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ACOUSTO-CONVECTIVE DRYING OF PINE NUTS

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An experimental investigation of the process of drying pine nut grains has been carried out by three methods: acousto-convective, thermoconvective, and thermal. A qualitative and a quantitative comparison of the dynamics of the processes of moisture extraction from the nut grains for the considered drying methods have been made. To elucidate the mechanism of moisture extraction from the pine nut grains, we carried out a separate investigation of the process of drying the nut shell and the kernel. The obtained experimental data on the acousto-convective drying of nuts are well described by the relaxation model, the data on the thermoconvective drying are well described by the bilinear law, and the data on the thermal drying are well described by the combined method consisting of three time steps characterized by different kinetic regimes of drying.

Keywords: *acousto-convective drying, thermoconvective drying, thermal drying, pine nut drying, drying of the pine nut shell, relaxation model.*

Introduction. Pine nuts are widely used in the medical, cosmetic, and food industries. The useful properties of the pine nut are due to the content in its kernels of a large number of vitamins, amino acids, and macro- and microelements [1]. As is known, the gathering of pine nuts take place in difficult-to reach regions in a stiff deadline in the fall [2]. As a result of this, harvested pine nuts have a high moisture content. To preserve the nourishing and medicinal properties of pine nuts, it is necessary to decrease the moisture content in the raw nut to 15%. Traditionally this is done by using the method of thermal drying, as a result of which large amounts of energy and time are expended, and the kernel loses its useful properties.

In the present work, it is proposed to use, instead of thermal treatment for drying pine nuts, the acousto-convective method based on the Hartmann effect [3]. The chief advantage of this method is the absence of heating of the material being dried, which permits saving the useful properties of the pine nut. Earlier in [4–6] the acousto-convective effect on materials representing a homogeneous solid was investigated. The distinguishing feature of the present work is the fact that we investigate a porous body having a complex structure, since the pine nut consists of several shells protecting the kernel (Fig. 1) [1, 2]. In the case where the nut is in a cone on a cedar branch, these shells are indispensable for protecting and nourishing the kernel and its development. After harvesting, the protective multilayer shell of the nut impedes the removal of moisture from the grains, which in turn promotes rapid mold growth. To retard this process, a part of the nuts is subjected to freezing, due to which the moisture content in the grains can increase significantly as compared to the initial value. We used for our experiments prefrozen grains of the Siberian cedar harvested in 2012.

Determination of the Initial Moisture Content. To perform experiments on acousto-convective drying in the acousto-convective drier (ACD) of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences, we prepared five portions of pine nuts of approximately equal mass. The initial moisture content of the nut was determined preliminarily. To this end, one of the five portions was subjected to drying in an SNVS-4,3.4,3.4,9/3U24n vacuum drying cabinet at a temperature of $120^{o}C$ for seven hours. The initial mass of the dried portion was 96.75 g. The mass of the absolutely dry portion of nuts was 63.54 g. The mass of the control portions of samples was measured with the help of a laboratory AND EK 610i balance with a maximum possible weight of 600 g and a discreetness of 0.01 g. Knowing the mass of the absolute dry portion of pine nuts, we find the initial absolute moisture content of the other portions of pine nuts. By the absolute moisture content is meant the ratio of the moisture mass to the mass of the dry material

$$W = \frac{m - m_0}{m_0} \cdot 100\% .$$

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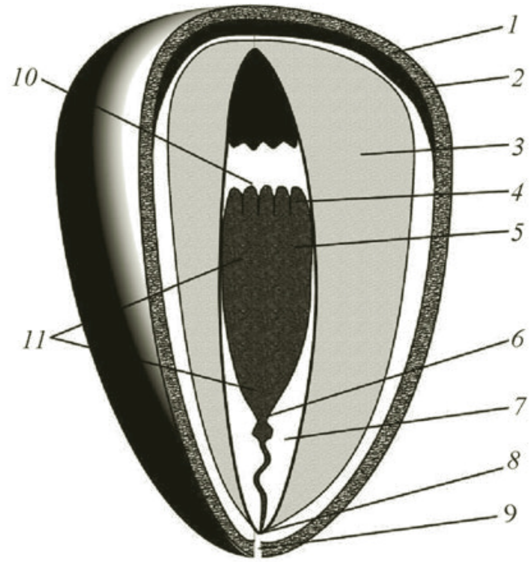


Fig. 1. Structure of the pine nut grain: 1) shell; 2) endospermal film; 3) endosperm; 4) seed lobes; 5) germ; 6) radicle; 7) suspensor; 8) nucleus remnant; 9) micropyle; 10) budlet; 11) subseedlobe knee.

