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RESEARCH OF METHODS AND MODES OF DRYING OF GLUTEN-FREE PASTA

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Abstract

The current problem is the provision of different countries with food products for the health and dietary purposes. For patients with celiac disease with a violation of the protein metabolism the treatment means exclusion of products containing gluten from the diet. A promising direction for expanding the range of such products is the development of the technology of pasta from corn flour.

The properties of corn pasta in comparison with wheat pasta are investigated in this work. The kinetics of drying and indicators of quality of wheat and corn pasta for convective, thermo-radiative and thermo-radial-convective methods of energy transmission have been studied. Different variants of combined drying methods, their influence on product quality and energy consumption during drying have been investigated: with the use of thermo-radial-convective drying in the first period, and subsequently - convective drying; with application of the thermo-radiative method in the first period to reaching the first critical humidity, and in the future - convective method; with application of the thermo-radiative method to reaching the first critical humidity, in the second period - 15 minutes of drying by thermos-radial-convective method and post-drying by convective way.The strength of pasta was determined on a Stroganov device, in Newtons (N). The transfer of dry matter into cooking water was determined after cooking until done, in% of dry matter (DM).

Application of thermo-radial-convective drying in the first drying period, and in the second period - convective drying promotes the obtaining of wheat and corn pasta of the best quality. The strength of wheat products is 3.7 N, and the rate of transition of dry substances to the cooking water - 10.7% to DM. The strength of gluten-free corn products is 3.5 N, dry matter transition - 13.9% to DM. This method also contributes to a reduction of energy consumption for the drying of wheat pasta by 1.1 times compared to the convective method for corn pasta by 1.35 times and is, respectively, 2.28 and 1.72 kW / kg of raw products.

It is proved that the use of thethermo-radial-convective method in the first period of drying of gluten-free pasta, and in the second period of the convective method allows to reduce energy consumption by 1.5 times and to ensure good quality of products.

***Key words**: Gluten-free pasta, Thermo-radiative drying, Energy consumption.*

1. Introduction

Nowadays humanity needs the provision of food products for health and dietary purpose in sufficient assortment. Recently, the number of diseases with metabolic disorders, including protein substances, such as phenylketonuria and celiac disease, has increased. Prevention and treatment of these diseases is provided by special diet. In particular, for patients with celiac disease, it means exclusion of products containing gluten from the diet.

Gluten-free pasta can be practically made from corn, rice, or buck wheat flour. Use of different raw materials requires the improvement of technological production regimes.

Different authors developed the technology of gluten-free pasta from corn flour [1, 2]. The most important process in pasta manufacturing is drying [15, 17, 18, 19, 24, and 26]. Predominantly, the convective method of drying is used in the pasta technology. From correctly selected parameters of this process, the following indicators of quality of finished products depend to a large extent: strength, vitreousness, breakage condition and cooking properties [21, 22, 25, 30, and 31]. However, drying of pasta is the longest process of production and it is the most energy intensive.

Promising direction in drying food products is the use of infrared radiation [16, 31, 32, 33, and 34]. In thermo-radiative drying, process of removing moisture is intensified due to a significant increase in the density of the heat flow on the surface of the irradiated material, and the penetration of infrared rays to the middle of the material. Infrared heating is more intense when heat is transferred from the heated drying air [3]. Consequently, the intensification of the processes of drying pasta can be achieved by using thermo-radiative drying method. However, the thermo-radiative method of drying has not found significant distribution in pasta production.

Many authors [4, 5, 10, 12, 14, 29, 33, and 34] have established the feasibility of using intermittent infrared irradiation, or a combined thermo-radial-convective method for drying pasta [31], but data on the use of these methods is limited. It is known [6], that with prolonged action of infrared radiation, moisture from pasta is removed more quickly, which can lead to cracks. This is primarily due to peculiarities of pasta dough and raw pasta as objects of drying. Pasta dough from wheat flour is a colloidal capillary-porous body, and during its drying moisture gradient crosses the product and a shrinkage of the product occurs, which leads to stress in various layers of products and their cracking [7]. Therefore, to justify different methods and modes of drying pasta, it is important to know their characteristic as an object of drying [13, 20, 23, 27, and 28].

Pasta dough and products from corn flour do not contain gluten - the main structure-forming component. They are structured by the use of various structure-forming agents [8].

Therefore, the aim of this paper: to study properties of pasta dough from corn flour as an object of drying and to investigate progressive methods of drying pasta, aimed at improving their quality, reducing the length of the process and reducing energy costs is an important task in the pasta field.

2. Materials and Methods

Experimental part of the work was carried out in the laboratory of the Department of Processes and Apparatus of Food Production and the Department of Technology of Baking and Confectionery products at the National University of Food Technologies in Kyiv, Ukraine.

