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Yevgen Pylypenko,
Dmytro Zaporozhets

EXPERIMENTAL STUDIES OF THE PLANT RAW MATERIAL DRYING PROCESSES IN THE CONDITIONS OF INFRARED AND MICROWAVE FIELDS

The object of research is the process of drying food plant raw materials. Among the existing methods of drying, convective has become the most common in industry, due to its practicality and ease of organization. However, modern convective drying technologies are accompanied by high-energy consumption, which is a serious problem in the conditions of global energy shortage. An analysis of options for solving drying problems proposed by the scientific community was carried out. The paper presents a solution to the problem through the use of electrodynamic dehydration technologies based on directed energy action. The principle of operation of such technologies is that the electromagnetic field directly interacts with polar molecules, which includes water, which leads to a significant increase in the energy efficiency of the drying process and a reduction in its duration. A set of experimental studies aimed at determining the effect of regime parameters, namely specific power, thickness of the product layer and type of edible vegetable raw materials on the drying process under the conditions of infrared and microwave fields, was carried out. The obtained graphic dependences indicate that the treatment of raw materials with ultra-high frequency radiation significantly reduces the time of the drying process and, as a result, is characterized by a low thermal load on the product, which is a significant advantage when processing heat-labile raw materials. This is due to the deeper penetration of the microwave field (up to 30 mm) compared to infrared (up to 0.003 m). In order to determine the effectiveness of innovative equipment, the paper presents the number of energy action, thanks to which a generalization of the experimental data base was carried out. As a result, criterion equations were obtained, which with an accuracy of ±16 % make it possible to calculate drying devices with infrared and microwave energy sources.

Keywords: *drying, dehydration, infrared and microwave radiation, edible vegetable raw materials, experimental modeling.*

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1. Introduction

Preservation of fruits and vegetables by drying method is one of the oldest types of preservation. The dynamics of the world market of dry food concentrates is growing steadily. There is a special interest in dried fruits and vegetables on the world market. Thus, over the past 4 years, the growth in the volume of sales of dried fruits has increased from 7.94 to 8.73 million tons. They contain a small amount of moisture (8–25 %), which ensures their long-term storage, high safety of quality and nutrients. During drying, the mass of the product is reduced by 75–80 %, which significantly reduces costs during long-distance transportation.

Convective drying, in which the drying material is in direct contact with the heat carrier, heats up and gives off moisture, has become the most widespread. Most drying equipment works on this principle. However, in almost all convective dryers, more than half of the energy used in the technology is lost. In conditions of moderate prices for energy carriers, convective drying technologies were fully justified and their spread was expedient. But the situation in the modern markets of energy carriers, the dynamic trends of price growth require urgent decisions regarding the introduction of progressive approaches in drying technologies, an important criterion for the assessment of which would be the energy characteristics [1]. Therefore, in recent years, fundamentally new drying units with electromagnetic energy sources have been actively researched in the world.

The main feature of electrodynamic drying devices is their effect directly on the moisture contained in the material and practically without losses on heating the material itself. This method of energy supply is highly efficient and allows for quick (inertia-free) control of the heat supply process. Combined drying methods allow combining the advantages of traditional and innovative types and compensating for individual limitations of each of them, as a result of which it is possible to obtain a drying method that may be technically difficult to implement, but with excellent indicators of productivity and/or quality of the dried product. Below is a series of studies devoted to studying the advantages and limitations of innovative and combined drying methods compared to classical dehydration methods.

Thus, scientists from Huazhong Agricultural University and Yichang Academy of Agricultural Sciences (China, 2019) conducted a number of experimental studies on the influence of various drying methods on the taste and chemical composition of black tea [2]. Along with traditional convective drying, microwave (MW) energy input, infrared (IR) drying, drying using a halogen lamp (HL) and the combined HL-MW method are considered in the work. As a result, it was established that with the use of MW technologies, black tea acquires a more uniform black color, a fresher taste and a sweeter aroma.

At the University of Warmian-Masurian Voivodeship (Olsztyn, Poland, 2018), hybrid vacuum MW drying with reverse osmosis was applied to cranberries, the principle of which consisted in the sequential application of reverse osmosis and the introduction of MW energy [3]. As a result, samples were obtained with a final moisture content of 15 % with an initial moisture content of 90 %.

In 2021, on the basis of Hunan University of Humanities, Science and Technology (China), the process of MW drying of corn grains, the initial moisture content of which was 54.6 %, was investigated [4]. The radiation power of the MW energy was 70 and 280 W, while the temperature of the raw material was at the level of 83 °C and 97 °C, respectively. In the end, a product containing only 13 % moisture was obtained. Similar studies were conducted in 2019 at the State University of Goias (Brazil) and McGill University (Canada) [5].

