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Dynamics of acousto-convective drying of sunflower cake compared with drying by a traditional thermo-convective method

Aleksandr A. Zhilin[a,b,*], Aleksandr V. Fedorov[a], and Dmitry M. Grebenshchikov[c]

[a] Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya Str. 4/1, Novosibirsk 630090, Russian Federation

[b] Siberian State University of Water Transport, Schetinkina Str. 33, Novosibirsk 630099, Russian Federation

[c] Ltd 'N-8-T TECHNOLOGIC' Koshurnikova Str. 61/2, Novosibirsk 630090, Russian Federation

* e-mail: lab20@itam.nsc.ru

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Abstract: The article is devoted to the dynamics of sunflower cake drying in a fundamentally new acousto-convective way. Unlike the traditional (thermo-convective) method, the method proposed allows extracting moisture from porous materials without supplying heat to the sample. Thermo-vacuum drying helped to determine the absolute and relative initial moisture for the analysed samples of the sunflower cake, which equaled 313.1% and 75.8%, respectively. The kinetic curves for drying by thermo- and acousto-convective methods were obtained and analysed. A study of the acousto-convective drying of sunflower cake showed that the rate of moisture extraction depended on the resonating frequency, while there is an optimal mode in which drying proceeds from two to three times more intensively. In thermo-convective drying of sunflower cake, increasing the temperature of the drying stream twice (from 74.2°C to 127°C) reduces the duration of drying to a final absolute humidity of 40% three times. Comparing the thermo-convective and acousto-convective drying methods showed that twice as much moisture was removed from the samples dried by the (ACDP) with a flow frequency of 790 Hz and at room temperature for a 30-minute interval as with thermal convective drying with a working flow temperature of 127°C. The relaxation mathematical model used to describe the drying phenomenon and the experimental data for sunflower cake drying allows obtaining the quantitative parameters characterizing different modes and methods of drying the samples under study. The article analyses a discrete drying regime that contributes to increasing the efficiency of the acousto-convective mode of moisture extraction.

Keywords: Acousto-convective drying, thermo-convective drying, porous materials drying, moisture extraction

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INTRODUCTION

Sunflower is an agricultural oilseed crop, which ranks third in the world in terms of production volumes following peanuts and soybeans [1]. The main product made from sunflower is sunflower oil, which is used in the food industry for cooking and foods. In addition to sunflower oil, sunflower flour is produced from sunflower as well; its nutritional properties are of great significance to humans as both a source of protein [2] and a powerful antioxidant [3]. It is also noteworthy that currently people all over the world are actively discussing ideas on transition from mineral energy sources to renewable ones, including sunflower oil. So, [4–7] deal with the study of diesel fuel production from sunflower oil.

Sunflower is the second in the world in terms of output level in production of vegetable oil from oilseeds. As part of processing sunflower seeds into sunflower oil, the feedstock passes through a number of technological stages, with some of the raw material becomes included into the final product, i.e. oil, and some part turns into waste. The sunflower oil obtained is the main commercial product that makes profit. On the other hand, waste products have to be disposed of, which leads to higher prices for the main products. One of the ways to reduce the cost of the main products is the recycling of production waste and the subsequent use of by-products in livestock breeding and agriculture. One such product is sunflower seed cake, which forms the basis of protein dishes for feeding cattle [8] and small ruminants [9].

A cake appears resultant from the subsequent processing of the sunflower meal. Obtained by processing, the product is a biological material, with relative moisture of about 80%. The high moisture content in the biological material does not allow storing it for a long time with the proper quality, which entails the loss of its useful properties. Therefore, to preserve all useful properties and characteristics of cake, the moisture content in the material must be significantly reduced. In addition, the removal of excess moisture from the product contents will considerably reduce the weight of the final material.

To drain the cake, a traditional thermo-convective approach is used [10, 11], which engages applying the hot, dried air stream to the material. This study proposes an alternative approach for cake drying, based on placing the material to be drained into a high-intensity acousto-convective flow. This technology has proved a noticeable intensification of moisture extraction from various porous biomaterials, such as meat [12], rice [13, 14], and pine nut [15] and inorganic materials, such as granular silica gel [16, 17], cellular aerated concrete [18], wood [19], etc. One of the main advantages of this technology is avoiding heating of the material to be drained, i.e. drying takes place at a room temperature [20]. In addition, the drying process is accelerated.

This work is focused on experimenting with moisture extraction from sunflower cake when drying by the acousto-convective method using a small ACDP developed by Insfitute of Theoveticol and Applied Mechanics, Siberian Branch of Russian Academy of Sciences (ITAM SB RAS) and comparing the results with ones for the thermo-convective drying method.