Pasta was made in the laboratory pasta press «MAKMA-M» in the form of short cut noodles. Dough with moisture content of 36% was mixed for 10 minutes, a warm basal was used at a temperature of 70 ^{0}C. Gluten-free pasta was made from corn flour of fine grinding and extruded corn flour with dosing extruded flour 20% to the mass of the mixture. Dried corn and wheat pasta was spread out in a thin layer (1 cm) on a special grid in a box-shaped net basket that was mounted in the drying chamber. Weight of pasta was 200 g. Raw pasta was dried in a thermo-radial-convective drying apparatus [9], to a mass fraction of moisture in products of 13%. Mass reducement was determined every 5 minutes with the help of a registration node made on the basis of technical scales.

In the first series of experiments for comparing properties of pasta from wheat and corn flour, was drying by a convective method with air temperature in the chamber 40 ^{0}C, air velocity was 1.5 m/s, and relative humidity was 70%. Changes in the characteristics of the process for wheat and corn pasta were also studied in the thermo-radiative drying process, which was carried out in a pulsating mode - the irradiation and detaching time was 41 and 136 s. respectively, as well as with the use of the thermo-radial-convective method while simultaneously supplying the heat of infrared rays and the external convective heating, when the irradiation and detachment time was 32 and 121 s., respectively.

In addition, different variants of the combined drying method were studied with application of thermo-radial-convective drying in the first period, and in the subsequent - convective drying (option I); or with application of the thermo-radiative method in the first period until the first critical humidity, and in the subsequent - the conventional method (option II); or with the application of the thermo-radiative method until the first critical humidity, in the second period - 15 minutes of drying bythermo-radial-convective method and after-drying by convective method (option III). In all experiments, the influence of technological modes of drying on the quality of pasta was determined based on organoleptic, physical and chemical parameters and cooking properties, as well as energy costs.

3. Results and Discussion

3.1 Kinetics of drying and indicators of quality of wheat and corn pastaat convective, thermo-radiative and thermo-radial-convectivepower delivery

In Figure 1 are displayed graphs of drying kinetics and drying speed of wheat products when using different drying methods, and in Figure 2 the same for the corn products.

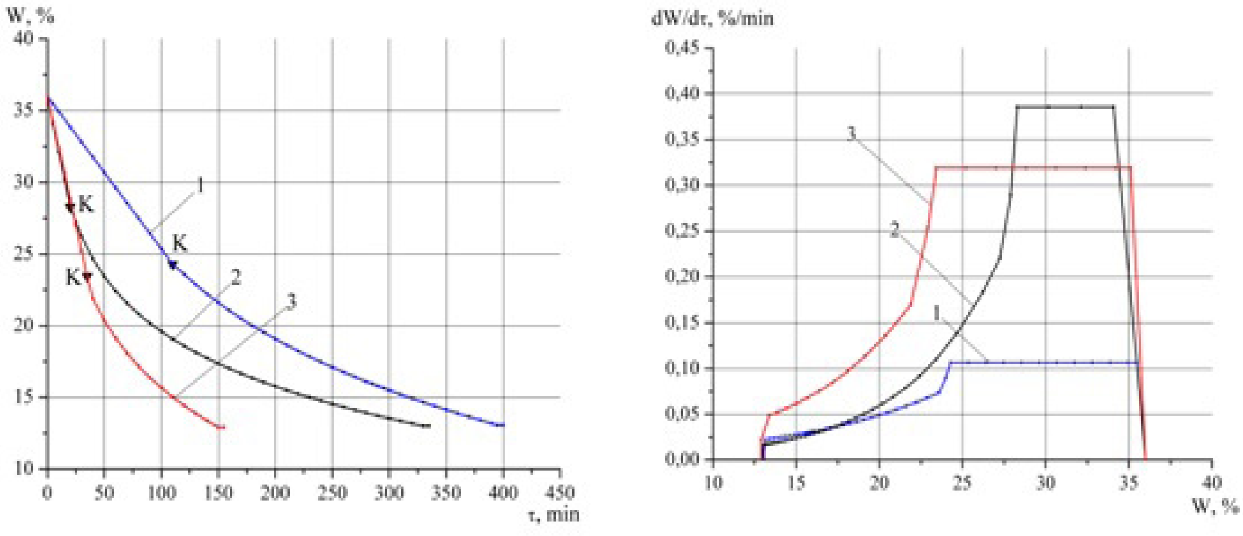

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Figure 1. Curves of drying kinetics W = f (τ) (a) and drying speed dW / dτ = f (W) (b) of wheat pasta at: 1 - convective method, 2 - thermo-radiative method, 3 - combined method

