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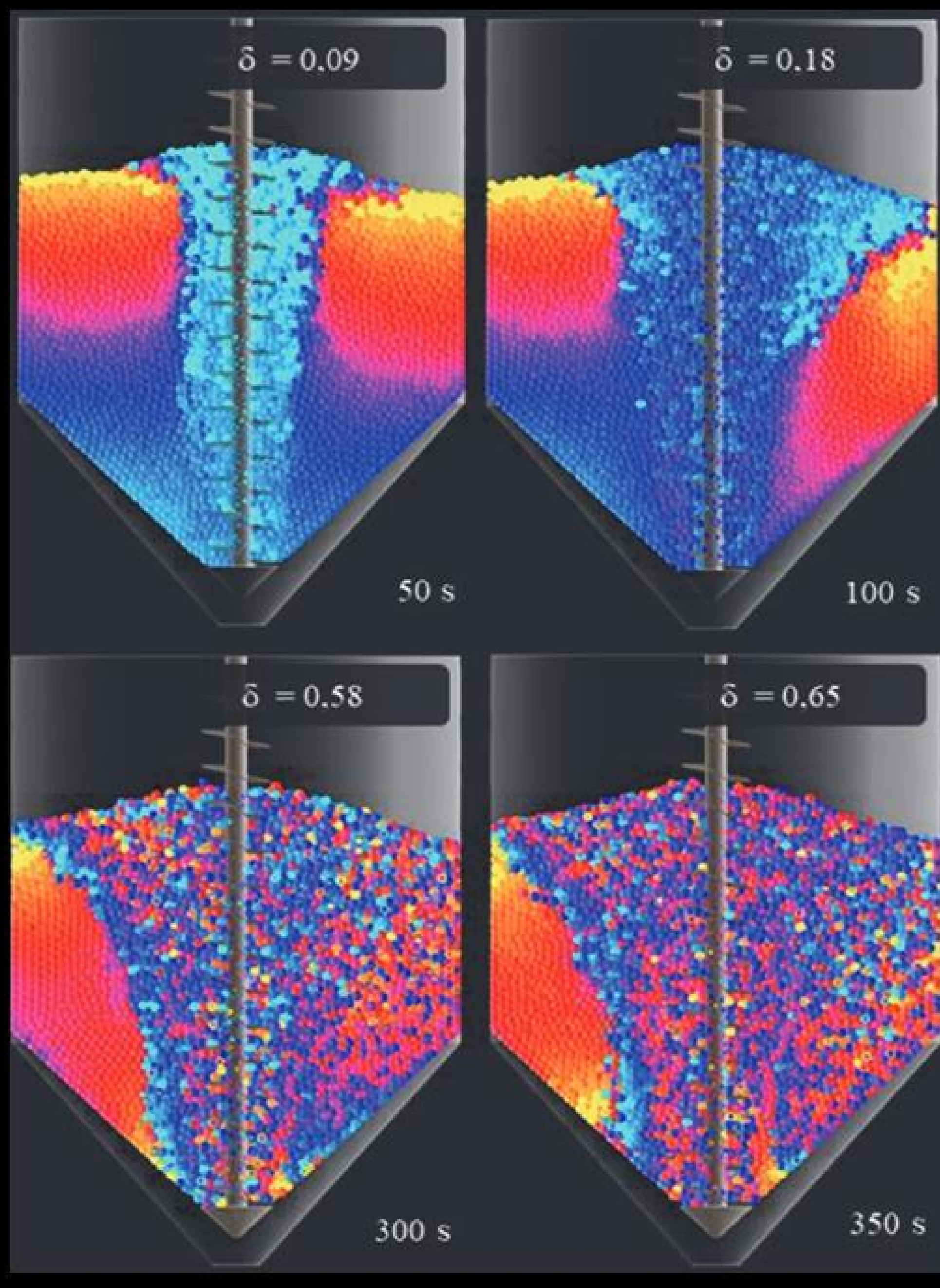

Modeling of the technological process of walnut drying in a convective dryer

Page 91

PRZEGLĄD ELEKTROTECHNICZNY Vol 2023, Nr 12

Spis treści

PRZEGLĄD ELEKTROTECHNICZNY Vol 2023, Nr 12

Spis treści

1. Hryhorii KALETNIK[1], 2. Vitalii YAROPUD[1], 3. Ihor KUPCHUK[1], 4. Elchyn ALIIEV[2], 5. Ihor BABYN[1], 6. Petro LAVRENIUK[1]

Vinnytsia National Agrarian University (1), Dnipro State Agrarian and Economic University (2)
ORCID: 1. 0000-0002-4848-2796; 2. 0000-0003-0502-1356; 3. 0000-0002-2973-6914; 4. 0000-0003-4006-8803; 5. 0000-0002-7070-4957; 6. 0000-0002-2480-7365