As a result of the investigation made, a initial moisture content of the pine nut equal to 52.27% was determined. The obtained value was taken as a reference value for the other portions of pine nuts.

Drying by the Acousto-Convective Method. The second portion of nuts was placed in a rectangular metal container of sizes 281 × 31× 28 mm having a rigid framework, and its walls were covered with a metal screen. The container with nuts was periodically placed in the working section of the ACD. The basic diagram of the drier is presented in [7]. The ACD was started without the material to be dried. The working pressure in the prechamber was registered by a standard pressure gauge and was equal to P_0 = 6.2 atm. In the process of the experiment in the prechamber the pressure was held constant with the help of a precision control value. The parameters of the formed acousto-convective flow at the inlet to the working section of the ACD were recorded with the help of an LKh-610 acoustic pressure cell. With the help of an L-Card E-440 analog-digital converter, the readings of the LKh-610 pressure cell were transferred to the PowerGraph program installed on a PC. The initial $P'(t)$ and the processed $P'(f)$ signals are given in Fig. 2a. From Fig. 2a it is seen that the acousto-convective flow formed in the working section has a frequency f = 272 Hz and an intensity I = 183.8 dB. With the help of an IVTM-7 MK-S moisture and temperature meter, the thermal parameters in the channel of the working section of the ACD were registered. The flow temperature was 12.4^{o}C, the moisture content was 5.9%, the content of water vapor was 0.6 g/m^3, and the dew point temperature was –21.3^{o}C. The prepared container with pine nuts was placed in the operating ACD and fixed in the working section of the drier with a screw. The amplitude-frequency characteristic of the flow were thereby somewhat changed (Fig. 2b). As is seen from Fig. 2b, the frequency decreased to f = 265 Hz and the intensity decreased to I = 183.6 dB, i.e., it remained practically unchanged. The container with nuts was removed from the drier at three-minute intervals and weighed on the balance. The dynamics of the change in the absolute moisturecontent of pine nuts is shown in Fig. 3, where it is seen that in 76 min the moisture content of the packed bed of pine nuts has decreased to 27.86%. A characteristic feature of the presented curve is its concave form with a monotone decrease.

Acousto-Convective Drying of the Pine Nut Shell and Kernel. Since the pine nut has a complex structure, it seems interesting to estimate the influence of the nut shell on the process of acousto-convective drying of the grain. To do this, we sampled the third portion of pine nuts with a total mass of 250.60 g. Then the nuts from the portion under consideration were cracked and divided into two fractions: shells and kernels. The shell mass was 107.40 g, and the weight of the kernels was 134.81 g; thus, 8.39 g was lost in the form of small crumbs of the shell and excess moisture in the gap between the shell and the kernel of the nut. The nut shells and the kernels were placed alternately in the same rectangular container as the whole pine nuts and dried in the ACD.