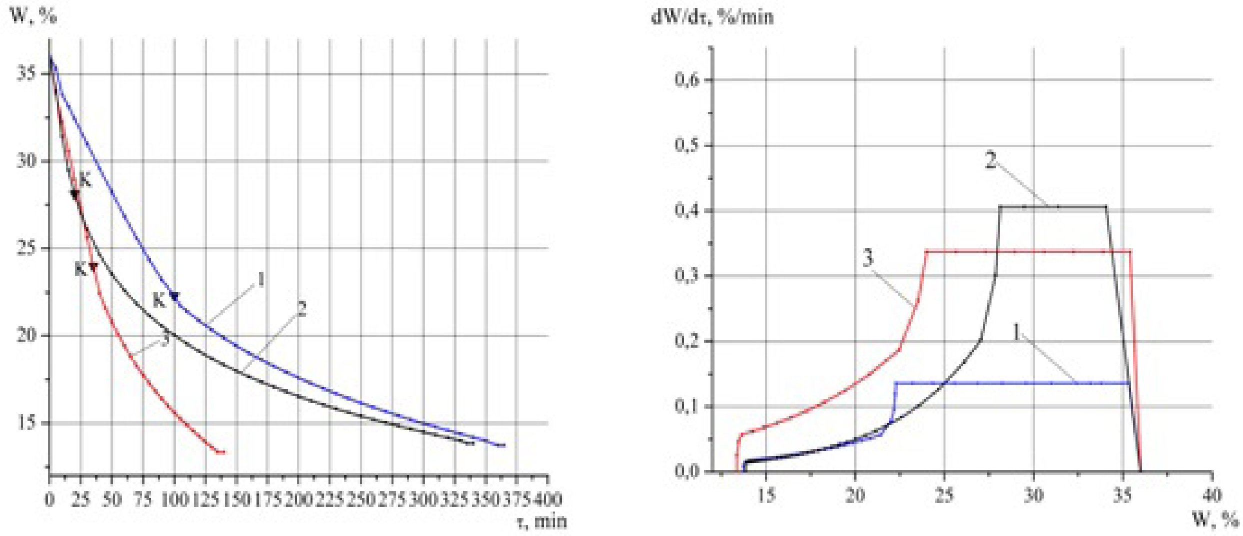

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Figure 2. Curves of drying kinetics W = f (τ) (a) and drying speed dW / dτ = f (W) (b) of corn pasta at: 1 - convective method, 2 - thermo-radiative method, 3 - combined method

It was established (Figure 1a) that the duration of drying of wheat pasta to 13% of humidity at convective method was the largest and was 400 min. at thermo-radiative - 335 min., and in the thermo-radial-convective method - 155 min. A similar dependence for different drying methods is observed when drying corn pasta (Figure 2a), but it was dried faster than wheat products and reached a moisture content of 13% for 350 min., 335 min., and 125 min. at convective, thermo-radiative- and thermo-radial-convectivemethods, respectively.

Data on the parameters of the drying process in the first period with constant drying speed are important for characterizing the product's properties as a drying object (Table 1).

Table 1. Characteristics of the process of drying wheat and corn pastaby different ways

Method of drying	Pasta	
	wheat	corn
	Drying speed in the first period, %/min.	
Convective	0.11	0.14
Thermo-radiative	0.39	0.41
Thermo-radial-convective	0.32	0.34
	Value of the first critical humidity of products, %	
Convective	24.3	22.3
Thermo-radiative	28.3	28.1
Thermo-radial-convective	23.4	23.9

Drying speed of both wheat and corn pasta in the first period was the lowest at the convective drying method and amounted to 0.11%/min. and 0.14%/min. respectively, and the largest at the thermal-radiation method: 0.39%/min. and 0.41%/min. In the case of a combined method, the drying speed was lower by 17 - 18% compared to the thermo-radiative method. However, the speed of drying of corn pasta at any drying method was somewhat higher, which obviously indicates a lower energy of binding of moisture in corn pasta.

Value of the first critical humidity for wheat pasta at the convective method was 24.3%, at thermal-radiation method - 28.3%, and at the combined - 23.4%. For corn products, in the case of using convective drying method, it was 22.3%, and it was lower by 2% compared to wheat products. However, when applying thermo-radiative and combined drying methods, the value of the first critical moisture content of corn products was slightly different and amounted to 28.1% and 23.9% respectively.

Thus, in spite of the growth of the drying speed in the first period, the drying process in general during the thermo-radiative method is intensified insignificantly. The energy of infrared radiation is mainly absorbed by the surface of the dried material, and in order to prevent its cracking and deformation and deterioration of the quality of the finished product, it is necessary to reduce the amount of supplied energy, although it reduces the drying speed and worsens the economic indicators of the process. Continuous supply of energy of infrared radiation worsens the same indicators, which creates a temperature gradient in the surface and near-surface layers, directed inside the product. This prevents heat transfer, which impairs the conditions of movement of moisture from the internal layers to the external. Water molecules that are on the surface of the material absorb rays and are heated [3, 7, 9, and 15]. Obviously, the air in the chamber during thermo-radiative drying is heated from the product of drying, so the heat that is lost is to be compensated for by additional irradiation, which leads to a deterioration of the quality of pasta. This dependence can be observed in Table 2, which shows the temperature of the air in the chamber and in different layers of pasta.