RESULTS AND DISCUSSION

Thermo-vacuum drying of the sunflower cake. Experiments to analyse the dynamics of heat and mass transfer in a sunflower cake require the data on the initial moisture content. To obtain them, a special study of the dried material in a vacuum oven CHBC-4,3.4,3.4,9/3U24n was carried out. Three control portions with different initial masses were prepared, which differed approximately two and four times from the initial mass of the first sample. Table 1 shows the numerical values of the initial mass of the prepared samples before placing in a vacuum drying oven.

A heating temperature of 50°C, maintained automatically throughout the experiment, was applied with the view to increasing the productivity of the vacuum drying using a temperature controller. After the target temperature was reached within the drying chamber, three prepared control portions were loaded into the vacuum drying cabinet. Then, a vacuum pump was activated; the air pressure in the drying chamber was reduced to 100 Pa.

After a preset time interval, the vacuum pump was deactivated, and the dried samples were briefly removed from the drying chamber for control weighing. The weighing was carried out by the electronic laboratory scales AND EK 610i with a maximum weight of 600 g and 0.01 g readability. The weighing data were processed to evaluate the current moisture contents. The thermo-vacuum drying continued until the current moisture of the samples with a large initial mass was higher than the current moisture contents of the samples with a smaller initial mass. Totally thermo-vacuum drying of the control portions of sunflower cake lasted 24 hours. Table 1 presents the experimental data on weight results after thermo-vacuum drying.

Two expressions are used to evaluate the initial moisture: the first, for an absolute moisture (W); and the second, for relative (w). The absolute moisture is calculated as a ratio of the moisture content to the mass of the absolutely dry material, using the following formula:

$$W = \frac{m - m_0}{m_0} \times 100\% \ , \quad (1)$$

and the relative moisture is calculated as a ratio of the mass of moisture to the current mass of the material under study:

$$w = \frac{m - m_0}{m} \times 100\% \ , \quad (2)$$

where m is the current mass of the wet sample, m_0 is the mass of the test sample in an absolutely dry state, i.e. the data obtained after the thermo-vacuum drying experiments. The calculated values of the absolute and relative moisture according to formulae (1) and (2) are presented in Table 1.

Resulting from the analysis of thermo-vacuum drying of the sunflower cake samples, the initial moisture content of the test material was determined. The averaged value of the initial moisture for the three control samples was W = 313.1% or w = 75.8%. The reported moisture value was taken as the initial W_0 (w_0) in all subsequent experiments with the sunflower cake.

Acousto-convective drying of sunflower cake. The acousto-convective drying of the sunflower cake was carried out on the acousto-convective drying plant (ACDP) of ITAM SB RAS. The ACDP flow-chart is shown in Fig. 1. The ACDP operation is based on a gas-jet radiator of the Hartmann type [21, 22].

The samples of the sunflower cake were placed in a tight gauze sleeve to prevent the loss of fine fractions of the material. The resulting material was placed in a cylindrical container made of a metal stainless mesh with a cell size of 0.7 x 0.7 mm and a wire thickness of 250 μm. The loaded container was closed and fixed to the substrate with screws. The assemblage was placed in the working part of the ACDP and fixed in it with a fastening system.

The experiments were conducted in a heated room with an ambient temperature of 25.1°C, a moisture of 16.7% (3.9 g/m^3), and a dew-point temperature of 1.5°C. The moisture temperature meter IVTM-7 MK-S recorded the temperature and humidity of the air.

The ACDP was first started without the material. After the process stabilisation, parameters of the generated acousto-convective flow were registered in the working part of the ACDP. The working flow temperature in the ACDP tract equaled 18.8°C. During the experiments, the parameters of the working flow varied depending on the initial data being set, but the pressure in the ACDP prechamber was kept constant by means of a precision airflow adjustment system. The static pressure in the ACDP prechamber for all the experiments was $P_0 = 4.7$ atm.

In this study, three modes of the ACDP operation were chosen by an analogy with [12]. The first operating mode of the ACDP is realised at a resonator depth of 300 mm, with the generated stream frequency of 270 Hz and intensity of 182 dB. The amplitude-frequency characteristics (AFC) of the mode are shown in Fig. 2. The second mode is achieved by decreasing the depth of the resonator to 80 mm, while the frequency of the working flow increases to 790 Hz at an intensity of 175 dB, its AFC is shown in Fig. 3. The third mode corresponds to the zero position of the resonator, that is, the flow goes around the barrier, having no pronounced resonant frequency, and the intensity equals 130 dB.