In 2018, scientists from the Universities of Sfax and Monastir (Tunisia) investigated the combined use of convective and MW energy supply methods for drying tomatoes [6]. The authors indicated that the use of electromagnetic radiation during dehydration of tomatoes contributes to better preservation of color and antioxidants.

A comparative analysis of convective and MH drying processes, as well as their combination, was conducted in 2019 by the scientific community of the University in Jiangnan (China), the Research Institute in Nanjing (China), and the University of Benin [7]. The product was slices of taro tubers, a popular food plant in Africa, Southeast Asia, and other tropical regions. During the sequential application of convective and MH drying with different radiation powers, the average temperature of the slices varied between 57–73 °C, but local overheating up to 90 °C also occurred, despite the presence of a vacuum system. But despite all this, the authors noted that the use of MH technologies in the drying process makes it possible to obtain a finished product of higher quality along with classic dehydration technologies.

Similar studies were conducted at the Universities of Igdir and Bursa (Turkey, 2019) [8], as well as at Gaziantep University [9]. In work [8], the raw material is pomelo with an initial moisture content of 86.8 %. The experiments were carried out at atmospheric pressure, the temperature of the heat carrier varied between 55–75 °C, the strength of the electromagnetic field was 90 and 160 W. The conclusions also note a number of advantages of MW drying, which consist in reducing the process time, high drying speeds and the quality of the finished product. In studies [9], similar manipulations were carried out with cherry berries. The combined convective-MW method was carried out at temperatures of the drying agent of 50–70 °C at a speed of 0.5 m/s and at a power of the MW field from 120 to 180 W. The moisture content of cherries was reduced to 25 % from the initial 80.75 %.

Quite interesting results were obtained in 2020 by scientists from the University of Mohage Ardabili (Iran) and the Autonomous University of Guerrero (Mexico) when drying the fruits of the turpentine tree using various technologies, including IR and MW methods [10]. As a result, it was noted that microwave drying is characterized by the least compression of fruits, low specific energy consumption and high energy efficiency.

Based on the analysis of the above-mentioned studies, it can be concluded that the use of the most modern microwave and combined IR-MW technologies and equipment in the drying industry would allow to significantly reduce energy costs for production. To do this, switching from fuel for the creation of combustion gases to electricity, which will go directly to heating the product, and not to adjacent energy carriers. However, the considered works do not fully reveal the prospects of these technologies and there is no clear scientific basis that would be the basis for the development of innovative equipment on a semi-industrial and industrial scale.

The aim of research is the creation of innovative energy-efficient equipment for the production of high-quality dry product from plant raw materials and the development of scientific and engineering principles for the design of such equipment.

2. Materials and Methods

The object of research is the process of drying food plant raw materials.

2.1. Analytical modeling of drying processes in an electromagnetic field. Analytical modeling is based on the «dimensional analysis» method, which was used to obtain a criterion equation in the form of dimensionless variables. In [11], the number of energy action, which takes into account the action of the electromagnetic field, is proposed:

$$Bu = \frac{N}{rwd^2\rho}, \tag{1}$$

where N – strength of the electromagnetic field, W; r – phase transition heat, J/kg; w – movement speed of the diffusion medium, m/s; d – equivalent diameter, m; ρ – liquid density, kg/m^3.

The physical meaning of the number is to establish the ratio between the radiated energy and the energy required to convert all the water containing the product into steam.

As the number of Bu approaches 1, the formation of the vapor phase increases, the pressure gradient increases, and the intensity of the release of saturated steam from the middle of the capillaries increases. Turbulization of the boundary layer increases, but heating of the solid phase and energy consumption increase. The Vu number characterizes the micro- and nanokinetics of mass transfer by barodiffusion [12–15]. The structure of the criterion equation in the form of dimensionless variables under the conditions of a stationary layer of raw materials and the flow of a diffusion medium will have the form:

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$$Sh = A \cdot Re^n \cdot Sc^m \cdot Bu^k, \quad (2)$$

where Sh – Sherwood number; Re – Reynolds number; Sc – Schmidt number; Bu – Bourdeau number; A, n, m, k – constants (obtained experimentally).

For devices in which the dispersed product layer is mixed, this intensification factor is taken into account by the Péclet (Pe):

$$Sh = A \cdot Re^n \cdot Sc^m \cdot Bu^k \cdot Pe^p. \quad (3)$$

The constants in relations (2) and (3) are determined as a result of experimental modeling of drying processes.