At the thermo-radial drying process, the temperature in all layers of products is considerably higher (about 4.0 - 11.5 ^{0}C) compared to the convective drying method, and the air temperature in the chamber remains lower by about 1 - 2 ^{0}C. At the combined heat transfer method, temperature of products in all layers is higher compared to the convective method by an average of 1.5 ^{0}C for corn products, and 4.0 ^{0}C at wheat flour products. The air temperature in the chamber is higher by 0.6 - 1.6 ^{0}C compared to the convective drying method. This dependence occurs both during the drying of pasta from wheat flour, and from corn flour.

Indicators of quality of wheat and corn pastaduring different methods of drying are given in Table 3.

Table 2. Temperature in the chamber and in the layers of wheat and corn pasta during drying by different ways

Method of drying	Temperature, ^{0}C, in the chamber I and in different layers of products			
	ir in the chamber	in the upper layer	in the middle layer	in the lower layer
	Pasta made from wheat flour			
Convective	40.9	41.3	40.7	40.2
Thermo-radiative	38.9	80.7	66.2	51.6
Thermo-radial-convective	41.5	45.2	44.9	44.6
	Pasta made from corn flour			
Convective	40.7	41.9	41.1	40.9
Thermo-radiative	39.7	82.4	67.6	52.7
Thermo-radial-convective	42.3	43.2	42.9	42.5

Table 3. Indicators of quality of pasta and energy costs at different drying methods

Indicators	Pasta					
	from wheat flour			from corn flour		
	Used method					
	Convective	Thermo-radiative	Combined	Convective	Thermo-radiative	Combined
	Organoleptic characteristics					
Color	Creamy			Light yellow		
Surface	Smooth					
The presence of microcracks	Absent					
Fracture	Glassy					
Taste, smell	Inherent for wheat products			Inherent forcorn products		
	Physical and chemical characteristics					
Strength, N	4.1	2.0	2.9	5.0	2.2	3.2
	Cooking properties					
Preservation of the form	Stored, products do not stick together					
Weight increase coefficient, K_m	1.8	1.5	1.6	1.8	1.6	1.7
Volume increase coefficient, K_v	1.9	1.6	1.7	1.8	1.7	1.7
Transfer of dry substances into cooking water, % to dry matter	8.5	12.9	10.8	13.5	15.5	14.8
Energy costs, kW/kgof products	2.51	2.58	2.26	2.32	2.54	2.04

Experimental data show that corn pasta has slightly higher levels of strength than wheat products. But, according to the cooking properties, in particular, the indicator of the transition of dry substances into cooking water is the best for wheat products. Such a pattern is observed at different ways of drying of pasta. Obviously, this is due first of all to the chemical composition of corn flour - the higher content of carbohydrates, in particular, starch.

The best quality was achieved for the convective method of drying both wheat and corn products. Products had, in comparison with other drying methods, the smallest indicator of the transition of dry substances to the cooking water and the highest index of strength: for the wheat products, the transfer of dry substances into the cooking water was 8.5% to DM, and the strength - 4.1 N, for corn transition dry matter is 13.5% to DM, and strength - 5.0 N. Energy costs for convective drying are 2.51 and 2.32 kW/kg of raw products from wheat and corn flour, respectively. The worst quality products had at thermo-radiative method. Strength of wheat and corn products was the lowest, and the transfer of dry substances to the cooking water was the highest - 12.9 and 15.5% to DM, respectively. Energy costs at this method were the largest and amounted to 2.58 and 2.54 kW/kg of raw products, respectively. Apparently, this can be explained by the fact ththat for providing the humidity of 70% the chamber was filled with moisture, sprayed by ultrasound, to improve the quality of the product, but, according to different authors [3, 11], steam over the product delay the penetration of infrared rays to pasta, which leads to an increase the cost of the drying process.

When drying by the combined method, the physico-chemical parameters and cooking properties of the products are somewhat worse than by the convective drying method, but they are better than at the thermo-radiative method. For wheat products, the strength index is 2.9 N, for corn - 3.2 N, the speed of transition of dry substances to the cooking water is 10.8% to DM and 14.8% to DM for wheat and corn products, respectively. Energy costs, in comparison with other methods, are the lowest and are reduced to 2.26 and 2.04 kW/kg of raw products, respectively.

Consequently, the use of thermo-radiative drying method worsens the quality of pasta and is the most energy-consuming. It is obvious that the rapid removal of moisture from the surface of products by using infrared irradiation creates a moisture gradient, which leads to tensions in products and a decrease in the quality of pasta products. Fact that during the thermo-radiative method the drying speed is significantly increased, but the value of the first critical humidity is high - 28.3% and is reached in a short time - 20 minutes which is negative. Reducing energy consumption in the case of using thermo-radial-convective method is conditioned by uniform heating of the layers and intensification of the drying process due to the simultaneous heating of the product with infrared radiation and air in the drying chamber. Quality of products in the case of using the combined method is somewhat reduced compared to drying by convective way, but it is quite high. Consequently, application of the thermo-radial-convective method for drying pasta requires the establishment of rational modes of drying process: first of all, the duration and sequence of drying periods by thermo-radiative and convective methods.