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Modeling of the technological process of walnut drying in a convective dryer

***Abstract**. The article presents the results of simulation in the Simcenter STAR-CCM+ software package of the work process of the developed convective dryer for walnuts, which is made in the form of a mixer with a vertical screw working body with a bottom injection of a warm air flow. A visualization of the process of redistribution (mixing) of walnut fruits in the area of the drying chamber under the action of the screw working body and the distribution of air flow speed and temperature in the area of the drying chamber was obtained.*

Streszczenie. *W artykule przedstawiono wyniki symulacji w pakiecie oprogramowania Simcenter STAR-CCM+ procesu pracy opracowanej suszarki konwekcyjnej do orzechów włoskich, która wykonana jest w postaci mieszalnika z pionowym korpusem roboczym ślimakowym z dolnym wtryskiem ciepłego powietrza przepływ. Uzyskano wizualizację procesu redystrybucji (mieszania) owoców orzecha włoskiego w obszarze komory suszącej pod wpływem działania korpusu ślimakowego oraz rozkładu prędkości i temperatury przepływu powietrza w obszarze komory suszącej.* (***Modelowanie procesu technologicznego suszenia orzechów włoskich w suszarce konwekcyjnej***)

Keywords: modeling, drying, mixing, parameters, experimental sample, dryer.
Słowa kluczowe: modelowanie, suszenie, mieszanie, parametry, próbka doświadczalna, suszarka.

Introduction

International nut production and processing industry has been actively developing in recent decades, being characterized by high growth rates compared to other types of agroindustrial business. Over the past 10 years, global production of nuts has increased by almost 40%, with sales volumes having been increased by 116% [1]. Particular surge in demand has been observed for walnuts – the major alternative source of main physiologically active compounds that replace food products of animal origin. Over the past five years, walnut consumption has doubled in the world.

The generalized technology of walnut fruit treatment involves the following operations (fig. 1). As soon as the walnuts are shaken off to the ground, part of the outer fruit's green mass (shells) is dried naturally. Then, manually or with the use of specialized equipment, the fruits are collected from the ground and transported to pre-processing workshop. At this stage, walnuts are called "freshly picked". According to the typical walnut fruit processing technology, the first stage consists of cleaning from the remains of external pericarp, organic and inorganic impurities. After that, they are washed, dried and sorted. In the course of walnut fruit washing, water from the surface is absorbed into the internal fertilization, thereby increasing the total humidity [2–4]. According to studies [2, 3], freshly harvested walnuts have moisture content in the pericarp, shell and kernel of 85.3–87.9%, 25–35%, and 15–25%, respectively. Moisture content of harvested walnuts is quite high, which makes them vulnerable to microbial contamination and spoilage [3]. Thus, for safe storage, walnuts must be dried

Fig. 1. Generalized technology of walnut fruit treatment

Walnuts are among the products most exposed to the risk of oxidative deterioration at the stages of storage, transportation and sale. At the same time, it should be taken into account that specific botanical varieties grown in different geographical regions have their individual chemical compositions that determine the intensity of oxidation processes, hence nuts of different batches have different potential for storage [3]. The lack of a traceability system for nut batches at the stages of production, logistics and sale, as well as lack of objective methods for assessment of potential level of preservation, leads to incorrect setting of walnuts' expiration dates and as a result, over 30% of walnuts with bitterness signs are sold via trade chains [5].

Therefore, a relevant task of scientific research lies in determination of technological conditions and justification of structural and mode parameters of technical means to be used for walnuts drying and their further storage.

Drying process is one of the oldest methods used for storage of agricultural products [6]. Therefore, drying is crucial for post-harvesting treatment of nuts, ensuring food safety and quality during storage. The recommended safe moisture content for a nut in the shell is 6-10% [7]. Dehydration is one of the best preservation methods that can extend the shelf life of food products and has been used for drying and preservation of fruits for several centuries [8]. The method is based on moisture removal from the product using a complex process with simultaneous heat and mass exchange

The traditional drying method is based on solar energy, yet the products can be easily spoiled due to various environmental conditions, which can lead to a significant loss of nut quality [6]. In addition, the heterogeneity of the fruits' internal structure within one variety or even within one fruit leads to the fact that plant tissue is a material susceptible to different types of thermal, mechanical or enzymatic processes. Technological treatment changes the structure of raw fruits, modifying not only the enzymatic reactions that occur within the tissue, but also, and first of all, affects the conditions of heat and mass exchange that occur within plant material [9]. In addition, an undesirable range of kernels' moisture content and water activity as a result of drying can increase enzymes' hydrolytic or oxidative activity, particularly that of lipase, peroxidase and polyphenol oxidase. Thus, drying process should be carefully applied to nut's shell after harvesting, so that not only to stop microbial reproduction, but also to delay quality deterioration, which is associated with oxidation of lipids in kernels [7].

