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ASSESSMENT OF EFFICIENCY OF DRYING GRAIN MATERIALS USING MICROWAVE HEATING

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Наведено результати експериментальних робіт з дослідження сушіння щільного шару зерна із застосуванням мікрохвильового нагрівання. Для оцінки ефективності використання енергії мікрохвильового поля вивчався ряд способів підведення теплоти до зерна. Досліджені мікрохвильовий, мікрохвильовий пульсуючий, микрохвильово-конвективний циклічний із продувкою шару нагрітим потоком повітря й повітрям без попереднього підігріву, одночасний микрохвильово-конвективний способи сушіння.

Дослідження кінетики сушіння в мікрохвильовому полі показало, що процес можна розділити на періоди прогріву (нульовий), постійної (перший) і падаючої (другий) швидкості сушіння. Ці періоди характерні для сушіння колоїдних капілярно-пористих тіл при інших способах підведення теплоти. На підставі узагальнення експериментальних даних по дослідженню сушки зерна гречки, ячменю, вівса та пшениці отримано емпіричні залежності для швидкості сушіння і середньої температури зерна в першому періоді. Представлені кінетичні залежності в безрозмірному вигляді, узагальнюючі дані по дослідженим зерновим.

Комплексні дослідження різних способів підведення теплоти при сушінні ставили метою визначення оптимального способу й раціональних режимних параметрів, що забезпечують високу інтенсивність процесу й необхідну якість готового продукту при мінімальних енерговитратах. Для забезпечення вірогідності зіставлення всі дослідження проводилися в ідентичних умовах з однієї й тією же зерновою культурою (овес). Визначено, що кращим є одночасний микрохвильово-конвективне підведення енергії, при цьому попередній підігрів повітря не передбачається, завдяки чому мінімізуються питомі витрати енергії. Експериментальні дослідження сушіння із застосуванням мікрохвильового поля дають можливість підібрати необхідні параметри процесу: потужність, темп нагрівання, масу й форму завантаження. На підставі цих даних передбачається розробка технології сушіння зерна із застосуванням енергії мікрохвильового поля

Ключові слова: мікрохвильове нагрівання, микрохвильово-конвективний, вологовміст, температура, швидкість сушіння, оптимальний спосіб

1. Introduction

Convective dryers are the most common for grain drying currently. They have a series of significant disadvantages. However, we can eliminate the disadvantages using microwave-convective heat supply [1, 2]. We obtained convincing evidence of applicability of microwave technology and feasibility of development of microwave dryers. There is successful combination of the processes of moisture removal and disinsection at grain drying in a microwave (MW) field [3]. Peculiarities of conversion of microwave energy into thermal energy provide the advantages of microwave drying [4]. The temperature at a surface of grain is higher than inside in the convective (as well as in the conductive) method of drying, while the direction of temperature and pressure gradients impede movement of moisture to a surface. Heating of material in the MW field produces the opposite effect: the temperature inside material becomes higher than on a surface, and the temperature and pressure gradients accelerate the drying process.

There are no sufficient studies on kinetics of drying grain materials for conditions of introduction of new technologies. Heat drying of grain is the most important and most energy-intensive technological operation, both for post-harvest processing and for production of cereals. The fact that producers dry 70–90 % of total harvested grain for now emphasizes the scale of the problem. As modern practice shows, attempts to create new equipment, in particular, for microwave drying, and its further use without first studying of the kinetics of the process does not lead to the desired result. The bases of new drying technologies are dependencies for calculation of the temperature and moisture content of grain. It is necessary to determine requirements for mode parameters under which it will be expedient to use one or another method of organization of the process.

2. Literature review and problem statement

There are a series of issues necessary to resolve to make microwave drying of grain technologies rational. One of the main issues is to ensure safety of the process and to determine an influence of a microwave field on the quality of a product. The results of study [5] determined that products after microwave heating are safe for consumers, while the quality of nutrients is similar to that the products obtained by heating by traditional methods. Author of a paper [6] noted that microwave heating has a series of positive characteristics, such as highly efficient heating over the volume of material, possibility of provision of even temperature distribution and a use of "clean" energy. They analyze non-uniformity of heating caused by the geometry and composition of the product, as well as non-uniform distribution of the electromagnetic field in a microwave chamber. These data give possibility to determine conditions for uniform heating of material in a microwave field.