Figs. 4 and 5 present the processed results on the dynamics of moisture extraction from the sunflower cake samples during the acousto-convective action on them under different operating conditions of the ACDP. These figures show that a 30-minute drying by a flow with operating parameters corresponding to the background mode decreases the absolute moisture content of the material by 94%, and the relative moisture by 7%. For the same time interval, the drying mode with a frequency of 270 Hz decreases the absolute moisture by 117%, and the relative moisture by 10%. When switching to the next mode of insonation by a working flow with a frequency of 790 Hz, there is a significant intensification of moisture removal, so the absolute moisture for the same half-hour decreases by 185%, and the relative one by 20%.

Table 1. Thermo-vacuum drying of the sunflower cake samples

№	*m*, g	m_0, g	*W*, %	*w*, %
1	19.88	4.86	309.05	75.55
2	40.34	9.78	312.47	75.76
3	81.61	19.54	317.66	76.06

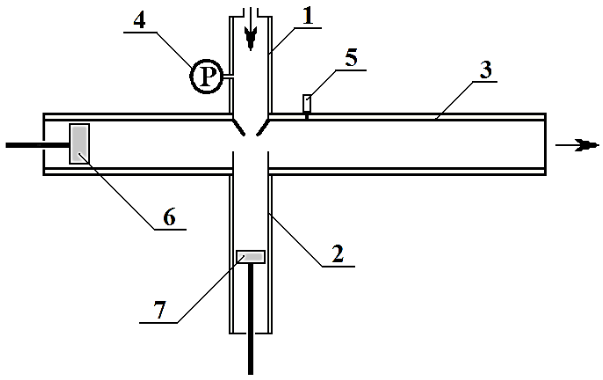


Fig. 1. The ACDP flow-chart: 1 – prechamber, 2 – resonator, 3 – working part, 4 – static pressure gauge, 5 – sensor LH-610, 6 and 7 – adjusting pistons.

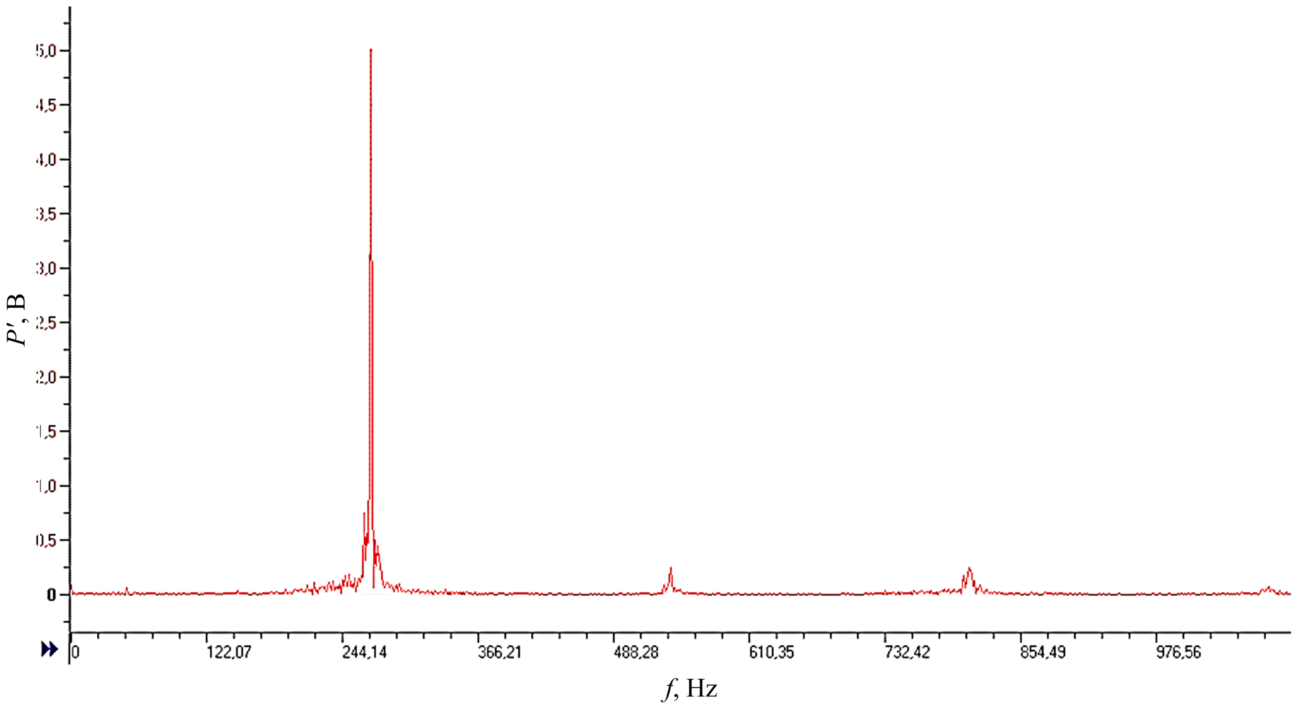


Fig. 2. The AFC of the working flow at a resonator depth of 300 mm.