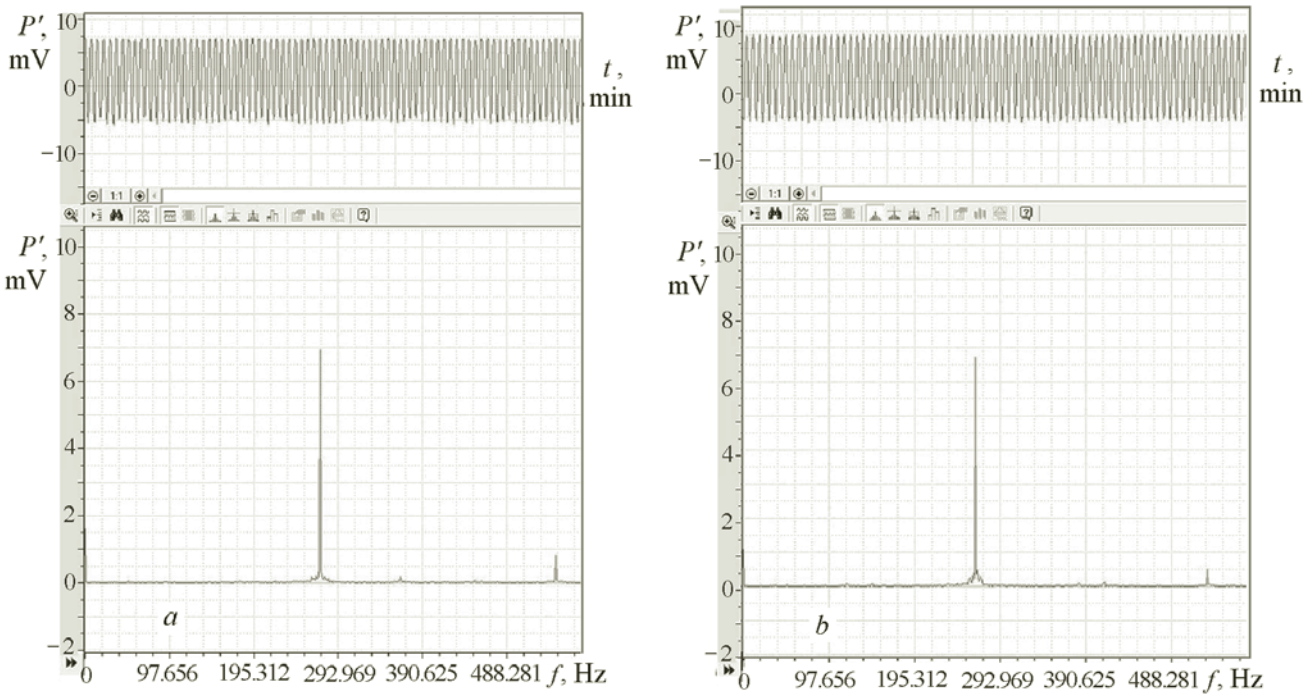


Fig. 2. Amplitude-frequency characteristic of the acousto-convective flow in the working section of the ACD: a) without the material to be dried; b) with the container placed inside.

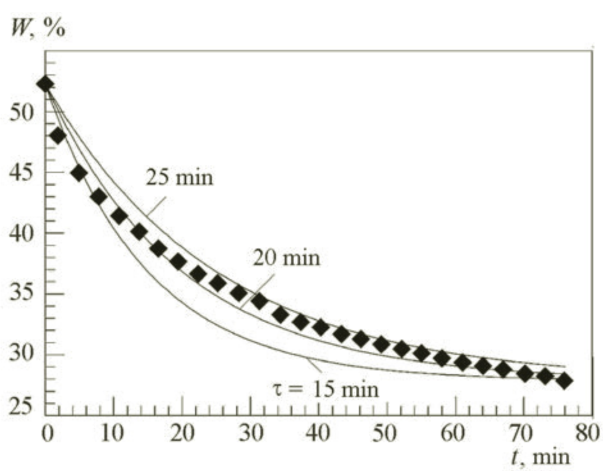
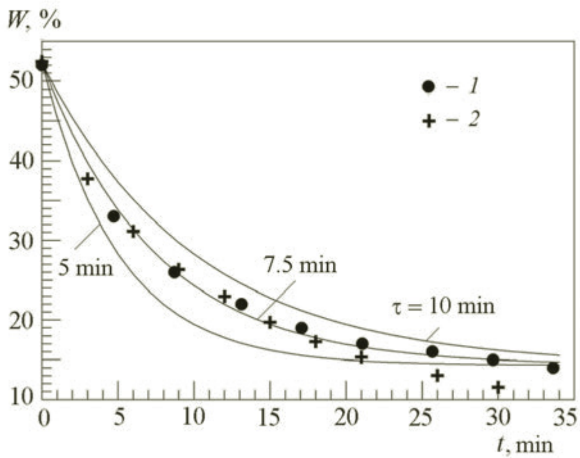


Fig. 3. Dynamics of moisture extraction from the grains of pine nuts in the process of acousto-convective drying (dots show the experiment, lines show the numerical calculation).