In response to changes in light and heat, lipid molecules are released with formation of free fatty acids, this being able to affect the stability of nut oil [10]. Light is the main factor controlling photooxidation, although its significance decreases as temperature increases. Oxygen concentration's effect on oil oxidation was more significant with increasing temperature and under the influence of light [11]. Therefore, it is important to maintain oil stability during nut drying process. In addition, quick post-harvest processing of nuts, particularly drying thereof, is an important parameter in terms of final product quality at the storage stage. Generally, in order to ensure a long-term shelf life and to protect nuts from bitterness formation processes, they should be dried immediately after harvesting [12]. Unfortunately, as against other food products, studies on walnut drying are limited [13]. Therefore, it is essential to develop and model walnut drying system in detail in order to ensure its highest quality.

Research materials and methods

The established technological requirements for walnut drying are as follows:

– ensuring the highest drying speed with a safe air flow temperature (up to 60 °C);

– ensuring the greatest uniformity of moisture removal throughout the product mass;

– ensuring the lowest specific energy consumption;

– reduction of damage to walnut fruits for further long-term storage.

Taking the above into account, a structural-and-process flow diagram of a convective walnut dryer with a vertical screw working body was developed (fig. 2). The convective dryer contains a drying chamber for nuts, which is rigidly placed on the frame. The bottom of the drying chamber is made in the form of a truncated cone, representing a net with 15 mm diameter. The air chamber is placed under the net, into which warm air is supplied through the air supply pipe. In the lower part of the drying chamber, a discharge nozzle with a damper passes through the air chamber. Above and below the drying chamber, bearing units are placed in the middle, with the screw working body installed therein. The upper part of the screw working body is connected to the gear motor. A cone-shaped air distributor is installed in the air chamber located in the lower part of the screw working body.

The convective walnut dryer operates in the following way. Walnuts are poured into the drying chamber through the hole in its upper part. After that, the stream of warm air is supplied to the air chamber through respective nozzle and passes through the net to nut mixture. To ensure uniformity of drying the entire of walnut volume, the screw working body is activated. At the same time, the nuts located at the bottom of the drying chamber rise up, contributing to the process of redistribution (mixing) of mixture layers. The open screw working body reduces the physical impact on the walnuts, accordingly reducing the injuries thereto.

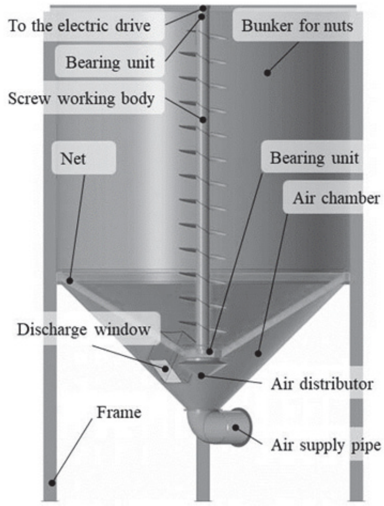


Fig. 2. Structural-and-process flow diagram of a convective walnut dryer

In order to evaluate the performance of presented structural-and-process flow diagram of the convective walnut dryer, we will simulate the drying process via Simcenter STAR-CCM+ software package using DEM method.

DEM method (Discrete Element Method) in Simcenter STAR-CCM+ is one of the numerical simulation methods used to analyze particles' motion and interaction. It allows simulating the movement of solid bodies that interact with each other through contact forces. DEM method is normally used to investigate the behavior of granular materials such as sand, rock and grain, as well as to analyze processes occurring in oil and gas, food, and pharmaceutical industries. DEM method ensures the possibility to allow for different types of interaction between particles, such as impacts, friction and adhesion. For this purpose, the model determines interaction parameters for each pair of particles, on which basis each particle's movement is calculated. In the course of calculations, the effect of particles' interaction with the surrounding medium, such as air or liquid, is also taken into account. DEM method is a powerful tool for analyzing the behavior of granular materials and other types of particulate systems. Its use allows increasing the efficiency and accuracy of designing processes related to mixing, transfer and sorting of granular material.

Generated was 3D model of convective dryer's area with a helical working body that is able to rotate around its own axis. Based on the net models selected, namely the generator of the surface net and the generator of polyhedral cells, established was the reference value of the linear size of 0.001 m, with the volumetric net of convective dryer's area having been generated (fig. 3).

The next stage of modeling lies in selection of physical models: three-dimensional model, non-stationary implicit model, mathematical model of one-component gas (air), model of ideal gas (air), model of turbulent air flow, k-ε model of air turbulence, isothermal fluid energy equation, Reynolds-averaged Navier-Stokes equation, separated flow, gradient and boundary methods, Lagrangian model of multiphase environment, multiphase interaction model, discrete element model (DEM), and gravity field [14-17].