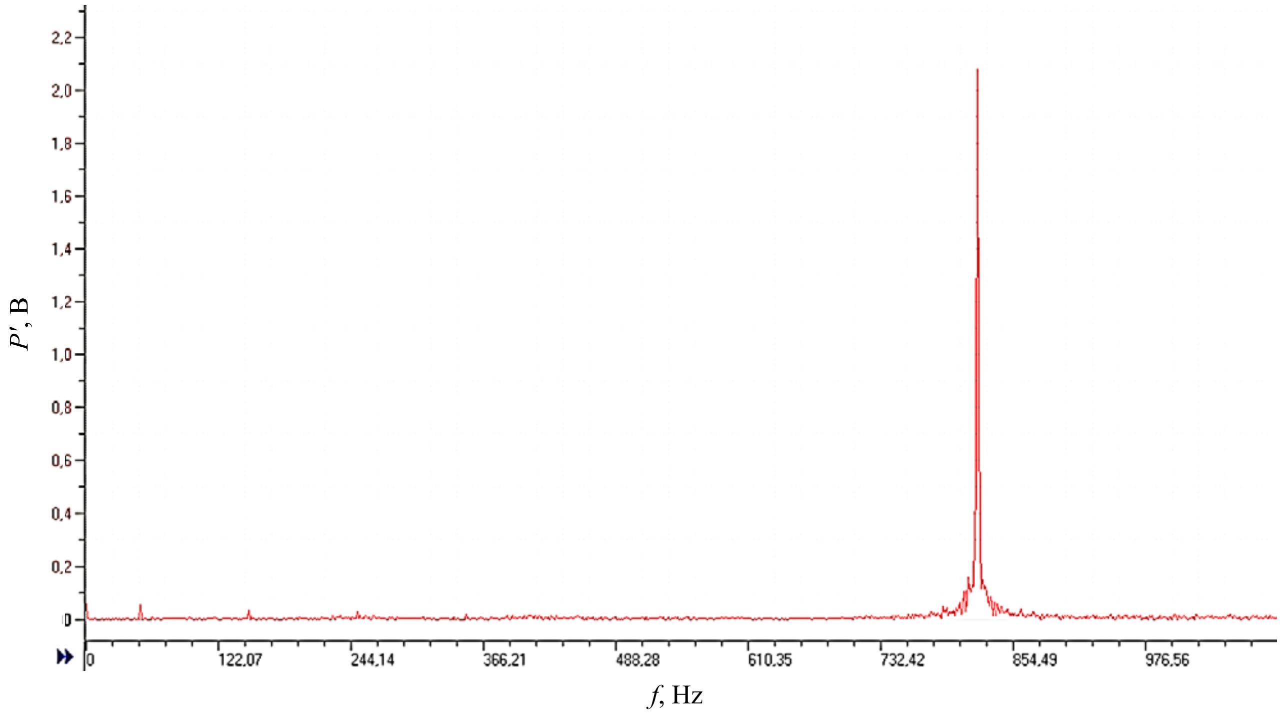


Fig. 3. The AFC of the working flow at a resonator depth of 80 mm.

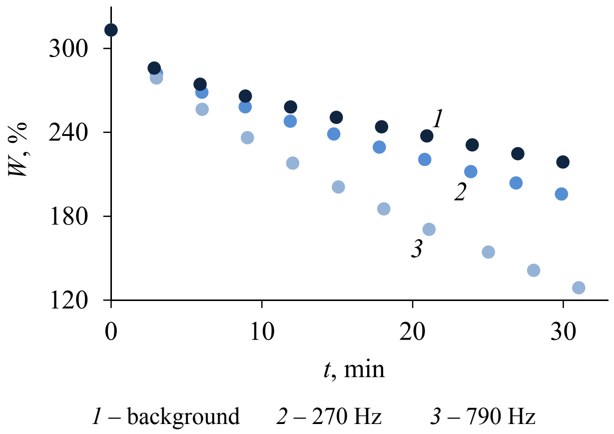


Fig. 4. The absolute moisture change for the sunflower cake during acousto-convective drying by different modes.