There is a danger of deterioration in the quality of material despite certain advantages of microwave heating in drying operations involving high energy efficiency. This can occur if, at the initial stage, to allow rapid evaporation of moisture and an intensive increase in temperature [7]. Therefore, producers use microwave heating in combination with other methods of heat supply, such as, for example, microwave-convective drying [8] and vacuum-microwave drying [9]. Work showed [8] that the use of tunnel microwave-convective dryers for organic raw materials makes it possible to achieve a high drying rate evenly distributed in thickness with achievement of high energy efficiency. Paper [9] presented the results of studies on vacuum-microwave and microwave-convective kinetics of drying of jackfruit and rehydration characteristics. Authors of the work determined that microwave-vacuum dehydration is 133 times faster compared with convective treatment. Results of work [9] showed that microwave-vacuum dehydration is preferable to microwave-convective from the point of view of the quality of the final product. However, the method seems to be expensive for drying of large volumes, which is typical for grains.

Paper [10] recommended applying microwave drying at the final stage, which will speed up the process and reduce shrinkage of material. Authors of [11] noted that it is advisable to conduct drying in a microwave field at a moisture content of 20 %, which usually corresponds to the moisture content of grain crops at the entrance to a drying device. There are a series of unresolved issues related to peculiarities of processes of interaction of dispersed material with a microwave field. It is a matter of provision of a uniform temperature field in material, an influence of the product geometry on the phenomena of overheating, a change in dielectric characteristics of materials during microwave heating. Paper [12] presented the results of the study on uniformity of material heating in a rectangular waveguide. The paper considered an influence of magnetron power, a type of dielectric materials, their size and location on absorption of microwaves and average temperature in dielectric materials in detail. The results showed that the location of a sample affects the heating uniformity more than other parameters. Thus, we can conclude that it is advisable to make microwave dryers spillable, which will improve uniform absorption of microwave energy by a grain layer. Study [13] confirmed that both the dielectric constants and the loss factor of unpurified rice and rice grains decrease as the temperature rises. The depth of penetration of microwaves in samples without salt added increased with increasing of temperature, whereas its value decreases in samples with salt additions (from 0.5 % to 3 %). Work [14] showed that the problem, which arose during microwave heating, is uneven temperature distribution in material. It is important to know dielectric properties to control non-uniformity of heating to control non-uniformity of heating, since they determine heat generation. A large number of factors influence dielectric characteristics, which makes difficult to predict the drying process without conduction of full-scale experiments. The complexity of resolution of these issues does not give possibility to obtain analytical or engineering design dependencies. And it is necessary to take into consideration the associated processes of transfer of heat and moisture at drying. It is necessary to conduct complex experimental studies to determine the optimal conditions with the required process parameters: power, heating rate, mass, and form of loading, which will make it possible to switch to a new energy-efficient drying technology.

3. The aim and objectives of the study

The objective of the study was to determine the optimal method of grain drying and reasonable operating parameters of the process.

We formulated the following tasks to achieve the objective:

– investigation of the kinetics of drying of grain materials by microwave heating;

– a study of grain drying by microwave (pulsating and continuous) and microwave-convective (cyclic and simultaneous) energy supply;

– comparison of the main characteristics of the drying processes with different ways of energy supply and determination of the best way and rational mode parameters.

4. Materials and methods of the study

We developed and manufactured the experimental plant to study the microwave-convective drying of a dense stationary layer of grain material. Fig. 1 shows the scheme of the plant.

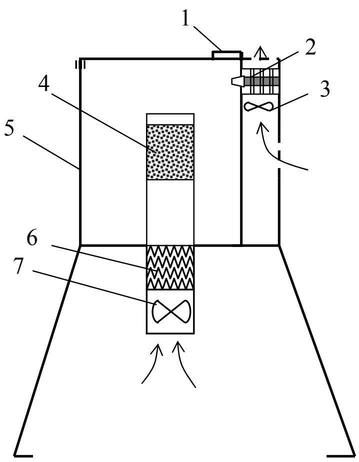


Fig. 1. The scheme of the plant for studying the kinetics of drying grain materials by microwave and convective heating: 1 – door, 2 – magnetron, 3 – magnetron cooling fan, 4 – experimental cell with research material, 5 – working chamber, 6 – electric heater, 7 – fan

The plant provides research in microwave, microwave-convective and convective drying. There is an air duct made of radio transparent material inside the working chamber. We placed a cell made in the shape of a parallelepiped of radio transparent mesh material in it. We poured the required amount of grain into the experimental cell. The dimensions of the cell strictly corresponded to the dimensions of the air duct, so there were no side overflows when the material was blown with air. The gate installed in front of the working chamber adjusted the air flow.