2.2. Experimental modeling of drying processes in an electromagnetic field. Experiments to determine the effect of regime parameters on the kinetics of the drying process in IR (Table 1) and MW (Table 2) fields were conducted with carrots, apples and onions in the form of slices.

Table 1

The range of experimental studies of IR drying of food raw materials

Raw aterial	Specific power q, kW/m^2	Slice thickness h, m	Loading mass m, kg	Tempera-ture t, °C	Duration of the process τ, p
Carrot	1.9–11.3	0.003–0.01	0.050	50–100	1200–3600
Apples	6	0.003	0.050	60–100	2100
Onion	6	0.003	0.050	60–90	3300

Table 2

The range of experimental studies of MW drying of food raw materials

Raw material	Specific power q, kW/m^2	Slice thickness h, m	Loading mass m, kg	Tempera-ture t, °C	Duration of the process τ, p
Carrot	6	0.003–0.01	0.050	50–90	1200
Apples	6	0.003	0.050	50–60	1200
Onion	6	0.003	0.050	50–60	1200

Research on the drying process was carried out on an experimental stand (Fig. 1), the principle of which consists in the effect of infrared and microwave fields on plant raw materials for the purpose of drying the product.

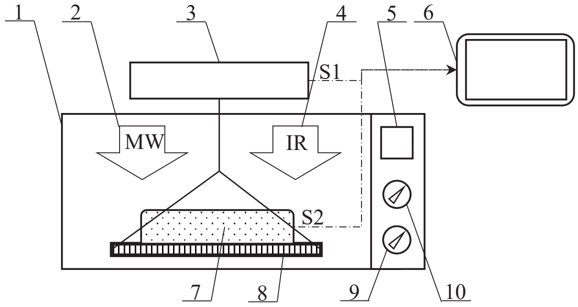

Fig. 1. Scheme of a universal stand for researching drying processes in electromagnetic fields: 1 – drying chamber; 2 – MW generator; 3 – electronic scales; 4 – IR generator; 5 – time table; 6 – data collection and payment system; 7 – vegetable raw materials; 8 – cassette; 9 – power regulator of the MW generator; 10 – IR generator power regulator; S1 – signal from electronic scales; S2 – temperature sensor signal

The experimental stand consists of a drying chamber 1, in which a cassette 8 with plant material 7 is placed. The power of the MW 2 and IR 4 emitters is set by regulators 9 and 10, the duration of operation is displayed on the analog sensor 5. The weight change is recorded on the Radwag PS 750.R1 electronic scale 3 (Poland). Using the CHUWI CW1506 tablet 6 (China) and the Arduino Nano controller (China), the system of automated collection and processing of data coming from electronic scales S1 and temperature sensor S2 Dallas DS18b20 (USA) was implemented. As a result, the thermogram, drying curves and drying speeds were displayed on the display screen. The amount of electricity consumed by the installation was recorded using the Feron TM55 energy meter (China).

3. Results and Discussion

3.1. Experimental studies of the drying process under the conditions of the IR field. At the first stage, studies of the influence of the level of reduced power of IR radiation were carried out on the example of carrot slices with a thickness of 0.003 m and a radius of 0.025 m.

The analysis of the effect of the supplied power on the change in product moisture content (Fig. 2) showed that the time spent on drying to the required moisture content of 11–15 % is 1100–4600 s.

The temperature of the product (Fig. 3) did not exceed 100 °C. At a power of 1.9 kW/m^2, the temperature did not exceed 63 °C even during long-term processing of raw materials. Short-term processing of raw materials at the indicated temperatures will not affect the quality of the finished product and will preserve the nutritional value of the raw materials. But this fact should be verified on the basis of tasting studies of ready dried carrot samples.

The next factor that determines the drying kinetics of vegetable and fruit slices is the thickness of the layer. Since the penetration depth of IR radiation does not exceed 0.003 m, experiments were conducted with a layer thickness higher than this value. In the experiments, the thickness of the layer of carrot slices was 0.003, 0.005, 0.007 and 0.01 m, with a radius of 0.025 m. The power of IR radiation was 6 kW/m^2.

As a result of the experiments, the dependence of the change in product moisture over time was established (Fig. 4). As the layer thickness increases, the limited penetrating ability of IR radiation slows down the drying process. The duration of the process increases with the growth of the layer thickness. Carrots are dried to the required moisture for 2100 seconds, when the layer thickness increases by 1.7 times, the process time increases by 1.5 times, when it increases by 2.3 times, the process time increases by 2 times, and when the layer thickness increases by 3.3 times time increases by 2.4 times.