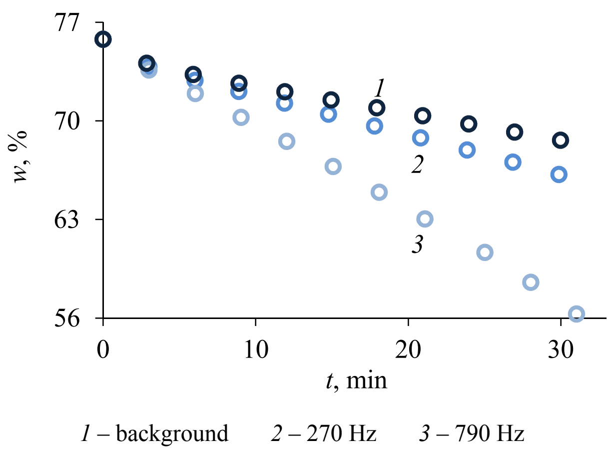


Fig. 5. The relative moisture change dynamics in the sunflower cake during acousto-convective drying by different modes.

Thus, when the material is insonated at a frequency of 790 Hz, the moisture removal is twice as large as when it is insonated at 270 Hz and three times, if there is no resonant frequency in the working flow. Comparing the results of insonation at a frequency of 270 Hz and without a resonant frequency shows that the mode with a resonant frequency of 270 Hz extracts water 1.5 times faster than in the background mode. The obtained result confirms that resonance intensifies moisture extraction from porous materials, in which the resonant frequency value has a significant effect on the rate of the moisture removal.

The understanding of the acousto-convective drying of porous materials is still incomplete today. One of the possible mechanisms describing the physics of extracting moisture from a porous material in a high-intensity acoustic field is presented in [19]. It applies the heterogeneous media mechanics to simulate acousto-convective drying. The mathematical model takes into account the difference of speeds and phase pressures in the porous skeleton and the liquid filling it and satisfactorily describes the initial stage of the drying process (as revealed by the verification of the numerical data obtained in the appropriate experiments). Asaresult, the difference of sound speeds in the skeleton of a porous body and the water caused compression waves, which travel in a solid body and squeeze out liquid onto its surface.

Thermo-convective drying of sunflower cake. Traditionally, the sunflower cake is dried by the thermo-convective method, which is based on heat input to the material, and thus it is necessary to compare the results for the acousto-convective drying dynamics with the ones for the traditional drying. To achieve that, the experiments were conducted with the help of an experimental stand where the sunflower cake was dried with a thermo-convective flow. The heat flow was produced by a thermal gun ETV–4.5/220 T with a nominal heating capacity of 4.5 kW and a flow rate of 7.6 mps. The heat gun has two modes: the first mode has the minimum temperature of the heat flow; the second one has the maximum temperature of the heat flow. The experimental stand launching and the process stabilisation were carried out without the material. After the process was stabilised, the heat flow temperature at the exit from the heat gun was recorded 74.2°C for the first mode and 127°C for the second mode.

The sunflower cake samples, previously put in the gauze hose, were placed in the center of the heat flow from the heat gun. Every five minutes the samples were removed from the heat flow and weighed. The experiment duration for the thermo-convective drying by the first and second modes was different.

The weight experiment results for the both modes of thermo-convective drying were processed and presented in Figs. 6 and 7. Fig. 6 demonstrates that draining the samples to an absolute moisture of 40% at a heat flow temperature of 127°C took 140 min, and at a temperature of 74.2°C took 460 min. Thus, doubling the temperature of the drying stream led to the acceleration of drying almost by three times, and consequently to cutting down the drying time. This acceleration derived from a change in the dehumidification mechanism, with a temperature below the boiling point, the moisture was extracted in small droplets, and with temperatures above the boiling point, in steam.

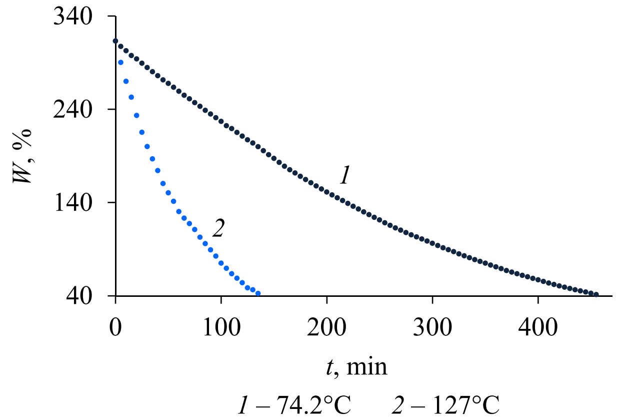


Fig. 6. Change in the absolute moisture content of the sunflower cake during thermo-convection drying with a flow at different temperatures.