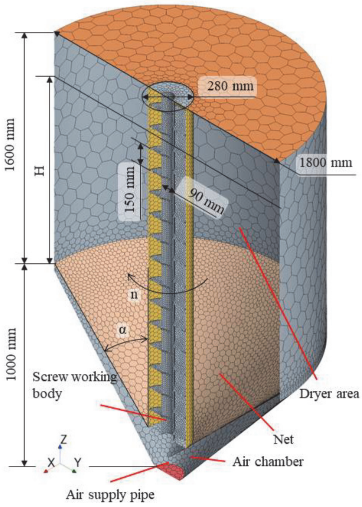


Fig. 3. Volumetric net of convective dryer's area and the screw working body

Walnut fruits were represented as a Lagrangian phase under the following models: constant density, pressure gradient force, particle drag force, spherical particles, single-component solid particles and DEM particles. The nuts had the following physical and mechanical properties: Poisson's ratio – 0.25; Young's modulus - 0.3 MPa; density – 600 kg/m^3; coefficient of static friction – 0.51; normal recovery factor – 0.45; tangent recovery factor - 0.45; the coefficient of rolling resistance being 0.25 [18-21]. Geometric dimensions of the nuts are assumed as follows: average value of the effective diameter – D = 0.030 m; minimum value of the effective diameter is D_{min} = 0.022 m; maximum value of the effective diameter is D_{max} = 0.038 m; standard deviation being σ_D = 0.01 m. Nut size distribution follows a normal Gaussian distribution.

The interaction between the nuts was subject to Hertz-Mindlin contact interaction model [22]: the coefficient of static friction –0.51; normal recovery factor – 0.45; the tangent coefficient of recovery being 0.45.

The following parameters were taken as environment properties: environment – air; dynamic viscosity – $1.85508 \cdot 10^{-5}$ Pa·s; turbulent Prandtl number – 0.9; free fall acceleration – 9.8 m/s^2 ; pressure – 101325 Pa. Air inlet flow temperature is 60°C, environment temperature being 20°C.

The diagram of walnut drying process modeling is shown in fig. 4.

The nuts are loaded in the upper part of the drying chamber based on the Lagrangian phase injection function with the following parameters: probability of nuts' appearance is 0.7, nuts' initial velocity is 0 m/s, nuts' loading Q = 100 pcs/s (this value is selected on the condition of ensuring the nuts' constant level in the drying chamber's area).

The screw working body rotated around its own axis with 60 rpm frequency.

The velocity of warm air flow was 8.84 m/s, this corresponding to the volumetric velocity of 1000 m^3/h.

Boundary conditions for modeling were chosen as follows. The interaction between the walnuts and the drying chamber's walls adhered to the Hertz-Mindlin contact interaction model: coefficient of static friction is 0.51; normal recovery factor – 0.45; tangent coefficient of recovery being 0.45. The net surface is opaque to nuts and transparent to air flow.

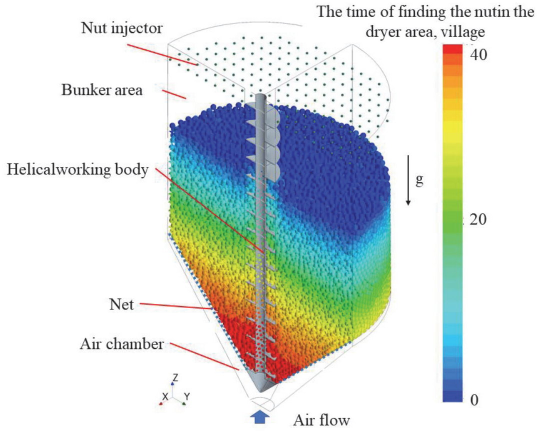


Fig. 4. Diagram of walnut drying process modeling

Total simulation time is 600 s. The number of iterations is 10. The simulation time step is 0.01 s.

The numerical modeling factors are the angle of the net's inclination relative to horizontal axis α, the screw working body's rotation frequency n, the height of the drying chamber's filling with nuts H (fig. 3). The levels of variation by factors are set out in table. 1. Numerical modeling was performed according to the full factorial experiment with the total number of experiments being 3^3 = 27.

Table 1 – Variation levels by numerical modeling factors

Level	Factor		
	α, ° (x_1)	n, rpm (x_2)	H, mm (x_3)
-1.0	30	60	0
0	45	120	500
+1.0	60	180	1000
Interval	15	60	500

The purpose of the numerical modeling was to determine the productivity of the process of mixing the nut layers in the drying chamber's area:

(1) $$Q = \rho V(\alpha, H)/T(\alpha, n, H)$$

where ρ is the nuts' bulk density, ρ = 260 kg/m^3 [2, 3]; $V(\alpha, H)$ – the volume of the drying chamber's area filled with nuts, m^3 ; $T(\alpha, n, H)$ is the time, at which the highest mixing quality is achieved, s.