As the layer thickness increases, the drying temperature (Fig. 5) of the product decreases, as IR radiation affects the surface 0.003 m of the product. Heat from the surface of the product passes to the lower layers, thereby reducing the temperature of the product on the surface. A series of experiments conducted on carrots allow to conclude that it is advisable to dry slices with a layer thickness of no more than 0.003–0.005 m.

When determining the effect of the type of product on the drying kinetics, all products were cut into slices with a thickness of 0.003 m and a radius of 0.025 m.

The mass of loading the cassette with the product was 50 g. The power of the supplied energy was 6 kW/m^2.

The change in product moisture (Fig. 6), depending on the type of product, to the required value of 11–15 % is 2000–3000 s. Onion drying time is the longest, other products have approximately the same drying speed.

Temperatures (Fig. 7) of different types of vegetables and fruits have almost the same growth pattern.

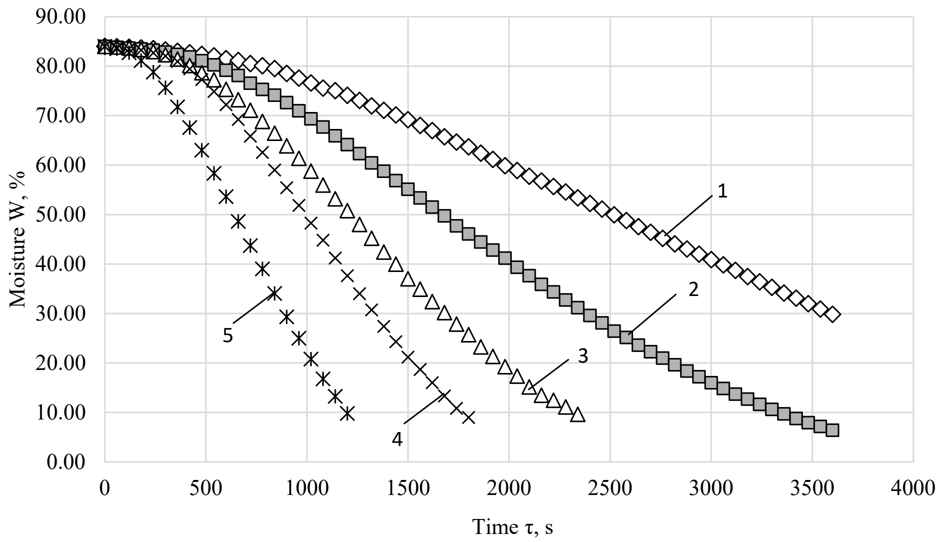

Fig. 2. The influence of the level of the supplied power of IR radiation on the change in product moisture content over time: 1 – 1.9 kW/m^2; 2 – 3.8 kW/m^2; 3 – 6 kW/m^2; 4 – 8.8 kW/m^2; 5 – 11.3 kW/m^2

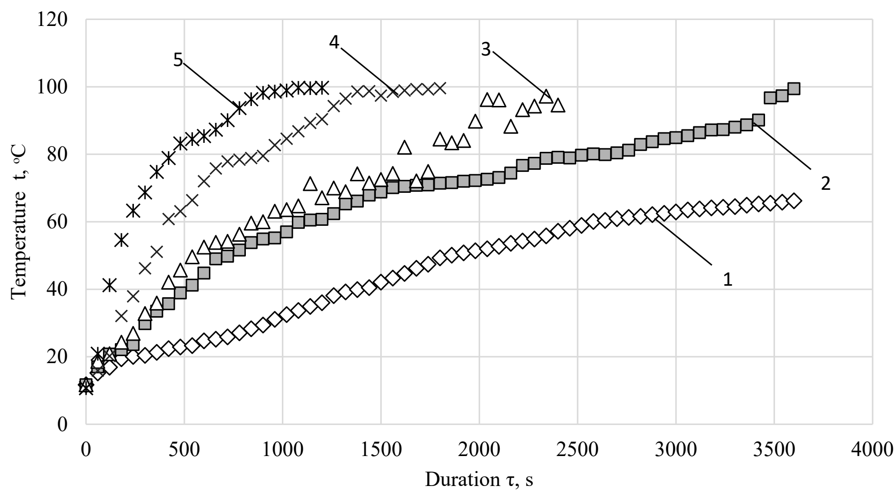

Fig. 3. The influence of the level of the supplied power of IR radiation on the change in the temperature of the product over time: 1 – 1.9 kW/m^2; 2 – 3.8 kW/m^2; 3 – 6 kW/m^2; 4 – 8.8 kW/m^2; 5 – 11.3 kW/m^2