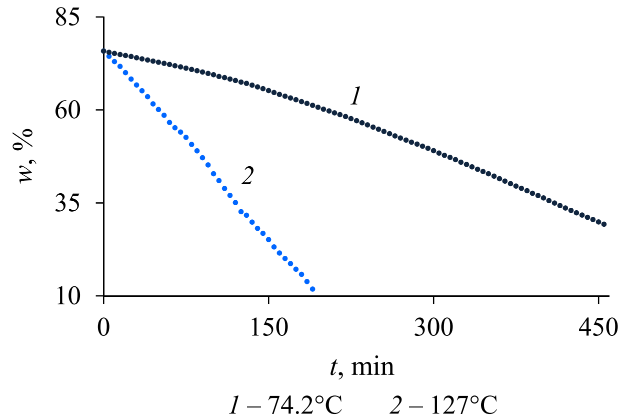


Fig. 7. Change dynamics for the relative moisture content in the sunflower cake when dried by a thermo-convective flow at different temperatures.

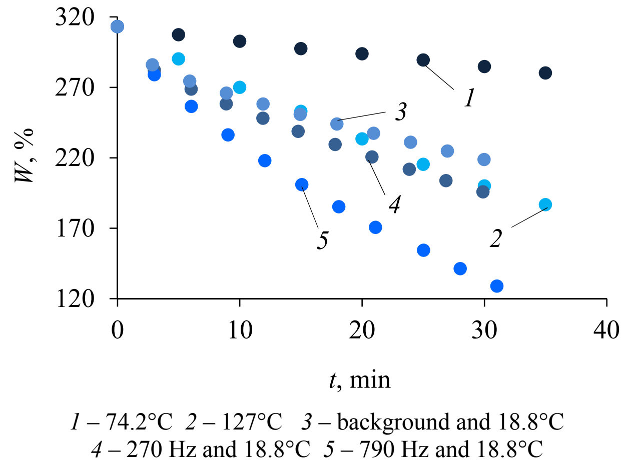


Fig. 8. Modes and methods of drying compared by the change of the absolute moisture in the sunflower cake.

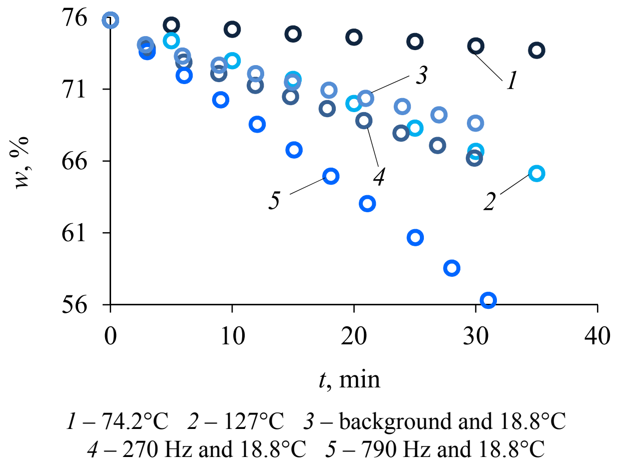


Fig. 9. Modes and methods of drying compared by the change of the moisture content in the sunflower cake.

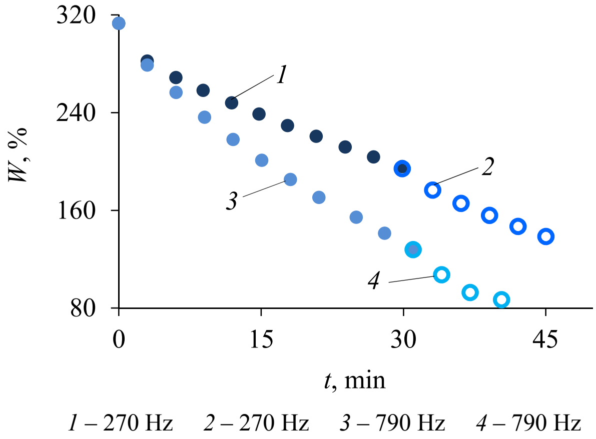


Fig. 10. Moisture extraction dynamics for the sunflower cake samples during acousto-convective drying with an hour-long pause.

In Fig. 7, the characteristic curve of the moisture yield from the sample to be dried shows that the required final relative moisture of 10% can be achieved by thermo-convective drying of the sunflower cake with the second temperature mode of 127°C for 195 min (3.25 h). To assess the two temperature modes, we compared the time when the samples reach relative moisture of 30%. In the first mode, the required moisture was achieved for 450 minutes (7.5 hours), in the second, it took only 135 minutes (2.25 hours). Consequently, the previously determined ratio of one to three holds true.