The quality of mixing was determined by the variation coefficient:

(2) $$\delta = 1 - \frac{1}{\overline{C}}\sqrt{\frac{\sum_{i=1}^{n}\left(C_i - \overline{C}\right)^2}{n-1}}$$

where $\overline{C}$ is the average of marked nuts' concentration in the total volume; C_i is marked nuts' concentration in the ith layer; n is the number of layers.

As a result of data processing via Wolfram Cloud software package, it is necessary to establish the dependence between mixing process's abovementioned criteria and research factors in the form of second-order regression equations. Statistical processing of the data obtained via Wolfram Cloud software package consisted in determination of the Student's criterion for each coefficient of regression equation and its comparison with the table value. Should the calculated value be less than the table value, the coefficient of regression equation would be insignificant and can be ignored. Obtained regression equation was checked for adequacy using Fisher's test and correlation coefficient.

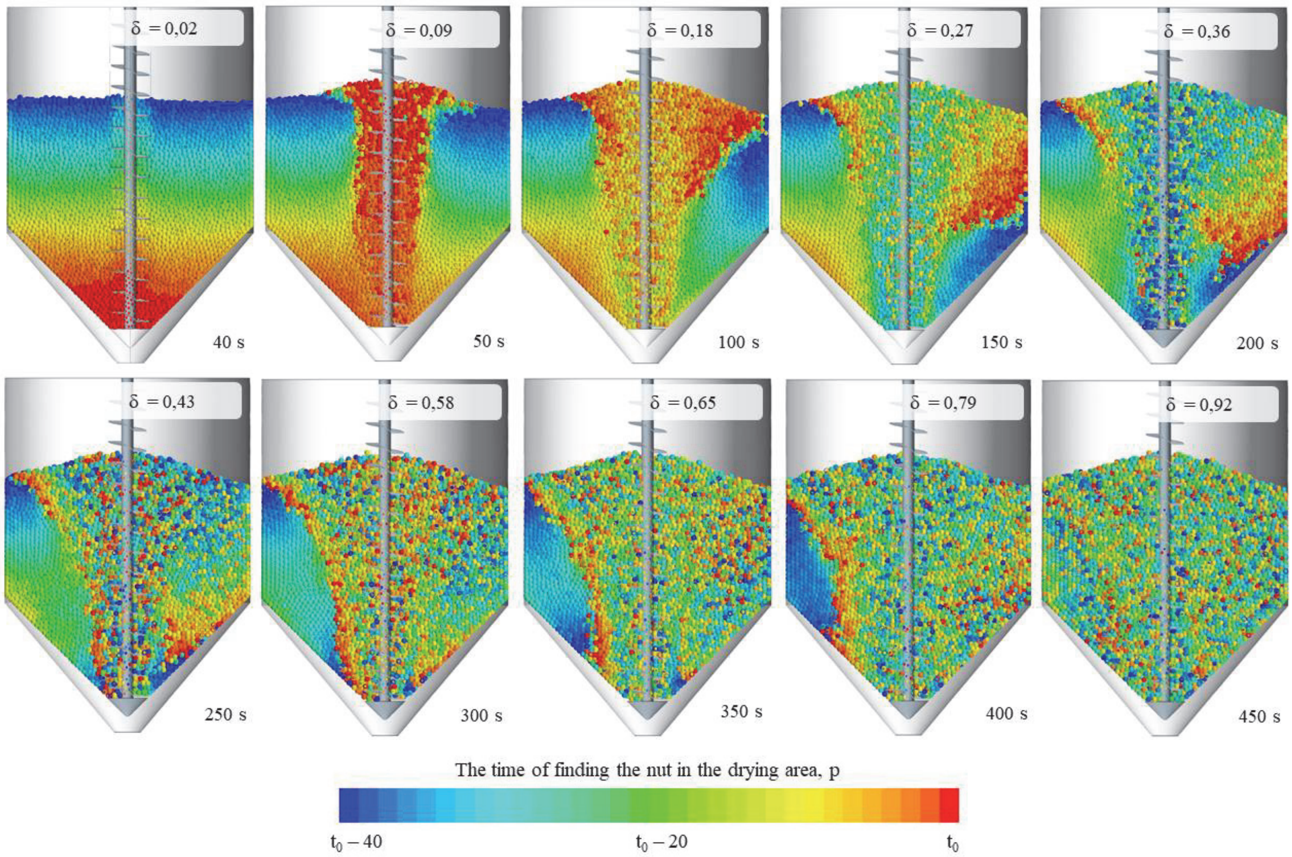


Fig. 5. Visualization of the process of walnut fruit redistribution (mixing) in the drying chamber's area under the action of the screw working body