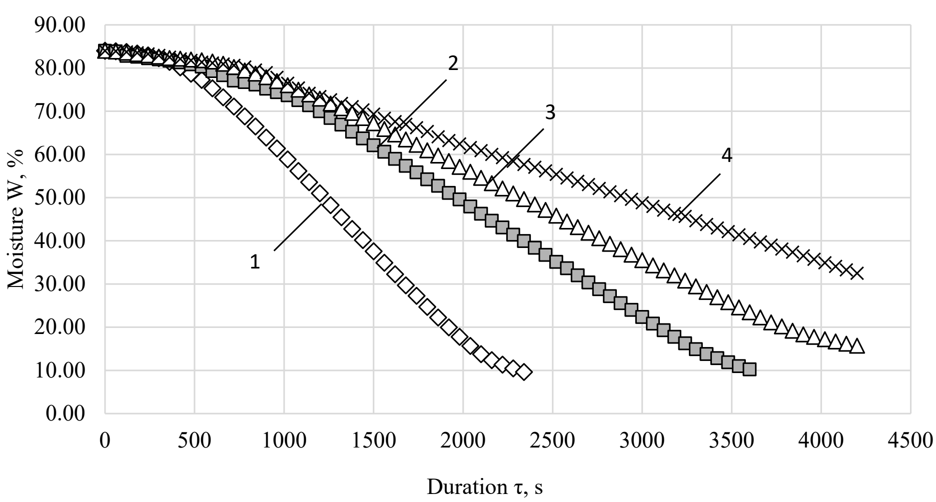

Fig. 4. The influence of the layer thickness on the change in product moisture over time: 1 – 0.003 m; 2 – 0.005 m; 3 – 0.007 m; 4 – 0.01 m

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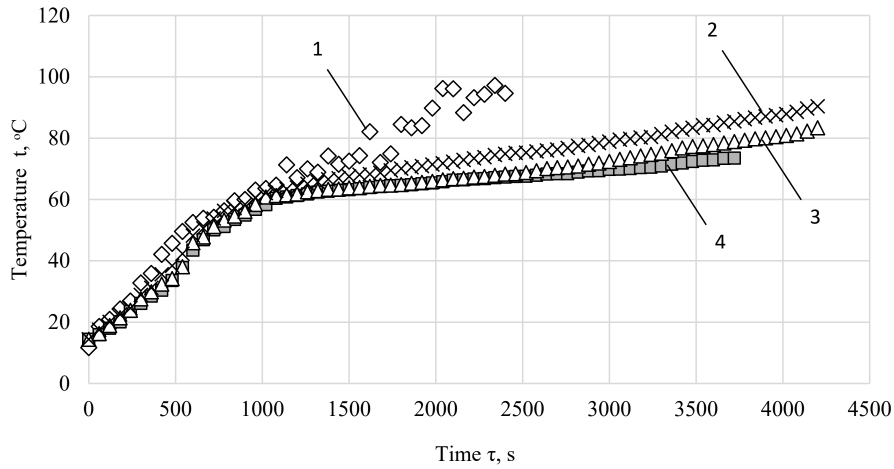

Fig. 5. The effect of layer thickness on the change in product temperature over time: 1 – 0.003 m; 2 – 0.005 m; 3 – 0.007 m; 4 – 0.01 m

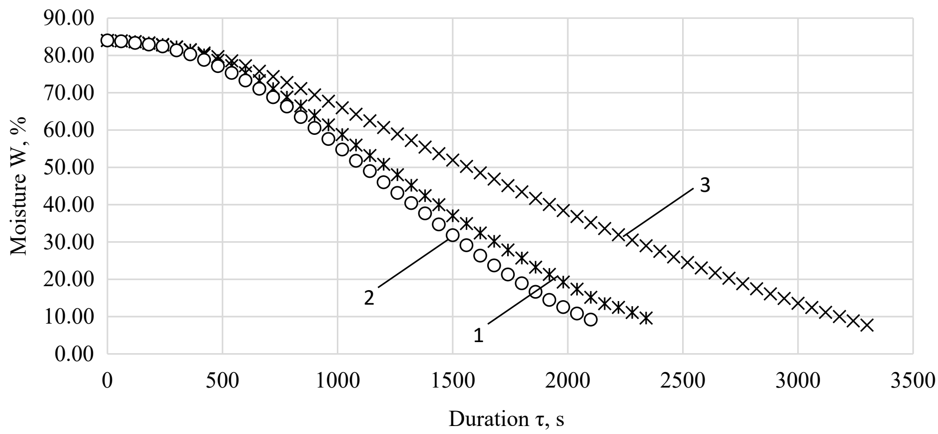

Fig. 6. Changes in moisture content of slices of vegetables and fruits over time: 1 – carrot; 2 – apple; 3 – onion