Figure 4 shows the dynamics of the change in the absolute moisture content of the shell in the process of acousto-convective drying. It is worth mentioning that in 33.5 min the moisture content of the shells decreased considerably and reached 14%. In the drying process, the shells remain uniformly distributed throughout the volume of the container, as in the case of drying the pine nuts grains. For comparison, Fig. 4 gives experimental data on the acousto-convective drying of granular silica gel from [6]. As is seen, the initial moisture content for both materials is practically the same, and the dynamics



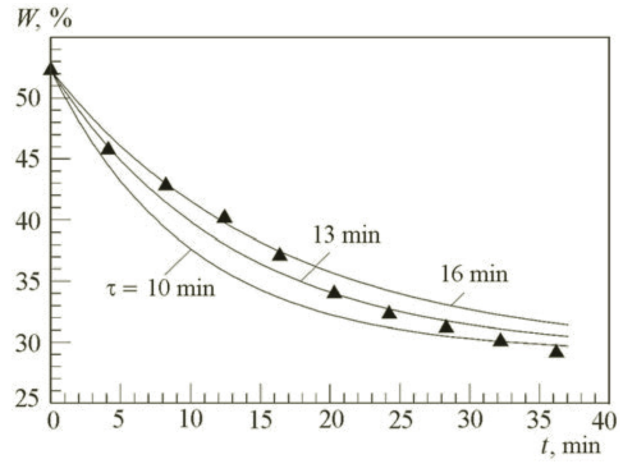


Fig. 4. Change with time in the moisture content in the shell of pine nuts (1) and in the silica gel grains (2) in the process of acousto-convective drying (dots show the experiment, lines show the numerical calculation).

Fig. 5. Kinetics of moisture extraction from the kernels of pine nuts in the process of acousto-convective drying (dots show the experiment, lines show the numerical calculation).

of the decrease in the moisture content in a drying time of up to 20 min is described by one and the same dependence with a characteristic relaxation time equal to 7.5 min. The subsequent difference at times longer than 25 min is due to the destruction of the silica gel grains. Therefore, it may be stated that the process of moisture extraction from the pine nut shells and from the silica gel grains has a similar physical mechanism.

Figure 5 shows the dependence of the absolute moisture content of the kernel on the drying time in the ACD. In 35.25 min the moisture content decreased to 29.13%. Thus, the drying process of the kernel of the pine nut is much slower than of its shell. A distinguishing feature of kernel drying is the fact that the moisture extracted from the kernel has characteristic oily properties. As a result, the kernels of the nuts uniformly distributed in the container at the beginning of the experiment begin to adhere to one another and togroup together near the end on the side opposite to the incident acousto-convective flow.

Thermoconvective Drying. To estimate the rate of moisture extraction from the packed bed of pine nut grains in the process of drying by the thermoconvective method, we constructed an experimental stand. It was based on a heat flow source formed by an ÉTV-4.5/220 T thermal gun with a heating power of 4.5 kW. For the heating element, a ribbed tube electrical heater was used. The thermofan throughput was 450 m^3/h. In performing experiments, the thermal gun was turned on well in advance in order to create a permanent heat flow in an outlet circular cross section of diameter 145 mm. Given data on the thermofan throughput and the diameter of the outlet cross section, we determined the heat flow velocity at the outlet from the thermal gun, which was equal to 7.6 m/s. The heat flow formed had a temperature of 120^{o}C and a moisture content of 0.1% or 0.9 g/m^3, and the dew point temperature was –25.6^{o}C.

The fourth control portion of pine nuts was placed in a heat- and moisture-proof container made from nonsterile medical gauze bandage of size 50 × 100 mm. The constructed container with pine nuts had the form of a cylinder with the following characteristic sizes: its length was 270 mm and its diameter was 35 mm. A cylindrical sample was placed in the center of the formed heat flow, one end of the sample lying immediately adjacent to the outlet cross section of the flow from the thermal gun. Thus, the thermoconvective flow not only blew on the surface of the cylindrical packed bed but also penetrated into its depth. After the given time interval the sample was removed from the thermoconvective flow, taken off the fastenings, and weighed.

