Also, the temperature inside the sample is higher than on the surface at the resonant distance of the height of the drying chamber. At the same time, in the center of the cube the temperature reaches 63 °C, while on the surface it is 53 °C, i.e. the difference is about 10 °C.

Due to the higher temperature inside the dried sample compared to the temperature on the surface during ultrasonic drying, the thermal diffusion gradient is directed towards the surface of the material, which accelerates the release of moisture to the surface.

Experimental studies of ultrasonic drying have shown that with a pore diameter of a capillary-porous body (cork material) of about 20 microns, ultrasonic vibrations penetrate into the material despite the rather long wavelength of ultrasonic vibrations in air (about 15 mm). The energy of ultrasonic vibrations is absorbed, heating the samples up to a temperature of 63 °C.

4 Conclusion

As a result of experimental studies on ultrasonic drying of capillary-porous material - cortical agglomerated plug, it was revealed that:

1) Ultrasonic exposure in the standing wave mode provides a higher temperature of the dried samples, a larger temperature difference inside and on the surface of the samples and, as a consequence, intensification of the drying process compared to the traveling wave mode;
2) cork material is characterized by a higher temperature inside the samples than on the surface, which makes it possible to direct the thermal diffusion gradient to the surface of the cork samples and thereby accelerate the release of moisture in the second drying period;
3) Ultrasonic vibrations penetrate into the material samples and are converted into heat.

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