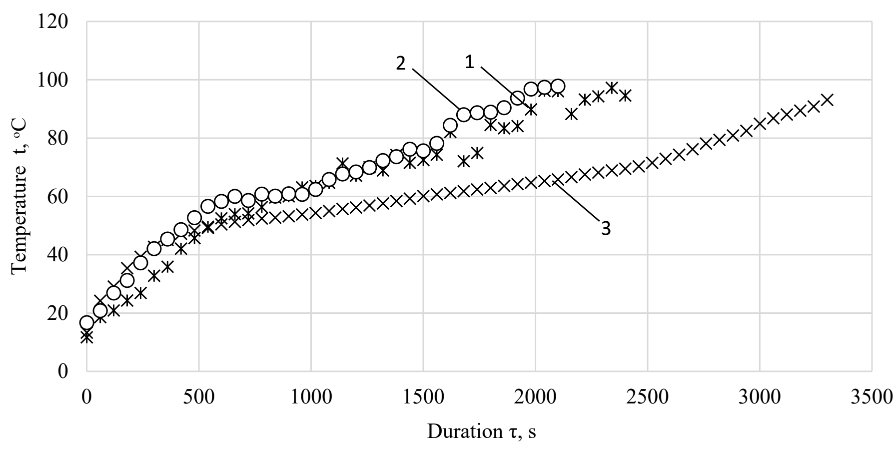

Fig. 7. Thermograms of slices of vegetables and fruits over time: 1 – carrot; 2 – apple; 3 – onion

These studies determined the influence of significant factors (power and layer thickness) on the product drying process.

3.2. Experimental studies of the drying process under the conditions of action of the MW field. Studies of the influence of layer thickness on drying kinetics were conducted at a specific power of MW radiation of 6 kW/m^2 with carrot slices. The radius of the slices is 0.025 m, and the thickness is 3, 5, and 0.01 m. The mass of loading the cassette with the product was 50 g.

It can be seen (Fig. 8) that, compared to drying in the IR field (Fig. 4), an increase in the thickness of the layer does not have a significant effect on the process of drying carrots. The thickness of the layer practically does not affect the duration of the drying process. It takes 1150 seconds to reduce the moisture content of the product from 84 % to 15 %.

The temperature of the product (Fig. 9) did not exceed 100 °C. An increase in the layer thickness has little effect on the rise in temperature when the MW energy is added.

Further studies of drying vegetables and fruits (carrots, apples, onions) were carried out with a layer thickness of

0.003 m and a specific power of the MW field of 6 kW/m^2. The weight of loading the cassette with the product was 50 g.

It turned out (Fig. 10) that the type of product has little effect on the kinetics of drying. The drying process when the moisture content of the product changes from 84 % to 15 % lasts 1000–1180 seconds.

Temperatures for carrots (Fig. 11) did not exceed 90 °C, and for apples and onions – 60 °C.

Processing of the experimental data base was carried out in accordance with the principles of obtaining the model (2), in the absence of the Reynolds number and the addition of the parametric dimensionless complex *H*, which takes into account the height of the raw material layer. For regimes in the IR field, the factor *Ff* was also introduced, which takes into account the specificity of the raw material.

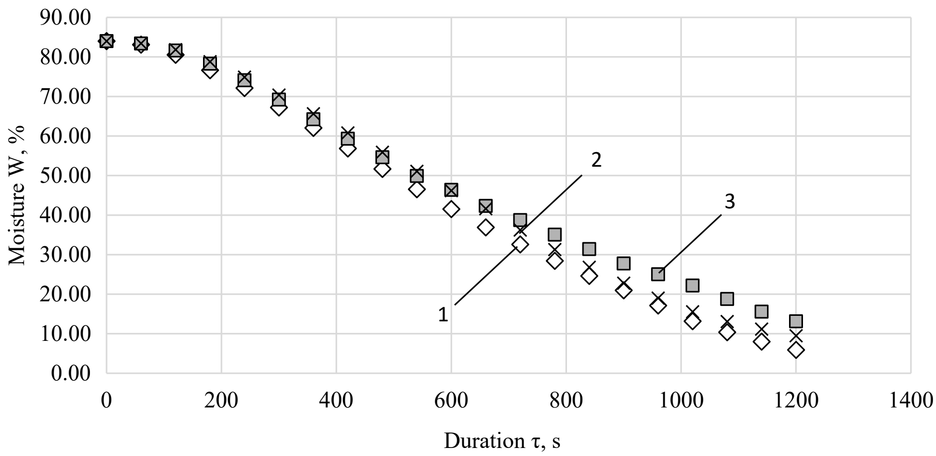

Fig. 8. The influence of the layer thickness on the change in product moisture over time: 1 – 0.003 m; 2 – 0.005 m; 3 – 0.01 m