We used grain buckwheat, barley, oats, and wheat for the study. The initial moisture content of the grain was u_0=20 %, the initial temperature t ranged from 17 to 26 °C, the mass m was from 0.05 to 1.2 kg, the layer thickness l was from 0.008 to 0.07 m, the surface area of the sample opened to remove moisture F – from $8 \cdot 10^{-3}$ to $94 \cdot 10^{-3}$ m^2, the output power of the magnetron P – from 80 to 800 W. Experimental studies of drying using a microwave field make it possible to select the required process parameters: power, heating rate, mass and form of loading. The data obtained make it possible to develop energy-efficient grain drying technology using microwave field energy.

We used the following research methods depending on the method of heat supply.

Continuous microwave supply: drying occurs due to the MW energy supplied to material from the magnetron only. We placed grain of a given mass in the experimental cell installed in the working chamber. We turned on the magnetron and took out the cell after a specified time interval. We measured the temperature using thermocouples and the grain mass. Then we filled the cell with a fresh portion of grain and placed in the chamber and we increased exposure time in the working chamber by a time step $\Delta\tau$. We carried out studies to achieve a moisture content of grain of 6–12 %.

The periods of the microwave supply alternate with pauses at the pulsating mode. The duration of the magnetron turned on τ_{MW} and pauses τ_p were fixed for each series of experiments. In the course of the research, we heated the grain in the experimental cell in a microwave field for a specified time interval τ_{MW}, then we kept it without energy supply for τ_p time. After this, we repeated the periods of heating and pause. We continued the experiment until we achieved a moisture content of 12–14 %.

In the cyclic mode of drying, the periods of the microwave supply τ_{MW} alternate with the periods of heated and unheated air blow τ_c. The duration of a blow τ_c, as well as the temperature of the air blowing through the layer, varied with the transition to the next series of experiments.

The microwave heating and blowing of the layer with heated or unheated air occurred simultaneously at the continuous mode of microwave-convective drying.

In all experiments, after each step, we weighed the material and measured the layer temperature at several points, and then we poured a new portion of material into the cell with the same weight and moisture content, and carried out the experiment with duration longer than the next period (MW or blow). We carried out the experiments with three repetitions, which made possible to judge reliability of the results.

5. Results of studying the kinetics of drying grain materials using microwave heating

5. 1. Kinetics of drying of grain materials in a microwave field

The type of curves of moisture content and temperature showed (Fig. 2) that we can divide the process of microwave drying into periods, which are characteristic for colloidal capillary-porous bodies at other methods of heat supply [16]. These are the heating (zero), constant (first) and falling (second) drying rates.

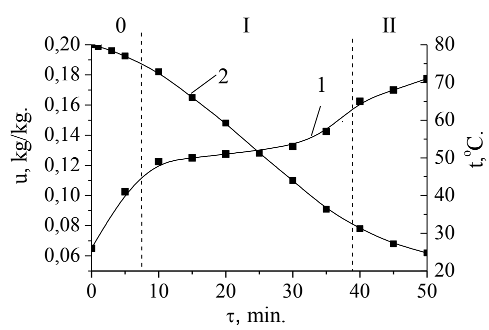
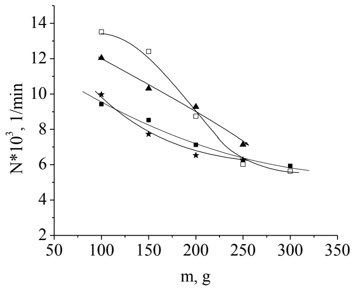


Fig. 2. Change in temperature (1) and moisture content (2) of buckwheat grain when dried in a microwave field. P=80 W; m=0.1 kg; l=0.016 m: 0 – heating period, I – period of constant drying rate, II – period of falling drying rate

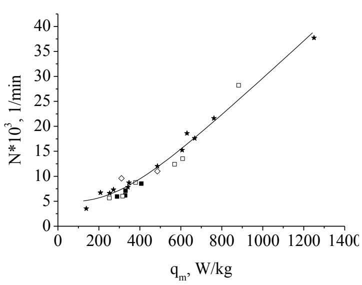
Evaporation of moisture almost did not occur (the moisture content remained almost constant) and the temperature increased markedly in the heating period. Then, at a certain temperature of the material, the moisture content began to decrease, and we consider this change as a linear one. The nature of the temperature change in this period differed in dependence on the supplied power. The temperature almost did not change at values of specific power up to $q = 450$ W/kg. The temperature increased at an increase in the specific power, and its change was significant at $q > 600$ W/kg. We determined the period of the falling drying rate by the change in the course of the moisture content curve: the curve became flat. The temperature in this period always increased. The picture described was typical for all materials studied.