3.2 Investigation of the influence of different variants of the combined method of energy transfer on the kinetics of drying and indicators of quality of wheat and corn pasta

In the next series of experiments, the thermo-radial-convective drying method was used in the first period until the first critical humidity was reached (within 35 minutes), and in the future - convective drying to the end of the removal of moisture (option I). Option II - in the first period until the first critical point of humidity was reached, thermo-radiative drying was applied for 20 minutes, and in the future - convective drying. In variant III, as in the previous one, thermo-radiative drying was used for 20 minutes until reaching the first critical humidity, after which another 15 min. thermo-radial-convective method (removal of osmotically bound moisture) was applied and in the future - convective until the required humidity was reached. Drying was carried out for the following parameters: relative humidity of air - 70%, air velocity - 1.5 m/s, and air temperature - 40 ^{0}C. With the use of infrared rays, wetting of products was not carried out. Curves of kinetics of drying and drying speed of wheat pasta are shown in Figure 3, and for corn products in Figure 4.

Main characteristics of the drying process of wheat and corn pasta in different drying modes are given in Table 4, and the influence of the modes of drying pasta on the temperature in different layers of pasta is given in Table 5.

It has been established that in the case of using first option of the combined drying mode, the speed of removal of moisture to the first critical humidity is the lowest, and the lowest values are for wheat and for corn products. In general, corn pasta is dried faster and in a shorter time.

Application of the thermo-radiative method of drying for 20 minutes in the first period, although it significantly increases the temperature in all layers of products, in the second period, the temperature in the upper layer of products decreases and becomes practically the same as in the first option, and in the middle and lower layers it is slightly higher (3.0 - 3.5 ^{0}C).

Corn products for the first drying mode have higher temperature than in the second period, due to the action of infrared irradiation, which intensively heats up the top layer. Corn products have higher temperature than wheat products in the middle and lower layers of products due to different structural and mechanical properties and as a result of the temperature conductivity and bond of moisture with colloidal pasta dough.

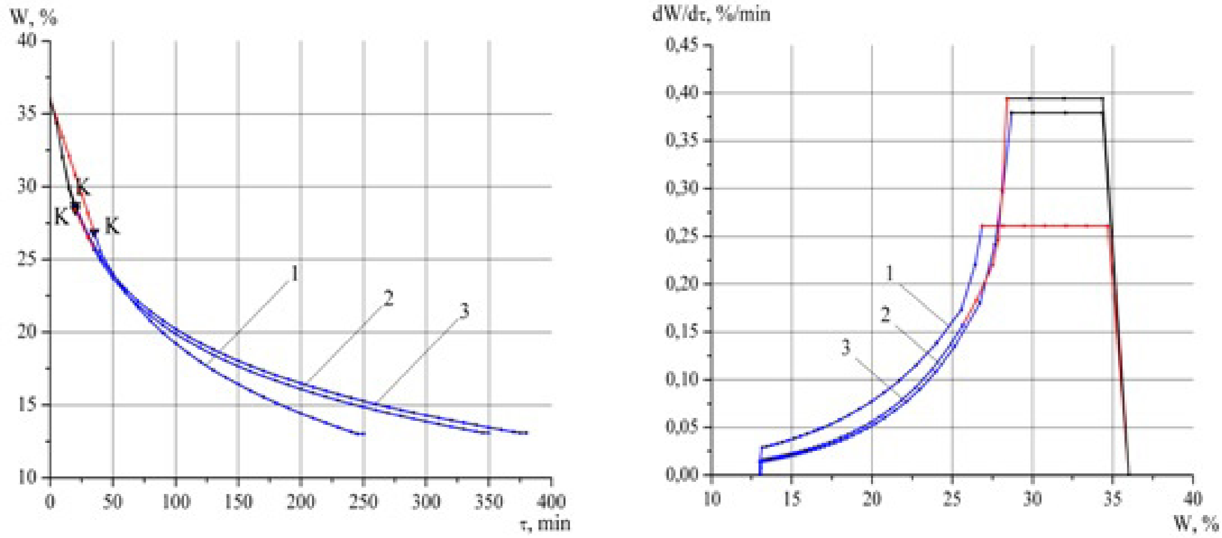

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Figure 3. Curves of drying kinetics W = f (τ) (a) and drying speed dW / dτ = f (W) (b) for wheat pasta at: 1 - option I, 2 - option II, 3 - option III