Figure 6 shows the dynamics of the change in the moisture content of the dried cylindrical packed bed of pine nut grains in the process of drying by the thermoconvective method. The total drying time was 1 h 28 min 39 s, and in this time the moisture content of the sample decreased to 29.21%. The moisture content of the control portion decreases linearly, i.e., the acousto-convective and the thermoconvective drying mechanisms have a radically different dynamics of moisture extraction.

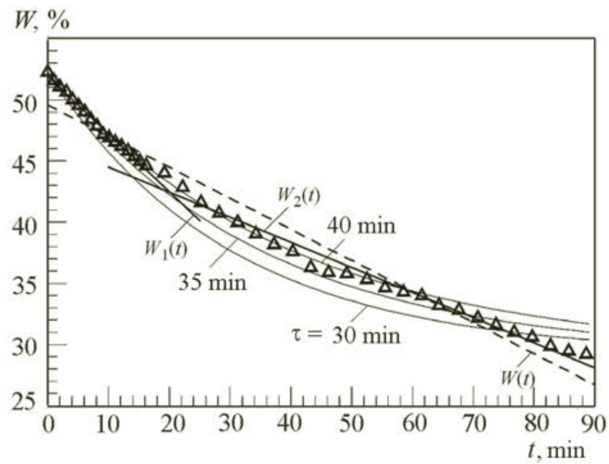


Fig. 6. Thermoconvective drying dynamics of pine nuts (dots show the experiment, lines show the numerical calculation).

Let us analyze the obtained time dependence of the moisture content in the sample. The presented experimental data can arbitrarily be subdivided into two sets: the first set pertains to the drying time interval from the beginning of the experiment to 15 min, and the second set pertains to the period from 15 min to the end of the experiment. In the first time interval, there is a rapid decrease in the moisture content due to the moisture evaporation from the surface of the grains and the shell. The second interval is characterized by an about twice lower rate of moisture extraction. This deceleration can be attributed to the fact that moisture is extracted from the inner part of the grain, and for this to take place, the moisture must seep through the nut shell. Let us obtain the law for the linear dependence in each time interval. To this end, let us find the coefficients for the sought linear dependence with the use of the least square technique. As a result, in the first interval we obtain the dependence in the form

$$W_1(t) = 51.958 - 0.473t .$$

In the second interval, the dependence will have the form

$$W_2(t) = 46.544 - 0.205t .$$

The obtained linear dependences are given in Fig. 6. It is seen that both curves in their time intervals describe well the experimental data. Let us estimate the degree of compliance of the experimental curves with the linear law in each time interval. To do this, let us determine the linear correlation coefficient. Calculations have shown that in the first interval it takes on a value of $r_1 = -0.9963$, and in the second interval its value is $r_2 = -0.9886$. It is worth noticing that the coefficients on t in the obtained dependences responsible for the rate of moisture extraction differ by a factor of 2.3. For comparison, Fig. 6 gives also the equation of the linear dependence for the entire time interval, which has the form

$$W(t) = 49.568 - 0.254t .$$

As would be expected, the degree of compliance of the experimental points with the linear law for the entire interval has a worse value equal to –0.9830.

Thermal Drying. The next step was to carry out an experiment aimed at elucidating the influence of the convective component on the process of thermoconvective drying. To this end, we placed the fifth portion of pine nuts in a glass jar (in order to exclude any air flow) and put the jar in an SNOL 67/350 drying cabinet (220 V, 2 kW) preheated to 100°C. The temperature in the drying cabinet was held constant automatically. At about 5-min intervals the control portion of nuts was removed from the drying cabinet and its mass was measured.