Experimental data obtained in the study on the drying of various grain materials showed that when the loading weight is less than 200 g, the drying rate depends on the type of grain (Fig. 3, *a*). Thickness of layers was different due to differences in density and porosity of layers of the studied grains. With a weight of 100 g, the thickness of the layer of oats was 35 mm, barley – 30 mm, wheat – 23 mm, buckwheat – 22 mm. Bulk density of oats was 530 kg/m^3, barley – 620 kg/m^3, wheat – 800 kg/m^3, buckwheat – 840 kg/m^3. Thus, an increase in the layer thickness at a fixed mass of the samples leads to a corresponding increase in the drying rate, due to an increase in the heat insulating properties. With an increase in mass above 200 g, differences in drying rates decreased. With a mass of more than 300 g, the type of grain material did not affect the rate of drying.

We summarized the data for all the materials studied in the form of the dependence of the drying rate on the supplied heat flow (Fig. 3, *b*), i. e. the ratio of a useful heat flow (an amount of heat consumed to heat material and evaporation of moisture from it) to the sample mass $q_m = \dfrac{Q_n}{m}$, W/kg.



a



b

Fig. 3. Dependence of the grain drying rate on variable parameters: *a* — effect of mass, *b* — effect of the useful heat flow. ■ — wheat, □ — oats, ▲ — barley, ★ — buckwheat. The output power of the magnetron *P*=180 W

$$N = 9.47 \cdot 10^{-6} \left(q_m\right)^{1,17}, \ \text{min}^{-1}. \tag{1}$$

It is convenient to use a formula that takes into consideration the energy consumed from the network *P*, the efficiency of the microwave chamber η_c and the efficiency of the magnetron η_m to calculate the useful heat flow

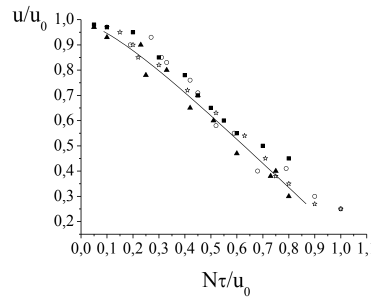
$$Q_u = P \cdot \eta_c \cdot \eta_m, \ \text{W}. \tag{2}$$

It is advisable to use the dependence obtained from the results of experimental studies is recommended to calculate the average grain temperature in the period of constant drying rate (first period):

$$t_1 = 13.22 \cdot \left(q_m\right)^{0.28} \ ^\circ\text{C}. \tag{3}$$

Dependences (1), (3) are valid for $200 \le q_m \le 1285$ W/kg with an error of ±15 % and ±13 %.

Fig. 4 presents the experimental data on the integral moisture contents and temperatures for all materials studied in the form of generalized drying and heating kinetics curves. We obtained the dependences of the dimensionless current moisture content u/u_0 and temperature t/t_1 on the dimensionless complex $N\tau/u_0$ we used the drying rate in the first period in this complex. We assigned a specific physical meaning to the complex $W\tau/u_0$. This is the relative moisture removal over the time interval from 0 to τ, which would have occurred if the average drying rate for this period was equal to the rate in the period of constant speed.



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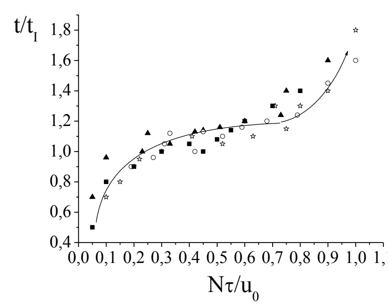

b

Fig. 4. Generalized drying kinetics curves: *a* — moisture content curve, *b* — a temperature curve, ▲ — buckwheat, ■ — barley, ○ — oats, ★ – wheat

We obtained the generalized moisture content and temperature curves for barley, oats, buckwheat, and wheat were obtained at different initial moisture contents, supplied capacities and material masses. We can summarize the data for all the studied grains in single equations with an acceptable error. The corresponding equations, which describe all periods of the drying process of the studied cultures at $0{,}036 \le \dfrac{N\tau}{u_0} \le 0{,}83$, take the following form:

$$\frac{\bar{u}}{u_0}=1.016-0.332\frac{N\tau}{u_0}-1.449\left(\frac{N\tau}{u_0}\right)^2+1.091\left(\frac{N\tau}{u_0}\right)^3, \quad (4)$$

$$\frac{\bar{t}}{t_1}=0.511+3.506\left(\frac{N\tau}{u_0}\right)-8.341\left(\frac{N\tau}{u_0}\right)^2+7.095\left(\frac{N\tau}{u_0}\right)^3. \quad (5)$$