Comparing dynamics of drying sunflower cake by acousto- and thermo-convective modes. To implement the obtained results in a production facility, it is necessary to compare the dynamics of the sunflower cake drying by acousto- and thermo-convective modes at different temperatures. Figs. 8 and 9 present the curves for moisture extraction from the sunflower cake samples during the first 30 minutes of drying. The slowest is thermo-convective drying at 74.2°C for a specified time interval, the moisture loss is 28.4% (1.8%). A faster moisture yield was recorded for acousto-convective drying by a background mode at 18.8°C, half an hour process resulted in the moisture loss of 94.4% (7.2%). Even faster was thermo-convective drying by the second mode at 127°C, for 30 min the moisture decreased by 113.1% (9.1%). Acousto-convective drying with a resonance frequency of 270 Hz and a flow heat of 18.8°C provided similar parameters, in particular 117.3% (9.6%). The fastest drying of the sunflower cake was realized by the acousto-convective method with a resonance frequency of 790 Hz and a temperature of 18.8°C; the ACDP functioning for half an hour accounted for the moisture loss of 184.3% (19.5%). Thus, the conducted comparison demonstrated that the acousto-convective drying method is twice as efficient as the traditional thermo-convective method. Moreover, [23] shows that power input is reduced by a half. Beyond doubts, these results are indicative of a considerable practical importance for the existing industry.

Therefore, the correct resonant frequency for the working flow can increase the efficiency of acousto-convective drying of sunflower cake, as shown by this case, almost twice, while the power input remains unchanged. If there is no resonance in the working acousto-convective flow or for some reason it disappears, the difference in drying dynamics becomes even more significant; in this study it amounted to almost 2.7 times by the 30th minute of the test.

An interval mode of acousto-convective drying. The experimental results obtained for acousto-convective drying show ed that within the first 15 minutes the moisture extraction dynamics had a significant nonlinearity. So within the first three minutes, the absolute moisture in mode 1 decreased by 31.0%, and in mode 2 – by 34.2%; for the second three minutes in mode 1 – by 13.5%, and in mode 2 – by 22.5%; for the third three-minute interval in mode 1 – by 10.4%, in mode 2 – by 20.3%; the fourth three-minute interval led to a moisture decrease in mode 1 by 10.3%, and in mode 2 – by 18.4%; in the fifth three-minute interval, the moisture reduction in mode 1 was 9.2%, in mode 2 – 17.0%. Thus, within the first 15 minutes the loss of absolute moisture for the sample in mode 1 equaled 74.4%, and in mode 2 – 112.5%.

During the second fifteen-minute interval, the moisture content of the samples decreased linearly, the average value for the five three-minute intervals in mode 1 was 8.6%, in mode 2, 14.4%. For the second fifteen-minute interval, the absolute moisture value in mode 1 decreased by 42.9%, and in mode 2 – by 72.1%, that is, the efficiency of moisture yield decreased for mode 1 by 1.7 times, and for mode 2, by 1.6 times. This trend shows that all subsequent fifteen-minute intervals will result in an even slower drying. To increase the efficiency of acousto-convective drying, it is worthwhile to remove the dried samples from the ACDP after thirty or fifteen minutes and allow those to stand at a room temperature, so that the moisture can redistribute inside the test material, as shown in [12, 13].

This study included experiments on the interval drying of the sunflower cake in which the material to be dried was held outside the acousto-convective flow for an hour. After the withstanding, the samples were placed in the ACDP, operating in the same mode as before the removal of the material from the tract of the working part. The study results, for the ACDP operating in the first and second modes are shown in Fig. 10. Acousto-convective drying in the first mode shows considerable intensification after one-hour withstanding; so within the first three minutes the sample lost 17.6% in absolute moisture, within the second – 10.8%, within the third – 9.8%, and within the fourth – 9.1%. Within the fifth three-minute interval of insonation, the moisture loss equaled 8.3%, which is less than the average value obtained earlier in the drying linear interval for this mode. The total moisture yield after one hour withstanding for the first mode was 55.6%, i. e. the efficiency gain amounted to 12.7%. For the second mode of acousto-convective drying, the efficiency gain held true only within the first two three-minute intervals; so in the first three minutes, the absolute moisture dropped by 20.5%, and in the second – by 14.4%, which compares well to the average value for the second fifteen-minute area described earlier for the corresponding operating mode of the ACDP.

This resulted in the optimal flow-process chart for acousto-convective drying of sunflower cake, which consists of two technological operations: drying in the ACDP for 15 minutes, and withstanding at the room temperature for an hour. As the flow-process chart demonstrates, no heat is applied to the material to be drained throughout the test drying. The flow temperature is similar to the initial one.