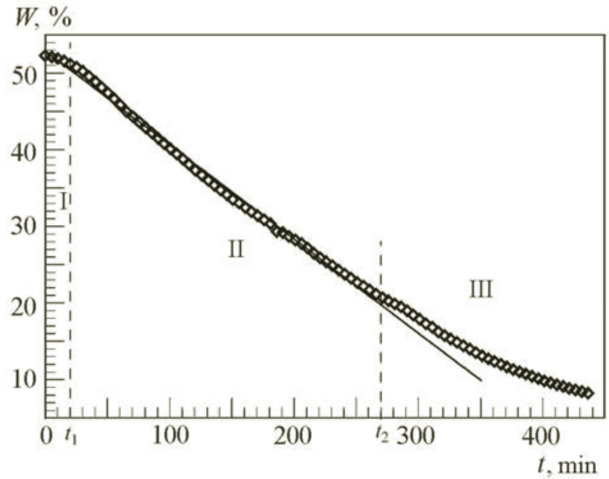


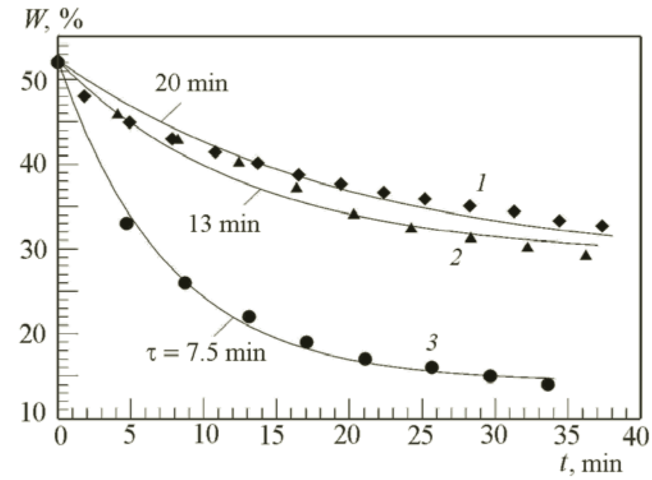
Fig. 7. Change with time in the moisture content of the pine nut in the process of ther mal drying.

Figure 7 shows the dynamics of moisture loss with time in nuts during thermal drying. The total duration of drying in the experiment was 7 h 16 min 21 s. During this time the moisture content decreased to 8.25%. The plot shows the existence of three regions. Region I is characterized by a slow loss of moisture in the sample, which is due to the heating of the surface of the pine nut grain and its content. It is worth mentioning that at the 20th min of heating, i.e., at the end of the first time step, resinous components were exuded from the nut shells. Thus, it may be assumed that in 20 min all elements (Fig. 1) of the pine nut grains are heated. In Region II, intense extraction of moisture was observed, and this process proceeded practically by the linear law. This region ends in the middle of the fifth hour of drying. To analyze the change in the moisture content, we found the form of the linear dependence. To this end, we used the least square technique and obtained coefficients for the sought linear dependence. As a result, we represent the dependence in the form

$$W = 52.926 - 0.123t \ .$$

This dependence is shown in Fig. 7 for time values from 0 to 350 min. It is seen that the obtained linear dependence in the interval from t_1 to t_2 completely coincides with the experimental data. Let us make a quantitative estimate of the degree of compliance of the experimental points with the linear law. To this end, let us determine the linear correlation coefficient. The calculations made have shown that in the interval from t_1 to t_2 the linear correlation coefficient r takes on avalue of –0.9977, i.e., an inverse (negative) correlation is observed. In Region III, the process of moisture extraction slows down and the graph goes to an asymptotic. An analogous dynamics with three characteristic regions was also observed earlier in the case of microwave drying in [6]. A characteristic difference of the method of thermal drying from the method of microwave drying is an increase in the length of the characteristic regions. Note that the thermal regime is the closest to the widely used methods of drying pine nut grains.

Results and Discussion. Let us consider in detail and compare the obtained results on the acousto-convective drying of the pine nuts kernel, shell, and grains. Figure 8 shows the results on drying the grains of pine nuts and their shells and kernels by an acousto-convective flow during the first 40 min. As would be expected, the first to reach the required moisture value of 15% is the nut shell. This can be explained by the fact that the shell has a clearly defined porous structure and a small thickness of the order of 0.5 mm. The moisture content of the kernel of the nut decreases to 30.62% by the 30th minute, which is almost twice that in the shell (15.11%). This fact is due, firstly, to the lower porosity of the kernel compared to the shell and, secondly, to the large characteristic sizes of the kernel measuring 10.75 mm in length, and the longitudinal section with the maximum area has an oblate form with a width of 7.1 mm and a height of 4.8 mm. Thirdly, in the process of drying, moisture with oily properties is exuded from the kernel, as a result of which the kernels cling together forming a single rather densely packed lump, i.e., the grains uniformly distributed in the container when poured into it throng together near one of the ends located down the stream, the other half of the container remaining practically empty.