The dependencies (4) and (5) are valid with a standard error of ±9.8 % and ±11.9 %, respectively. Here, $\bar{u}$ is the average moisture content of a layer at τ time τ, u_0 is the initial moisture content of a layer, $\bar{t_I}$ is the average temperature of grain in the period of constant drying rate (the first period).

5. 2. Studying grain drying with different ways of heat supply

We carried out a separate series of experiments to determine which method of energy supply and which operating parameters provide a high intensity of the drying process and the required quality of the finished product with minimal energy consumption. We studied microwave, microwave-convective pulsating, cyclic and continuous methods of heat supply. The periods of the microwave supply alternate with pauses, during which grain cools during natural convection and moisture evaporates, under the pulsating mode. We studied the influence of the duration of the magnetron on τ_{MB} and pauses τ_n on patterns of changes in temperature and moisture content of material, drying rate, and specific energy consumption.

We investigated the effect of the pause duration on characteristics of the process – drying rate, layer temperature, energy costs. We carried out three series of experiments, which differed in the duration of the microwave supply: 30 s, 60 s and 90 s. In each series, the pause duration was 20, 40, 60 and 80 s. The order of the experiments was as follows. We poured the grain into a rectangular mesh cell. The period of operation of the magnetron was 10 s (series 1), 20 s (series 2) and 30 s (series 3). Then we turned off the magnetron and kept the grain (oats) without heating. The number of inclusions of the magnetron, regardless of the duration of the pause, was the same for each of the series. We also carried out the experiments with a continuous MW heat supply with duration of 30, 60 and 90 s for a comparative evaluation of the drying efficiency. Table 1 shows the results. We carried out the calculation of energy consumption per unit mass of the removed moisture according to the formula: $q_{sp}=P\cdot\tau_m/\Delta m$, where τ_m is the total time of operation of the magnetron, Δm is the mass of moisture removed from grain, P is the power of the magnetron. The initial moisture content of the grain was u u=0.20, the sample mass m=100 g, the layer thickness δ=57.5 mm, the magnetron output power P=600 W in all the experiments.

With an increase in duration of pauses, the energy consumption per 1 kg of moisture decreases slightly, since the moisture decreases without energy consumption in the period of "rest". It is almost independent to the pause duration: about 1.25 g is removed at 30 s, about 5 g at 60 s, about 9.5 g at 90 s. A continuous MW supply leads to rapid heating of material and development of unacceptably high temperatures. Moisture evaporates at pulsating MW heating during the pause period, and temperature decreases slightly, so it is possible to carry out the drying process under a mode, which is sparing for grain.

Table 1

The drying under the pulsating mode. τ_p – duration of a pause, τ_Σ – duration of an experiment, m_f – final mass of a sample, Δm – moisture loss, q_{sp} – specific energy consumption per 1 kg of evaporated moisture, u_f – final moisture content, N – drying rate, $\bar{t}$ – average temperature of a sample, τ_{MW} – duration of MW heating

τ_p, s	τ_Σ, s	m_f, g	Δm, g	q_{sp}, MJ/kg	u_f, kg/kg	N, s^{-1}	$\bar{t}$, °C
τ_{MW}=10 s. Full time of the magnetron operation – 30 s							
0	30	98.86	1.14	15.79	0.1864	0.00045	81.7
20	90	98.88	1.12	16.07	0.187	0.00014	73.3
40	150	98.77	1.23	14.63	0.185	0.0001	74
60	210	98.47	1.53	11.76	0.182	0.00009	59.3
80	270	98.53	1.47	12.24	0.182	0.00007	60.7
τ_{MW}=20 s. Full time of the magnetron operation – 60 s							
0	60	94.84	5.16	6.98	0.138	0.00103	90.7
20	120	95.57	4.43	8.13	0.147	0.00044	85.3
40	180	94.82	5.18	7.00	0.138	0.00034	84
60	240	94.72	5.28	6.86	0.137	0.00026	83.7
80	300	94.76	5.24	6.86	0.137	0.00026	82
τ_{MW}=30 s. Full time of the magnetron operation – 90 s							
0	90	90.01	9.99	5.41	0.080	0.0013	113
20	150	90.75	9.25	5.83	0.089	0.00074	108.3
40	210	91.13	8.87	6.09	0.094	0.0005	98
60	270	91.34	8.66	6.23	0.096	0.00039	93.7
80	330	90.81	9.19	5.88	0.090	0.0003	93