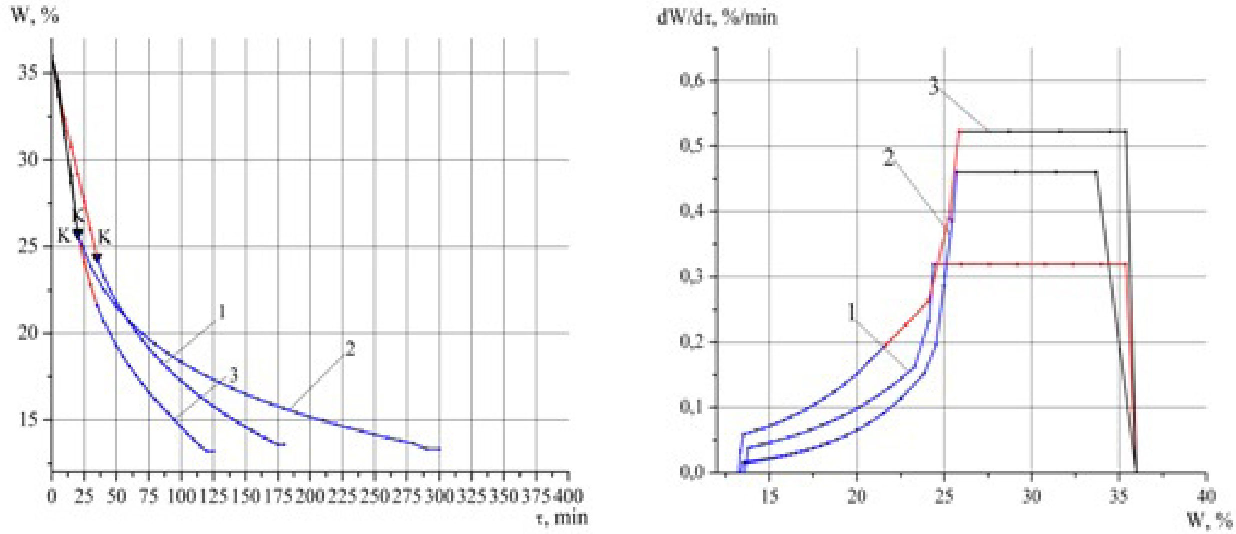

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Figure 4. Curves of drying kinetics W = f (τ) (a) and drying speed dW / dτ = f (W) (b) for corn pasta at: 1 - option I, 2 - optionII, 3 - option III

Table 4. Main characteristics of the drying process of wheat and corn pasta using different options of the combined drying method

Drying method option	Characteristics of the drying process		
	Time to remove free moisture, min	Drying speed in the first period, %/min	Total drying time, min
	Wheat pasta		
I	35	0.26	250
II	20	0.38	380
III		0.39	350
	Corn pasta		
I	35	0.32	180
II	20	0.46	300
III		0.52	125

Table 5. Influence of drying modes on temperature in layers of pasta

Method of drying	Temperature in layers of pasta, ^{0}C								
	I option			II option			III option		
	Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower
	Wheat pasta								
in the first period	Thermo-radial-convective			Thermo-radiative			Thermo-radiative		
	42.5	41.0	39.9	54.0	48.9	42.5	64.7	52.3	49.6
in the second period	Convective			Convective			Thermo-radial-convective (15min.)		
	42.3	38.4	36.5	42.3	41.1	39.7	48.7	47.5	46.2
							Convective		
							42.5	41.4	40.1
	Corn pasta								
in the first period	Thermo-radial-convective			Thermo-radiative			Thermo-radiative		
	42.9	40.9	39.7	56.2	49.0	46.3	64.3	51.0	49.5
in the second period	Convective			Convective			Thermo-radial-convective (15min.)		
	46.5	45.0	37.1	44.1	40.3	37.6	47.3	42.3	39.8
							Convective		
							47.8	46.2	37.9

Table 6. Indicators of quality of pasta and energy costs when different drying methods are combined

Parameters	Pasta					
	from wheat flour			from corn flour		
	Drying modes					
	I	II	III	I	II	III
	Organoleptic characteristics					
Color	Creamy		Yellow	Light yellow		Pale yellow
Surface	Smooth					
The presence of microcracks	Absent		Singles	Absent		Singles
Fracture	Glassy		Floury	Glassy		Barelyfloury
Taste, smell	Inherent for wheat products			Inherent forcorn products		
	Physical and chemical characteristics					
Strength, H	3,7	3,3	2,3	3,5	3,1	2,1
	Cooking properties					
Preservation of the form	Stored, products do not stick together					
Weight increase coefficient, K_m	1.8	1.7	1.5	1.9	1.7	1.7
Volume increase coefficient, K_v	1.9	1.7	1.6	1.8	1.8	1.7
Transfer of dry substances into cooking water, % to dry matter	10.7	11.8	13.4	13.5	13.9	14.7
Energy costs, kW/kg of raw products	2.28	2.47	2.36	1.72	2.10	1.95

Table 5 shows that the use of infrared rays in the first period increases the temperature in all layers of products, indicating an increase in the coefficient of potential conductivity. Obviously, the use of thermo-radial-convective drying is advisable to the starch gelatinization temperature (62 ^{0}C) and the denaturation of proteins (70 ^{0}C), since it contributes to the growth of the internal moisture transfer velocity (Figures 3b and 4b).

Table 6 shows the quality of pasta products for a combination of different drying methods.