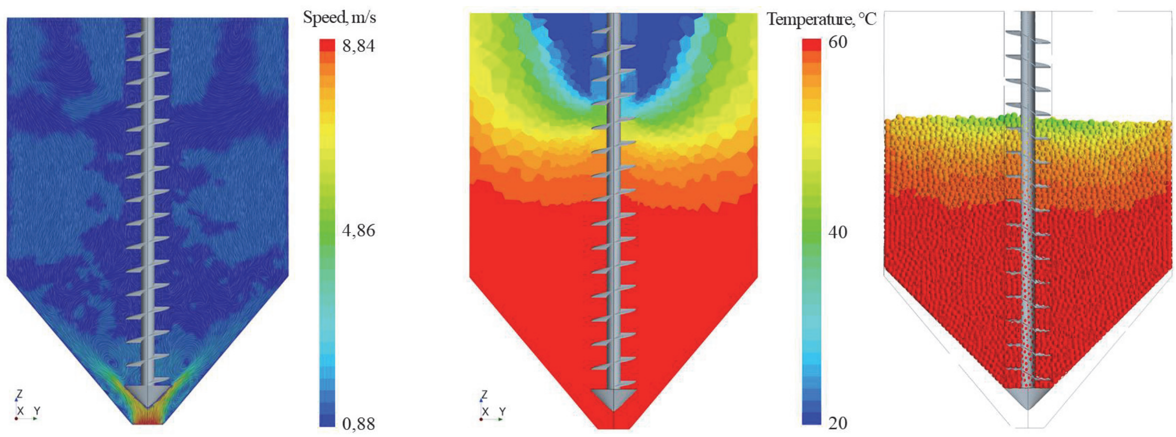


Fig. 6. Distributions of the air flow's and walnut fruits' velocity and temperature in the drying chamber's area

Research results

Based on the simulation results, the visualization of the process of walnut fruit redistribution (mixing) in the drying chamber's area under the action of the screw working body was obtained (fig. 5).

The analysis of redistribution process's and calculated variation coefficients' visualization showed that mixing quality improves over time. As soon as 432 s parameter is reached, the variation coefficient becomes the largest δ = 0.92±0.02 and further stabilizes at this level. That is, one complete mixing of the mixture in the drying chamber is carried out during the period from 432 s to 40 s = 392 s.

Based on simulation results, the distribution of air flow velocity in the drying chamber's area was obtained, which is shown in fig. 6 (a). The highest air velocity at the entrance to the air chamber is 8.84 m/s. Next, the air flow gets evenly distributed in the air chamber and passes through the net and the walnut fruit mixture. In the walnut fruits mixture, the air flow is turbulent with the lowest absolute velocity of 0.88 m/s.

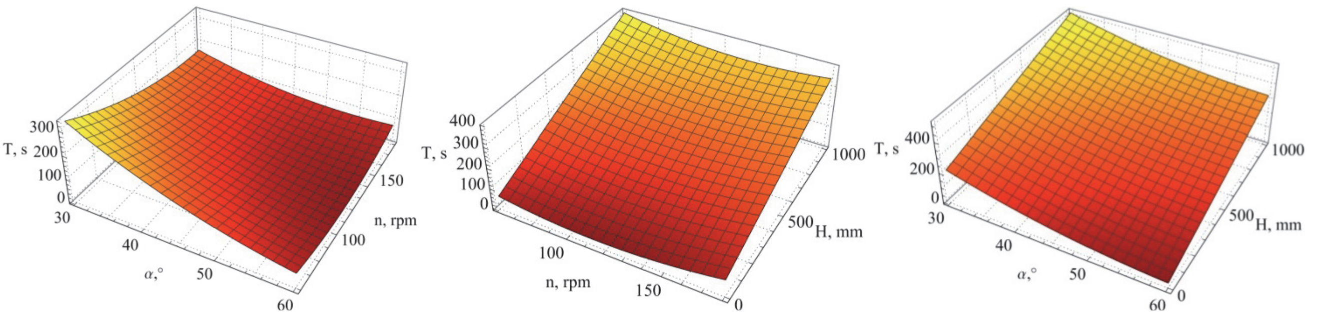
According to simulation results, the distribution of the air flow's and walnut fruits' temperature in the drying chamber's area was obtained, which is shown in fig. 6 (b). It can be seen from the figure that the highest temperature is observed in the lower part of the drying chamber, which is 58±2°C. Further on, a downward temperature gradient is observed. The temperature on the walnut mixture surface is 43±2 °C. Given a rather fast mixing (392 s), the nuts from "warm" lower layers are moved to the "cold" upper ones.