The periods of the microwave supply alternate with the periods of heated and unheated air blowing air under the cyclic mode. We studied the effect of the duration of a blow, as well as the temperature of air blowing through a layer, on a change in temperature and moisture content of material, drying rate and specific energy consumption. The methodology of the experiments was as follows. We loaded 100 g of grain (oats) with an initial moisture content of 0.2 kg/kg into the microwave plant. The duration of the MW heating period was the same in all the experiments and it was 10 s. The magnetron power was 600 W. The duration of the blow period was 10, 20 and 30 s. We carried out the experiments in two ways with the aim of selection of the one that provides the least error. In the first method, after each of the periods, we took out the sample and made necessary measurements. Then we poured fresh grain with the same initial moisture content into the cell, and the process lasted longer for the corresponding period.

We carried out the experiment with one sample (one portion) in the second method. We took it out at the end of each period and placed again in the working chamber after necessary measurements. We determined that both methods give almost identical results. The air temperature was 20 °C, the filtration rate was 1 m/s. The initial temperature of grain was 20 °C. Table 2 presents the results of the experiments at blow with unheated and heated air of τ_c duration. The output power of the magnetron was P=600 W, the air rate was 1 m/s, the flow rate was 0.0118 kg/s, τ_{MB}=10 s, the number of cycles was 6.5.

Table 2

Cyclic microwave-convective drying with unheated and heated air

Drying characteristics	t_{air}=20 °C			t_{air}=50 °C	
	τ_c=10 s	τ_c=20 s	τ_c=30 s	τ_c=10 s	τ_c=20 s
Total specific energy consumption, MJ/kg	9.07	9.68	8.96	11.72	14.33
Average drying rate for the entire period, s^{-1}	0.00036	0.000274	0.000224	0.00038	0.00032
Average rate of MW drying, s^{-1}	0.00024	0.000201	0.000157	0.000257	0.00021
Average rate for the blow periods, s^{-1}	0.00048	0.000278	0.000233	0.000533	0.00043

We studied an influence of the rate and temperature of the air blown through a layer and the process duration on the final moisture content of material and the specific energy consumption at the simultaneous microwave-convective energy supply. Table 3 shows the results.

Table 3

Simultaneous microwave-convective drying of grain. The power of the magnetron was 600 W. Air temperature was 19 °C, rate – 1.1 m/s

τ, s	m_f, g	Δm, g	u_f, kg/kg	N, s^{-1}	$\bar{t}$, °C	q_{sp}, MJ/kg
30	98.3	1.7	0.1797	0.0006	69.27	11.54
60	93.98	6.02	0.12778	0.00121	89.1	6.04
70	92.74	7.26	0.1129	0.00135	94	5.82
80	91.92	8.09	0.103	0.00121	106.5	5.95
90	90.28	9.72	0.0832	0.00130	110.55	5.57

The drying rate and the temperature of material increased with an increase in the duration of the process, and the specific costs decreased. These values change the most significantly with an increase in the drying duration from 30 s to 60 s. However, there is overheating of material at $\tau = 60$ s and $\tau = 90$ °C.

Comparison of characteristics of drying at the microwave and in the microwave-convective supply showed that an increase in the rate of blown air and its temperature contributed to an increase in the rate of drying. Dependence (6) reflects this result, which summarizes the relevant experimental data:

$$\frac{N_{MW\text{-}C}}{N_{MW}} = 1 + 0{,}0003937\,\mathrm{Re}^{0{,}799}\left(\frac{t_{air}}{t_a}\right)^{1{,}037}, \qquad (6)$$

where $N_{MW\text{-}C}$ is the rate of drying at microwave-convective energy supply, N_{MW} N_{MB} – at microwave supply, t_{air} is the temperature of the air blown through a layer of material, t_a is the ambient temperature.

The formula is valid with an error of 5.7 % for Reynolds numbers up to $\mathrm{Re} = 4500$ and temperatures of blown air within $t_{\mathrm{air}} = 19...70$ °C.