It was found that the products with the lowest quality are the products of the third option of drying: for wheat pasta, the strength is 2.3 N, and the transfer of dry substances to the cooking water - 13.4% to DM; for gluten-free corn pasta strength is 2.1 N, and dry matter transition - 14.7% to DM. Application of infrared irradiation for 35 min. in the third option of drying results in a high speed of removal of moisture, which leads to the formation of microcracks and reduced strength of products. Somewhat better quality was for wheat products which were dried in the II option. They had cream color, glassy scrap, the transition of dry substances was 11.8% to DM and the strength - 3.3 N.

The best quality of wheat pasta is achieved with the use of option I, or in other words, use in the first period of the thermo-radial-convective method helps to obtain pasta with the best quality. Strength of products is 3.7 N, and the speed of transition of dry substances to the cooking water is 10.7% to DM.

Quality of gluten-free pasta from corn is not significantly different from the strength indicators and the transition of dry substances to cooking water when using I, and II options. Obviously, for corn products, use of infrared irradiation in the first period does not significantly affect the quality of products.

Lowest energy costs are achieved when using option I, compared to other methods, which for wheat products is 2.28 kW/kg of raw products, for corn - 1.72 kW/kg of raw products. When using these drying options, compared to the convective method, energy consumption for wheat products is reduced by 1.1 times, and for corn by 1.35 times.

Consequently, when using thermo-radial-convective method in the first period of drying, and convective drying in the second period, it is possible to obtain products of satisfactory quality and to substantially reduce energy costs for the production of pasta.

4. Conclusions

- It was found that the drying speed of corn pasta at any drying methods is slightly higher, and the value of the first critical humidity is lower, indicating a lower binding energy of moisture in corn pasta. The energy costs for corn pasta drying are lower for all drying methods.

- Use of combined thermo-radial-convective drying method contributes to the reduction of energy consumption due to the uniform heating of the layers and the intensification of the drying process due to the simultaneous heating of the product with infrared irradiation and air in the drying chamber. The quality of products in the case of using the combined method is somewhat reduced compared to drying by a convective way.

- Application of thermo-radial-convective drying in the first drying period (with the removal of free moisture), and convective drying in the second period promotes obtaining wheat and corn pasta with the best quality. The strength of wheat products is 3.7 N, and the speed of transition of dry substances to the cooking water - 10.7% to DM. The strength of gluten-free corn products is 3.5 N, dry matter transition - 13.9% to DM.

- Application of thermo-radial-convective drying in the first period, and convective drying in the second reduces energy costs for the drying of wheat pasta by 1.1 times compared to the convective method, for corn pasta - by 1.35 times and is respectively 2.28 and 1.72 kW/kg of raw products.

5. References

[1] Yurchak V., Rozhno O. (2015). *Patent of Ukraine, 101981* (in Ukraininan). State Patent Office of Ukraine, Kyiv, Ukraine.

[2] Rozhno O., Yurchak V., Rak V. (2017). *Investigation of food, biological value and digestibility of gluten-freepasta from corn flour*. Scientific works of the National University of Food Technologies, 23, (5), pp. 158-168.

[3] Ginzburg A. (1966). *Infrared technology in the food industry* (in Russian). Food industry, Moscow, Russia, pp. 407.

[4] StroganovaL. Mukhina S., Nesterova K., Tikhomirova N. (1963). *Irradiation of raw pasta with infrared rays to speed up their subsequent drying* (in Russian). Food industry, Moscow, Russia, pp.15.

[5] Malyshkina V., Pishchuhin A., Zinyukhin G. (2004). *Analysis of the process of drying pasta by infrared dryers* (in Russian). Bulletin of the Orenburg State University, 4, pp. 135-138.

[6] Ginzburg A., Chamelis S., Savina I. (1954). *The equilibrium moisture of pasta* (in Russian). Zintipischeprom,Moscow, Russia, pp. 12.

[7] [7] Medvedev G. (2005). *Pasta technology* (in Russian). Giord, Sankt Petersburg, Russia, pp. 308.

[8] Rozhno O., Yunenko S., Yurchak V. (2015). *Investigation of the effect of various structure-forming agents on the quality of gluten-free pasta*. Scientific works of UFT, Plovdiv, Bulgaria, Vol. LXII, pp. 109-114.

[9] Dubkovetskyy I., Malezhik I.,Burlaka T., Strelchenko L. (2016). *Patent of Ukraine, 112348: Radiation and convection drying plant* (in Ukraininan). State Patent Office of Ukraine Bulletin 16.

[10] Hereschenko B.,Tokarchuk G., Anaevich O. (1998). *The use of infrared irradiation for grain disinfection during storage* (in Russian). Grain storage and processing, 6, pp. 36-37.

[11] Ilyasov S., Krasnikov V. (1978). *Physical basis of infrared food irradiation* (in Russian). Food industry, Moscow, Russia, pp. 359.

[12] Strelchenko L., Dubkovetskyi I., Malezhykl. (2019). *Influence of differentialheat treatment on foodstuffs with apples obtained by the convection-thermoradiation method of drying* (in Ukraininan). Ukrainian Food Jornal, 8, (1), pp. 155-168.