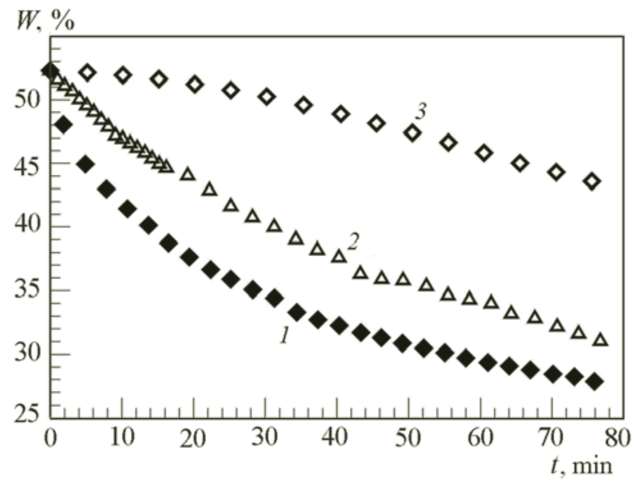


Fig. 8. Comparison between the rates of moisture extraction from the pine nut (1), the shell (3), and the kernel (2) in the process of drying in the ACD (dots show the experiment, lines show the numerical calculation).

Fig. 9. Comparison between the dynamics of moisture extraction from the pine nut for different drying methods: 1) acousto-convective, 2) thermoconvective, 3) thermal drying.

As would be expected, moisture is most slowly extracted from whole grains, since it has been established that their moisture decreased to only 34.07%. However, from Fig. 8 it is seen that from the first instants of time to the 10th min of drying, the dynamics of moisture extraction from whole grains is slightly higher than from kernels. This can be explained by the fact that in the beginning there occurs intense drying of the surface of the grain, i.e., of the nut shell, and, as was shown before, shell drying is the fastest process. At the next instants of time the picture changes and the dynamics of moisture extraction from the grains becomes slower. This would be expected since there is continual flow of moisture from the space between the inner surface of the shell and the kernel to the shell of the whole nut, but at the same time this air space retards the process of moisture extraction from the grain.

Thus, in the mechanism of acousto-convective drying of pine nut grains we can distinguish three stages proceeding simultaneously. The first stage is due to the drying of the nut shell. The second stage is connected with the decrease in the moisture content in the space between the shell and the kernel. At the third stage, drying of the kernel occurs, and the moisture extracted from the grain flows into the space between the grain shell and the kernel and is then carried through the shell into the incident acousto-convective flow.

Let us compare the above-considered drying methods: the methods of acousto-convective, thermoconvective, and thermal drying. To this end, Fig. 9 brings together the dependences of the change in the moisture content of grains on the drying time in the time interval from the beginning of the process of extraction to 1 h 15 min. The first notable thing is the functional form of the moisture curve. In the case of acousto-convective drying, the moisture can be described by a convex monotonically decreasing function, in thermoconvectivedrying it can be described by a bilinear function, and in the case of thermal drying the moisture content can be described by a concave monotonically decreasing function.

Let us consider the dynamic parameters of drying. As is seen from Fig. 9, decreasing the moisture content of nuts to:

1) 45% requires less than 5 min for the acousto-convective regime, 15 min for the thermoconvective regime, and 1 h 5 min for the thermal regime;

2) 40% required 14 min in the case of acousto-convective drying, 30 min in the case of thermoconvective drying, and 1 h 43 min in the case of thermal drying;

3) 35% took 30 min in the case of acousto-convective drying, 54 min in the case of thermoconvective drying, and 2 h 20 min in the case of thermal drying;

4) 30% required 57 min for the acousto-convective regime, 1 h 20 min for the thermoconvective regime, and 3 h 4 min for the thermal regime.

Consequently, acousto-convective drying for about 30 min saves us twice the time in the case of thermoconvective drying and about five times that in the thermal regime. The rate of drying by the thermoconvective method is higher by a factor of about 3 than the rate of drying by the thermal method. Thus, we have obtained a quantitative relation between the drier capacities in the cases of using the acousto-convective, the thermoconvective, and the thermal regimes of drying pine nut grains.