Table 4 shows the results of experimental studies obtained in the study of pulsating, microwave-convective and convective drying under modes that provide the most favorable characteristics of the process. We conducted all studies under identical conditions for the reliability of the comparison results. We carried out the studies with the same grain (oats) with an initial moisture content of 0.2 kg/kg, the mass of a portion was 100 g.

Table 4

Characteristics of the drying process at different methods of energy supply. *N* is drying rate, t_f is the final temperature of material, q_{sp} is the specific (per 1 kg of evaporated moisture) energy consumption

Type and mode of energy supply	N, s^{-1}	t_f, °C	q_{sp}, MJ/kg
MW constant $\tau_\Sigma = 60$ s, $P = 600$ W	$10.3\cdot10^{-4}$	90.7	6.98
MW-pulsating $\tau_\Sigma = 120$ s, $\tau_{MB} = \tau_n = 20$, $P = 600$ W	$4.4\cdot10^{-4}$	80.3	8.13
MW-convective, cyclic $\tau_\Sigma = 130$ s, $\tau_{MW} = \tau_c = 10$ s, $t_{\mathrm{air}} = 20$ °C, $w_{\mathrm{air}} = 1$ m/s	$3.6\cdot10^{-4}$	80.5	9.07
MW-convective, simultaneous $\tau_\Sigma = 60$ s, $t_{\mathrm{air}} = 19$ °C, $w_{\mathrm{air}} = 0{,}9$ m/s	$12.7\cdot10^{-4}$	71	5.65

We obtained the following conclusions on expediency of selection of the drying method of drying based on the data from Table 3:

1. The optimal method is the simultaneous MW-convective method of energy supply. It provides achievement of the maximum drying rate, the minimum specific energy consumption and the temperature of material does not exceed the acceptable one.

2. The characteristics of the mode with cyclic MW-convective supply are comparable to the characteristics of the mode with pulsating MW-supply, but the plant is more complicate due to the need to organize a blow.

3. The continuous MW supply provides the highest drying rate, however the final material temperature is unacceptable.

Thus, the most effective method is simultaneous MW-convective energy supply.

6. Discussion of results of studying grain drying at different methods of heat supply

We carried out the complex studies of the kinetics of drying grains (oats, buckwheat, wheat barley) with microwave (continuous and pulsating), and microwave-convective (cyclic, simultaneous) energy supply. The variable parameters were magnetron power, duration of energy supply, rate and temperature of a drying agent. We obtained generalized empirical dependences, which describe changes in dimensionless temperatures and moisture content of material, as well as formulas for calculation of the drying rate.

Analysis of the experimental data led to the following conclusions:

– At a rational choice of the magnetron power, the duration of its activation and pauses under the pulsating mode, we achieve a lower drying rate N=4.4·10^{-4} s^{-1} in comparison with continuous MW drying N=10.3·10^{-4} s^{-1}, but at the acceptable material temperature. In this case, energy consumption is comparable. The specific energy consumption per 1 kg of evaporated moisture at the microwave drying is 6.98 MJ/kg, at the pulsating one – 8.13 MJ/kg;

– The average drying rate, the temperature of material and the total costs for the whole process increase at cyclic microwave-convective drying, when the microwave supply alternates with convective one, with an increase in N and τ_{MW} at τ_c=*idem*. An increase in the duration of the convective supply period at N=*idem*, τ_{MW}=*idem* leads to opposite results. It is not expedient to increase duration of τ_c in excess of 10–20 s and a series of cycles in excess of 3–4, since a significant amount of energy is consumed during periods of switching on the magnetron to heat material cooled during periods of drying of a drying agent through a layer. The most favorable indicators shows the mode N=600 W, the total operating time of the magnetron – $\tau_{\Sigma MW}$=70 s, the total time of convective drying – $\tau_{\Sigma c}$=60 s, the number of cycles n=6.5. Under this mode, the average drying rate for the entire process is 4.4 10^{-4} s^{-1}, the material temperature is 80.5 °C, and the specific energy consumption is 9.07 MJ/kg moisture;

– At simultaneous microwave-convective supply, a blow of unheated or heated air through a layer carried out during microwave heating provides intensification of intercomponent heat and mass transfer, active evaporation of moisture diffusing from the volume of particles to their surface, increases the rate of drying, prevents overheating of material, reduces total and specific energy costs. The optimum mode among the studied modes is the mode with the following characteristics: N=600 W, t_{air}=19 °C, w_{air}=0.7 m/s, N_1=12.71·10^{-4} s^{-1}, q_{sp}=5.69 MJ/kg moisture;