Hence, the phenomenon of heat and mass transfer is observed

According to the results of numerical modeling data processing, the following dependence between the change in time T(α ,n, H), at which the highest quality of mixing is achieved, and the research factors in a decoded form was obtained:

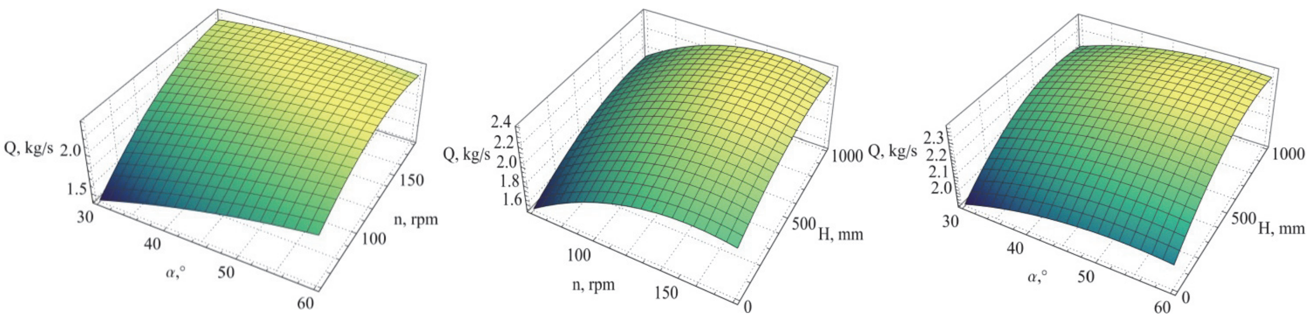
(3)
$$T(\alpha,n,H) = 1221.81 - 27.2604\,\alpha + 0.164644\,\alpha^2 + 0.369664\,H - 5.95003\,n + 0.053278\,\alpha\,n - 0.000565535\,H\,n + 0.0121194\,n^2.$$

Statistical analysis of equations (3) within the variation range under research showed that Pearson correlation coefficient is 0.92. At the same time, Fisher's criterion is $F = 2.12 < F_t = 2.49$, respectively. This confirms the adequacy of obtained models. Graphical interpretation of dependence (3) is shown in fig. 7 below.



with H = 0 mm with α = 60 ° with n = 114 rpm

Fig. 7. Dependence between the change in time T(α ,n, H), at which the highest quality of mixing is achieved, and the net's inclination angle relative to horizontal axis α, the frequency of the screw working body's rotation n, the height of the drying chamber's filling with nuts H



with H = 784 mm with α = 53,3 ° with n = 148 rpm

Fig. 8. Dependence between changes in productivity of nut layers' mixing process in the drying chamber's area Q (α,n, H) and the net inclination angle relative to horizontal axis α, as well as the frequency of the screw working body's rotation n, and the height of the drying chamber's filling with walnuts H

By solving the geometric problem, the dependence of the volume of the drying chamber's area filled with nuts V(α, H) was established:

(4)
$$V(\alpha,H)=\pi\left(\frac{D}{2}\right)^2\left(H+\frac{1}{3}\frac{D}{2}\mathrm{ctg}\alpha\right)-\frac{1}{3}\pi\left(\frac{d}{2}\right)^3\mathrm{ctg}\alpha=$$
$$=2{,}5434H+0{,}760148\,\mathrm{ctg}\alpha.$$

By substituting (3) and (4) into (1) and approximating in the form of a second-order regression equation, we obtain the dependence between the productivity of the process of nut layers' mixing in the drying chamber's area and the research factors in a decoded form:

(5)
$$Q(\alpha,n,H) = -1.56705 + 0.0563161\,\alpha - 0.000280336\,\alpha^2 + 0.00094621\,H - 5.07823\cdot10^{-7}\,H^2 + 0.0280252\,n - 0.000178066\,\alpha\,n - 1.01277\cdot10^{-6}\,H\,n - 0.0000597783\,n^2.$$

Statistical analysis of equations (5) in the variation range under research showed that the Pearson correlation coefficient is 0.88. In turn, Fisher's criterion is $F = 2.41 < F_t = 2.49$, respectively. This confirms the adequacy of obtained models. The factors' optimal values under the condition of maximum productivity ($Q = 2.38$ kg/m$^{3)}$ are α = 53.3°m, n = 148 rpm, and H = 784 mm. Graphical interpretation of dependence (5) is presented in fig. 8.

Experimental sample generation

For further experimental studies of walnut drying process, an experimental sample of convective dryer SGK-4 "TIRAS" was developed and generated taking into account obtained optimal values of structural parameters. The general view of the convective dryer is shown in fig. 9 (a). The screw working body is shown in fig. 9 (b). The system of air heating and pumping into the drying chamber is shown in fig. 9 (c).

Convective dryer's operating modes are controlled by respective control unit (Fig. 10), which includes a frequency converter and thermostats.