Mathematical Treatment of the Experimental Data. To describe the experimental curves of moisture extraction, one uses the relaxation equation in the linear form

$$\frac{dW}{dt} = \frac{W_f - W}{\tau} \tag{1}$$

with the corresponding initial conditions

$$t = 0, \quad W = W_0 \; . \tag{2}$$

Equation (1) has a solution in the form

$$W = W_f + \left(W_0 - W_f\right) e^{-(t/\tau)} \; . \tag{3}$$

Figures (3)–(5) present the results of numerical calculations obtained with the use of expression (3) at various values of τ. To obtain a satisfactory description of the dynamics of moisture extraction from the pine nut grains by the method of acousto-convective drying, we use τ equal to 20 min.

To obtain a good description of the change in the moisture content in the pine nut shell in the case of acousto-convective drying with the help of Eq. (3), the τ value should be taken equal to 7.5 min.

Figure 5 shows that a satisfactory agreement between the experimental points and the theoretical dependence for pine nut kernels is observed at τ = 13 min. The obtained relaxation times for the pine nut grains are comparable to the values obtained in [5] for acousto-convective drying of sorbents for characteristic relaxation times from 18 to 50.6 min. The relaxation time for the pine nut shell found by us is close to the values obtained by the authors of [8] in modeling a porous body in the form of an assemblage of microcapillaries, here τ = 9 min for capillaries oriented along the incident flow and τ = 6 min for capillaries located perpendicular to the flow.

We made an attempt to describe by the proposed model the results of experiments on the dynamics of moisture extraction from pine nut grains in the process of thermoconvective drying. The thin solid lines in Fig. 6 show the results of calculations performed at τ values equal to 30, 35, and 40 min. As is seen, the results of calculations at τ = 40 min describe the experimental data well only up to 60 min. Note that the obtained value of the characteristic relaxation time for thermoconvective drying is twice longer than the time determined for the acousto-convective regime of drying.

Figure 8 gives the calculated dependences at the τ values obtained earlier for each material dried by the acousto-convective method. As is seen from the presented results, the determined times (7.5, 13, and 20 min) follow a certain pattern. It can be given in the form of the proportionality coefficient k, where $k = 1$, $k = 2$, and $k = 3$ correspond to 7.5, 13, and 20 min, respectively. Thus, a pattern is observed according to which the rate of moisture extraction from the pine nut shell is twice that of the rate of extraction from kernels and three times that of the rate of moisture extraction from whole grains.

CONCLUSIONS

1. We have determined experimentally the dynamics of the moisture extraction from the pine nut grains, shell, and kernels in the thermoconvective, acousto-convective, and thermal regimes of drying.

2. For the acousto-convective regime:

– we have analyzed the contribution of the pine nut grains (shell and kernels) to the drying dynamics of the nut;

– we noted a similarity between the dynamics of moisture extraction from the pine nut grains and from the grains of granular silica gel, which is most likely due to similar physical processes proceeding in the dried materials.

3. It has been shown that in the process of thermoconvective drying a bilinear law of moisture extraction is observed, and in the thermal regime a combined law consisting of three time steps characterized by different regimes of drying kinetics takes place.

4. The obtained quantitative characteristics of the dynamics of moisture extraction from the pine nut grains for the three methods of drying have shown that the efficiency of drying by the acousto-convective method is twice higher than that of the thermoconvective method and five times higher than the efficiency of drying in the thermal regime.

5. To describe the dynamics of moisture extraction, we propose a simple relaxation model describing well the experimental data on acousto-convective drying of pine nut grains, shells, and kernels.

The authors acknowledge the participation of M. V. Bondarenko, NGAVT student, in performing experiments on drying pine nuts.

NOTATION

f, frequency, Hz; I, intensity of acoustic vibrations, dB; k, proportionality coefficient, arbitrary units; m and m_0, mass of the moist and the absolutely dry sample, g; P_0, prechamber pressure, atm; P', pulsation component of pressure, mV; r, linear correlation coefficient, arbitrary units; t, time, min; W, moisture content, %; τ, relaxation time of moisture extraction, min. Subscripts: 0, initial value; f, finite value.

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