– Comparison of the main characteristics (drying speed, material temperatures, specific energy consumption, and efficiency of supplied energy use) of the drying processes with different ways of energy supply evidences that:

a) cyclic MW-convective supply with a rational choice of duration of periods, number of cycles, magnetron power, rate and air temperature ensure approximately the same drying rate and specific energy consumption as pulsing MW one, however, the plant is more complicated due to the transport system and air heating at the combined supply;

b) the simultaneous MW-convective method of supply is the optimal method. It provides three times higher drying rate and the specific energy consumption by 40 % lower than with a pulsating MW supply;

– We can describe a change in dimensionless average-integral moisture contents in drying processes for all the studied methods and modes of energy supply by a single generalized equation $\frac{u}{u_0}=f\left(\frac{N\tau}{u_0}\right)$. This indicates that the patterns of drying kinetics are the same, and the complex $\frac{N\tau}{u_0}$ takes into consideration the effect of the method and mode of energy supply and material properties.

A blow through a layer of a drying agent simultaneously with bulk MW heating intensifies inter-component heat and mass transfer, accelerates evaporation of moisture moving as a result of thermal diffusion from the bulk of grains to their surface. As a result, the drying rate increases significantly (almost three times), the duration of the process and the specific energy consumption decrease (by about 40 %). In this case, the complexity of the plant due to the system of transport and air heating is fully justified.

It was the first time when comparison of a series of different ways of energy supply, carried out according to the results of complex experimental studies, was performed. We carried out the studies using one unified experimental setup and grain material with a fixed initial moisture content, which determines the reliability of this comparative analysis. Conducted comprehensive experimental studies solve the problem of selection of the optimal method of drying using microwave heating and assessment of rational mode parameters such as: specific energy consumption, temperature of a drying agent and duration of drying. This opens up a possibility of transition to an energy-efficient and intensive technology of drying of grain materials.

The research results apply to grain materials with an initial moisture content of 20 %. It is not possible to apply them to materials of another type with high moisture content. The disadvantage of the study is that the source of microwave energy was a magnetron with a generation frequency of 2,450 MHz, which imposes restrictions on the choice of frequency of microwave oscillations. In addition, the recommendations received apply to fixed-layer apparatuses; dryers with a moving layer require separate studies.

We recommend to investigate sustainability of magnetrons operation during long-term operation of industrial devices and increasing of efficiency of a microwave drying chamber in future. It is also necessary to determine an influence of changes in moisture content during the drying process on energy consumption, which will make it possible to regulate and optimize power of heat sources.

7. Conclusions

1. We determined that the kinetics of drying grain materials under microwave heating is characteristic for the kinetics of drying colloidal capillary-porous bodies at other methods of heat supply. There are periods of heating, constant and falling drying rates. It is possible to summarize moisture content and temperature curves for barley, oats, buckwheat and wheat by single equations with an acceptable error: the error is ±9.8 % for dimensionless moisture content $\bar{u}/u_0$, and it is ±11.9 % for dimensionless temperature $\bar{t}/t_1$.

2. Pulsating microwave heating gives possibility to conduct the drying process sparingly for grain. The drying rate N=4.4·10^{-4} s^{-1} is lower under the pulsating mode, in comparison with continuous MW drying N=10.3·10^{-4} s^{-1}, but with an acceptable temperature of material. In this case, energy consumption differs slightly. The specific energy consumption per 1 kg of evaporated moisture at the microwave drying is 6.98 MJ/kg, at the pulsating one – 8.13 MJ/kg.

An increase in duration of the period of convective supply leads to a decrease in temperature of material at the cyclic microwave-convective drying. It is not expedient to increase duration of the period of convective supply in excess of 10–20 s. The average drying rate for the entire process is

$4.3\ 10^{-4}\ s^{-1}$ under the optimal mode, the material temperature is 80.5 °C, the specific energy consumption is 9.07 MJ/kg.

3. Comparison of the main characteristics of the drying process at different methods of energy supply showed that the simultaneous MW-convective method of supply is optimal. It provides the drying rate about three times higher and the specific energy consumption 40 % lower than at a pulsating MW supply. The mode with the following characteristics is preferable: the output power of the magnetron is P=600 W, the temperature of the air flow is t_{air}=19 °C, the rate is w_{air}=0.7 m/s. The drying rate is N=12.71 $10^{-4}\ s^{-1}$ under the mentioned conditions, the specific energy consumption (per 1 kg of evaporated moisture) is q_{sp}=5.69 MJ/kg moisture.

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