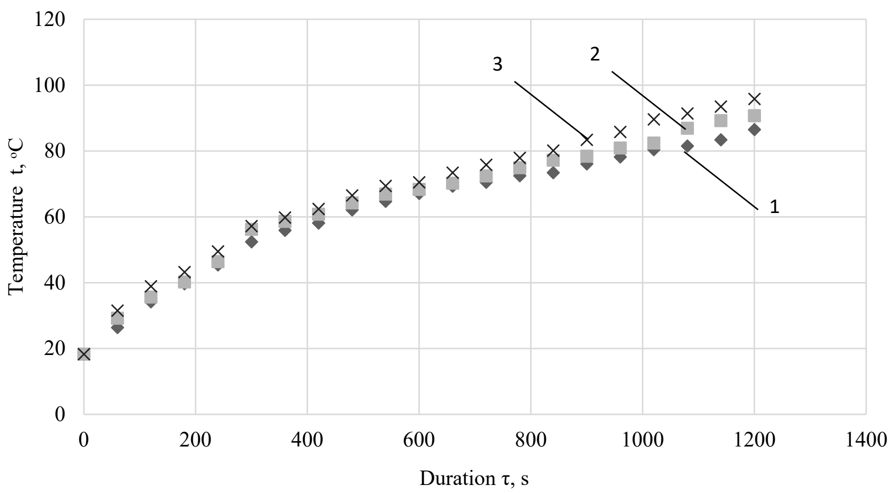

Fig. 9. The effect of layer thickness on the change in product temperature over time: 1 – 0.003 m; 2 – 0.005 m; 3 – 0.01 m

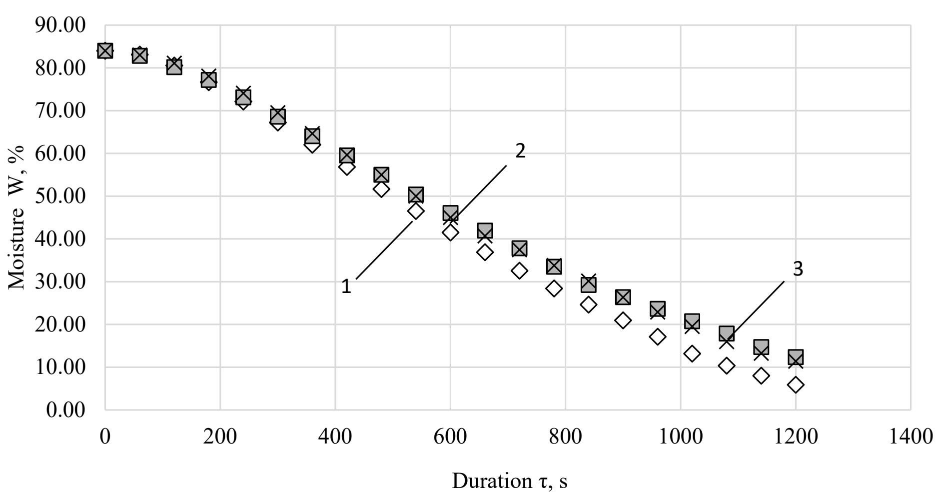

Fig. 10. Change in moisture of slices of vegetables and fruits over time: 1 – carrot; 2 – apple; 3 – onion

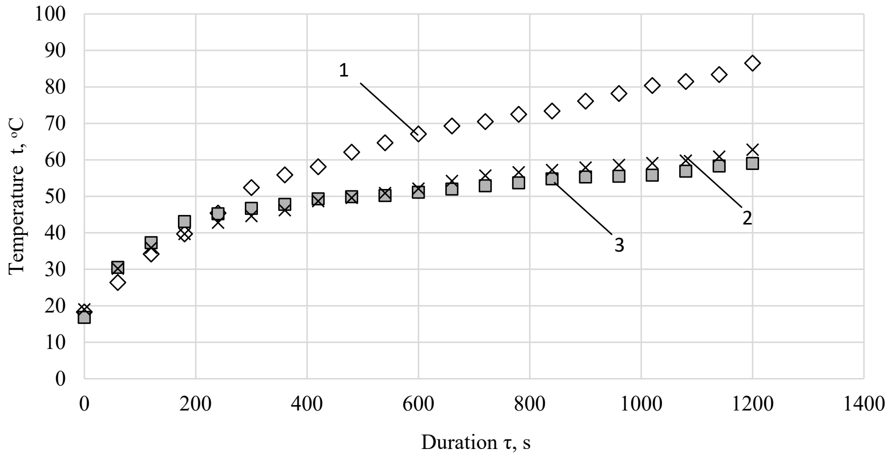

Fig. 11. Thermograms of slices of vegetables and fruits over time: 1 – carrot; 2 – apple; 3 – onion