[13] Tan M., Chua K. J., Mujumdar A. S., and Chou S. K. (2001). *Osmotic dehydration of potato and pineapple-effect of intermittent radiation and continuous convection in a heat pump dryer*. Drying Technology, 19, pp. 2193-2207.

[14] Queiroz R., Gabas A. L., Telis V. R. N. (2004). *Drying kinetics of tomato by using electric resistance and heat pump dryers*. Drying Technol., 22, pp. 1603-1620.

[15] Seco J. I. F. G., Seco J. J. F. G., Prieto E. H., Garcìa M. C. (2004). *Evaluation at industrial scale of electric-driven heat pump dryers (HPD)*. Holz Roh Werkst, 62, pp. 261-267.

[16] Swasdisevi T., S. Devahastin P. Adchom S., and Soponronnarit S.(2009). *Mathematical modeling of combined far-infrared and vacuum drying banana slice*. Journal of Food Engineering, 92, (3), pp. 100-106.

[17] QiuY., Li M., Hassanien E.H. R., Wang Y., Luo X., and Yu Q. (2016). *Performance and operation mode analysis of a heat recovery and thermal storage solar-assisted heat pump drying system*. Solar Energy, 137, pp. 225-235.

[18] Ibrahim M., Sopian K., Daud W. R. W., Alghoul M. A. (2009). *An experimental analysis of solar-assisted chemical heat pump dryer*. Int. J. Low- Carbon Technol., 4, pp. 78-83.

[19] Colak N., Kuzgunkaya E., Hepbasli A. (2008). *Exergetic assessment of drying of mint leaves in a heat pump dryer*. J. Food Proc. Eng., 31, (3), pp. 281-298.

[20] Erbay Z., Icier F. (2009). *Optimization of drying of olive leaves in a pilot-scale heat pump dryer*. Drying Technol., 27, (3), pp. 416-427.

[21] Fadhel M. I., Sopian K., Daud W. R. W., Alghoul M. A. (2011). *Review on advanced of solar assisted chemical heat pump dryer for agriculture produce*. Renew Sustain Energy Rev., 15, (2), pp. 1152-1168.

[22] Fatouh M., Metwally M. N., Helali A. B., Shedid M. H. (2006). *Herbs drying using a heat pump dryer*. Energ. Convrs. Management, 47, (15), pp. 2629-2643.

[23] Goh L. J., Othman M. Y., Mat S., Ruslan H., Sopian K. (2011). *Review of heat pump systems for drying application*. Renew Sustain Energy Rev., 15, (9), pp. 4788-4796.

[24] Hawlader M. N. A., Jahangeer K. A. (2012). *Heat pump design for food processing*. In: Ahmed J., Rahman M. S. (Eds.), Handbook of food process design, Wiley-Blackwell, Oxford, UK, pp 578-620.

[25] Hawlader M. N. A., Perera C. O., Tian M. (2006). *Comparison of the retention of 6-gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods*. Drying Technol., 24, (1), pp. 51-56.

[26] Abonyi B. I., Feng H., Tang J., Edwards C. G., Chew B. P., Bolland K.(2000). *Evaluation of quality retention of strawberry and carrotdried by a novel drying method*. Institute of Food Technologist, Dallas, USA.

[27] Nindo C. I., Tang J. (2007). *Refractance window dehydration technology: A novel contact drying method*. Dry Technology, 25, (1), pp. 37-48.

[28] Sabarez H. T., Gallego-Juarez J. A., Riera E. (2012). *Ultrasonic assisted convective drying of apple slices*. Dry Technol., 30, (9), pp. 989-997.

[29] Garcia-Perez J. V., Rossello C., Carcel J. A., De la Fuente S., Mulet A. (2007). *Effect of air temperature on convective drying assisted by high power ultrasound*. Defect Diffus Forum, 258, pp. 563-574.

[30] Jindarat W., Rattanadecho P.,Vongpradubchai S., and Pianroj Y. (2011). *Analysis of energy consumption in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system*. Drying Technology, 29, (8), pp. 926-938.

[31] Onwudel. D., Hashim N., Abdan K., Janius R., Chen G. (2019). *The effectiveness of combined infrared and hot-air drying strategies for sweet potato*. Journal of Food Engineering, 241, pp. 75-87.

[32] Ding C., Khir R., Pan Z., Wood F. D., Berrios J. (2018). *Influence of infrared drying on storage characteristics of brown rice*. Food Chemistry, 264, pp. 149-156.

[33] Younis M., Abdelkarim D., Assem Zein El-Abdein. (2018). *Kinetics and mathematical modeling of infrared thin-layer drying of garlic slices*. Saudi Journal of Biological Sciences, 25, 2, pp. 332-338.

[34] Song X., Hu H., Zhang B. (2018). *Drying characteristics of Chinese Yam (Dioscorea opposita Thunb.) by far-infrared radiation and heat pump*. Journal of the Saudi Society of Agricultural Sciences, 17, 3, pp. 290-296.