Preliminary tests have shown the effectiveness of the process of nuts' mixing in the drying chamber. To check the adequacy of the theoretical conclusions drawn, it is necessary to conduct experimental studies aimed at determining the dependence between indicators of nuts' mixing quality, moisture loss during warm air flow around them and various operating parameter.

Such as the screw working body's rotation frequency, warm air flow velocity and temperature. The coefficient of variation in the nut layers' redistribution, their average temperature and humidity should be chosen as the evaluation criteria for further experimental research. It is necessary to develop an appropriate methodology and to use task-orientated instrumentation to define specified parameters.

a)

b)

c)

Fig. 9. General view of convective walnut dryer. a – the front view, b – the screw working body, c – system of air flow heating and injection into the drying chamber

Conclusions

Based on the research results, substantiated was the structural-and-process flow diagram of a convective walnut dryer, which is made in the form of a mixer with a vertical screw working body with a bottom injection of a warm air flow.

The technological process of drying in the convective dryer having been developed was simulated via Simcenter STAR-CCM+ software package. The visualization of the process of walnut fruits' redistribution (mixing) in the drying chamber's area under the action of the screw working body and air flow velocity and temperature distribution in the drying chamber's area was obtained. According to the coefficient of variation, it was established that mixing quality is the best (δ = 0.92±0.02) and remains at this level within 392 s from the time of the screw working body's rotation start. It was established that the temperature gradient is observed in the drying chamber's area: the temperature in the lower part being 58±2 °C, and in the upper part – 43±2 °C. Given a rather fast mixing (392 s), such a temperature difference is not critical.

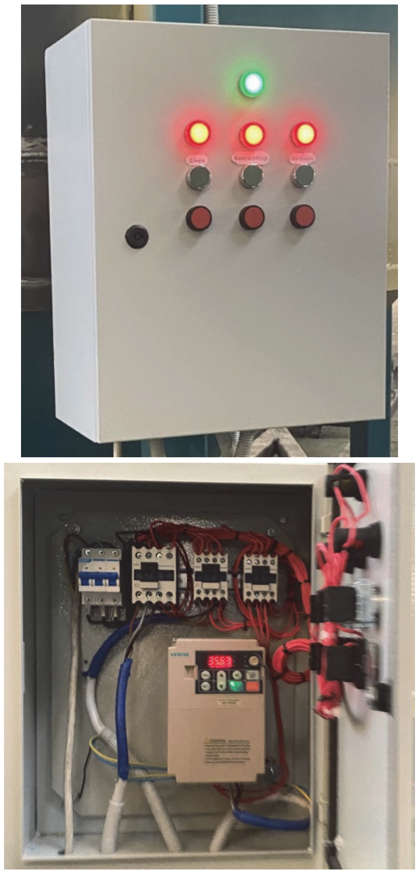


Fig. 10. General view of the convective walnut dryer's control unit

Based on the results of numerical modeling of the process of nuts layers' mixing in a convective dryer, the dependencies between time T, under which the highest quality of mixing is achieved, as well as productivity Q of nut layers' mixing process in the drying chamber's area and the angle of the net's inclination relative to horizontal axis α, the frequency of the screw working body's rotation n, and the height of the drying chamber's filling with nuts H.

When solving the problem of optimality, under which mixing process's productivity Qf should be maximal, Wolfram Cloud software package obtained rational mode parameters of the convective walnut dryer: H = 784 mm, α = 53.3° and n = 148 rpm.

For further experimental research of walnut drying process, an experimental sample of a convective dryer was developed and generated taking into account the design parameters' optimal values.

***Authors**: KALETNIK Hryhorii – Dr. Sc. in Economics, Professor, Academician NAAS of Ukraine, Head of the Department of Administrative Management and Alternative Fuel Resources, Vinnytsia National Agrarian University (21008, 3 Soniachna str., Vinnytsia, Ukraine); YAROPUD Vitalii – PhD in Engineering, Associate Professor, Dean of the Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Soniachna str., Vinnytsia, Ukraine), e-mail: yaropud77@gmail.com; KUPCHUK Ihor – PhD in Engineering, Associate Professor, Deputy Dean for Science, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Soniachna str., Vinnytsia, Ukraine), e-mail: kupchuk.igor@i.ua; ALIIEV Elchyn – Dr. Sc. in Engineering, Senior researcher, Professor, Dnipro State Agrarian and Economic University (Serhii Efremov Str., 25, 49600, Dnipro, Ukraine), e-mail: aliev@meta.ua; BABYN Ihor – PhD in Engineering, Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Soniachna str., Vinnytsia, Ukraine), e-mail: ihorbabyn@gmail.com; LAVRENIUK Petro – postgraduate student, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Soniachna str., Vinnytsia, Ukraine), e-mail: lavreniuk.petro.1239@gmail.com.*

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