Mathematical description of the experimental data for sunflower cake drying. The mathematical processing of the kinetic curves obtained in the moisture extraction experiments for the sunflower cake was carried out by means of a linear relaxation equation, which had the following form:

$$\frac{dW}{dt} = \frac{W_K - W}{\tau}. \qquad (3)$$

The determined value of the initial moisture served the initial condition for Eg. (3)

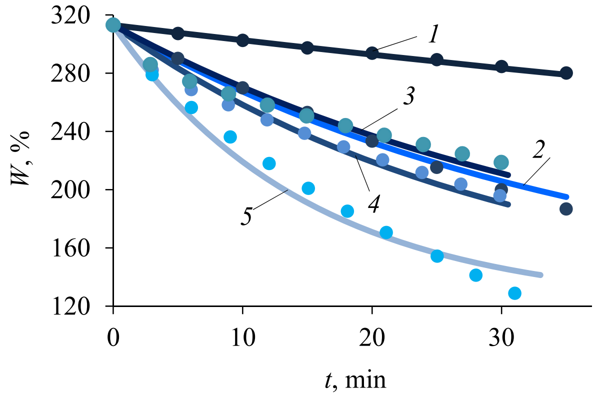
when $$t = 0,\ W = W_0. \qquad (4)$$

Here, W_0 is the initial moisture, W_K is the final equilibrium moisture, and τ is the relaxation time of the moisture extraction. The formulated Cauchy problem in Egs. (3) and (4) has an analytic solution in the form:

$$W = W_K + (W_0 - W_K)e^{-t/\tau}. \qquad (5)$$

The processing results for the experimental data are shown in Fig. 11. Here, solid and dashed lines represent the results of numerical calculations obtained with the help of Eg. (5) with optimally selected values of τ for the acousto- and thermo-convective drying modes, respectively. The fastest moisture extraction, realized by acousto-convective drying at a frequency of 790 Hz and a temperature of 18.8°C, has a minimum relaxation time of 15 minutes. The next efficient mode of acousto-convective drying at a frequency of 270 Hz and at a temperature of 18.8°C has a relaxation time 30 min. The third place in efficiency is held by the mode of thermo-convective drying at a temperature of 127°C: it has a characteristic relaxation time of 35 min. The fourth in efficiency is the background mode of acousto-convective drying at a temperature of 18.8°C, with τ = 40 min. The slowest moisture extraction from the sunflower cake by thermo-convective drying at 74.2°C has a relaxation time of 180 min, or 3 hours.

To compare quantitatively the determined relaxation intervals for the sunflower cake drying process in the ACDP, there was compiled a summary Table 2, which presents the results of acousto-convective drying for other materials. It is obvious ly that the relaxation times agree well with other materials.



(1) – 74.2°C *(2)* – 127°C *(3)* – background and 18.8°C
(4) – 270 Hz and 18.8°C *(5)* – 790 Hz and 18.8°C

Fig. 11. Mathematical description of the experimental data.

Table 2. Relaxation time for drying various materials in the ACDP

no	Material	Relaxation time, min	Reference
1	pine nuts	20	[15]
2	pine nut shell	7.5	[15]
3	pine nut kernel	13	[15]
4	sorbent	18–50.6	[16]
5	tube assembly along the flow	9	[24]
6	tube assembly across the flow	6	[24]
7	meat fiber	10	[12]
8	cellulous gas-concrete	18	[18]
9	sunflower cake	15–40	this study

CONCLUSIONS

(1) With the help of thermo-vacuum drying, the initial absolute and relative moisture contents were determined for sunflower cake as 313.1% and 75.8%, respectively.

(2) If the sunflower cake was dried by acousto-convective method at a room temperature (18.8°C), a resonating frequency intensified moisture extraction.

(3) There was determined the quantitative proportion associating the released moisture contents with the sunflower cake acousto-convective drying in different operating modes of the ACDP within 30 minutes:

– at a frequency of 790 Hz and 270 Hz as 2:1;
– at a frequency of 790 Hz and the background as 3:1; and;
– at a frequency of 2 70 Hz and the background as 1.5:1.

(4) As demonstrated, doubling the temperature of the thermo-convective flow drying the sunflower cake (from 74.2°C to 127°C) reduced the duration of drying to a final absolute moisture of 40% by three times.

(5) The comparison of thermo-convective and acousto-convective drying methods showed that within a 30-minute interval the samples dried in the ACDP with a working flow frequency of 790 Hz and at a room temperature yielded moisture twice as much as the samples dried by thermo-convective method with a working flow temperature of 127°C.

(6) The optimal flow-process chart was constructed for interval drying mode of the sunflower cake as consisting of two repetitive technological operations.
(7) The mathematical relaxation model describing the drying process and the experimental data for sunflower cake drying allowed obtaining quantitative parameters that characterised different methods and modes of samples.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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ORCID IDs
Aleksandr A. Zhilin http://orcid.org/0000-0003-3731-7581