As a result of processing, the following equation is proposed for calculating the intensity of dehydration of slices under the conditions of an IR field:

$$Sh = A \cdot Bu^{1.91} \cdot H^{-1.28} \cdot Ff^{-0.0037}, \quad (4)$$

and in the conditions of the MW field:

$$Sh = 7.1 \cdot 10^{-6} \cdot Bu^{7.18} \cdot H^{0.51}. \quad (5)$$

In a certain range of dimensionless variables (Table 3), these models with an error of no more than 16 % determine the intensity of mass transfer during dehydration of slices of vegetables and fruits.

As the advantages of the obtained studies, it can be highlighted that the above results are the basis for the design of innovative electrodynamic drying devices for a certain type of food raw materials in the corresponding ranges of regime parameter changes. Restrictions on the use of such installations are related to periodicity in the operating mode, which significantly affects the overall productivity and complicates the further implementation of the technology in production.

Prospects for further research are in the implementation of a continuous mode of operation and determination of the influence of the movement of raw materials on the kinetics of the drying process under conditions of IR and MW radiation, since this operating condition of such drying units is one of the mandatory ones for the introduction of such technologies into the production process. It is also planned to expand the range of food raw materials and carry out appropriate processing of the obtained results, which in turn will make it possible to obtain a more universal model for calculating dryers with IR and MW energy sources.

Table 3

Range of values of dimensionless variables

Product	A	Bu	H	Ff	Bu	H
	IR field				MW field	
Carrot	$0.6 \cdot 10^{-7}$	3.4–15	0.003–0.01	0.009–0.4	2.53–3.06	0.003–0.01
Apple	$13.6 \cdot 10^{-12}$					
Onion	$1.7 \cdot 10^{-9}$					

Since the introduction of martial law in Ukraine, the most negative factor that significantly affected the quality and continuous conduct of experimental research, as well as further processing of the data array, was the power outage. However, later, with the improvement of the state of the energy system in the country, the necessary experiments were successfully conducted.

4. Conclusions

The paper puts forward a hypothesis that the solution to the problem is possible when switching to innovative energy sources – electromagnetic generators of the infrared and microwave ranges. In the course of analytical modeling, implicit models were obtained in the form of criterion equations with generalized variables for the calculation of innovative equipment for dehydration of food raw materials. It has been established that dehydration processes (drying in an electromagnetic field) are able to reduce specific energy consumption almost to the theoretical level of up to 3 MJ per 1 kg of removed moisture. At the same time, the temperatures of the drying process mostly fluctuated between 60–80 °C under the conditions of the IR field and 50–70 °C under the conditions of the MW field, which is quite acceptable when processing heat-labile raw materials, which are usually food products. In addition, the duration of the dehydration process up to 10 % moisture in the raw material at an average specific power of IR and MW radiation of 6 kW/m^2 did not exceed 40 (IR) and 20 (MW) minutes. This indicates that food raw materials are not exposed to long-term thermal stress and thus there are serious reasons to believe that the quality of the final product is quite high compared to the results of traditional drying equipment. It was determined that the intensity of the process can be controlled by the parameters of the electromagnetic field. Approbation of the obtained models showed that when determining the intensity of mass transfer during dehydration of food raw materials, their accuracy varies within ±16 %. Electrodynamic devices have a significant reserve for increasing energy efficiency, since electromagnetic radiation interacts directly with moisture in the product. The obtained results confirm the above hypothesis and are of interest for improving the technologies of dehydration of food and medicinal plant raw materials on a production scale.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data.

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✉***Yevgen Pylypenko,*** *Postgraduate Student, Department of Processes, Equipment and Energy Management, Odesa National University of Technology, Odesa, Ukraine, e-mail: pylypenkojack@gmail.com, ORCID: https://orcid.org/0000-0001-8059-3835*

Dmytro Zaporozhets, *Postgraduate Student, Department of Processes, Equipment and Energy Management, Odesa National University of Technology, Odesa, Ukraine, ORCID: https://orcid.org/0009-0008-0567-4297*

✉*Corresponding author*