Mathematical modeling of spicy herbs intensive drying with ultrasound

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Abstract. Ultrasound drying experiments of wicking and foam materials, spicy herbs in particular, with improved quality characteristics were carried out with sufficient efficiency of the created plant based on the steam convection oven. It was shown that drying optimization process can be preliminarily calculated using a theoretical model of ultrasonic exposure together with the supply of a heated drying agent to a temperature significantly lower than that accepted in industry (no more than 50-55 °C). Consequently, the drying time was reduced 2, as well as energy consumption level demonstrated 30% decrease.

1. Introduction
The drying process in food industry is quite an energy intensive process. This process is characterized by different intensities of material dehydration (moisture conductivity) and its further evaporation from the surface (moisture exchange). The main difficulty of the drying process is to remove moisture from the center of the product [1]. It is important to be able to quickly and efficiently manage the drying process and support operating parameters at the set theoretical level. These problems are solved by mathematical modeling based on a system analysis strategy [2-3]. Moreover, the process is presented as a complex interactive hierarchical system with further qualitative analysis of its structure, and development of mathematical description and evaluation of unknown parameters. Thus, mathematical modeling allows to predict the results in real conditions. The resulting mathematical model is an object that differs from the original in features to be further studied.

Using ultrasonic (US) drying technology, we reduce the energy consumption for the process and save biologically active substances, while increasing the speed of the process and the storage time of the dried product at a reduced cost. Thus, traditional drying machines (drum machines, spray machines, vibro-boiling layer machines, tunnel machines and others) are easily equipped with ultrasonic devices, significantly increasing their productivity. Ultrasound drying can be used in production of milk powder, malt, dried vegetables, dried tomatoes, spices and other dried production [4-5].

2. Methods and Equipment
The intensification of the dehydration process stimulates the application of continuous drying plants. They are especially productive for drying termolabile products (easily oxidized and heat-sensitive). In some cases, high intensive ultrasound is also used to reduce the level of bacterial contamination in the finished products. Mathematical modeling [6] proves to be an effective method to increase the
efficiency of the drying process. Dehydration problem is actual since modern science and technology need correct prediction of heat and mass transfer processes, experimental studies of which are quite expensive and complex. Using mathematical modeling without involving experiments, it is possible to increase the calculation and realize energy saving potential while saving the quality of the dried product [7].

The paper aims to theoretically study the influence of their mophysical properties of phytogenic materials on the drying process and analysis of heat and mass transfer of various herbs types during dehydration.

To achieve this aim, the following tasks were solved:

- Analysis of new literature sources
- Formulation of mathematical model for herb drying process
- Calculation and reliability assessment of theoretical results in MATLAB system and their verification with experimental data.
- Results analysis.

The practical significance of results is presented in the form of the physical and math theory development, which allows simulating the processes of heat and mass transfer during spicy herbs drying under convective radiation heating intensified by ultrasound with 130-140 dB power. MATLAB calculations make it possible to use the formulated mathematical model to select effective drying schedules for herbs and similar products.

Moisture transfer and thermal properties of several types of spicy greens were studied using ultrasound. Despite the fact that the cheapest and the easiest method of drying is atmospheric, it does not require such capital expenditures, compared with the chamber one. Chamber drying method has a lot of disadvantages, for this method of drying requires large areas with a large supply of material and the process becomes uncontrollable, especially in regions with high air humidity due to probability of product damage with bacterial microorganisms, and in areas with intense heat due to severe melanoidino formation, color fading, and loss of aroma substances. When drying, moisture outside and free moisture evaporate first. Free moisture is contained in limps and tracheids in the form of lymph and is passed to all parts of the leaf, nutrifying it.

The amount of free moisture is always quite high (over 600%), and it represents most of the plant moisture. Free moisture is removed easily and quickly [7, 8].

Bound moisture is a moisture held within the walls of the cells. It begins to evaporate only after the complete removal of free moisture. The process of removing bound water is more difficult and lengthy, and at the same time, strongly affecting the quality properties of herbs. Here, the effect of cavitation and other ultrasound properties significantly change the qualitative characteristics of dried herbs enhancing their aroma. It is the intensive movement of moisture inside the material (from the central zone to its surface) that ensures the possibility of obtaining high technical and economic indicators of drying biomass.

The information about drying methods and their physics is given in [8]. The choice of drying mode is presented in [7], where soft, normal and forced drying modes are described. It also provides recommendations for choosing a drying mode based on many factors such as: structure, thickness and purpose of the material. Drying defects and warnings are described in [7].

The advantage of ultrasonic artificial drying offered in this paper is the possibility of creating a completely controlled climate inside the chamber, which does not depend on the outside environment. Climatic conditions change gradually to cause moisture removal from herbs with the least loss of aroma substances and in a much shorter period of time compared to natural drying. Moreover, moisture conduction, i.e. moisture distribution of throughout the material, becomes more uniform due to reduction of friction using ultrasound and moisture movement is accelerated towards lower humidity area (out). Thermal moisture conduction, i.e. the phenomenon of moisture movement due to temperature difference in the center and on the surface of the material, ensures the accelerated
movement of moisture in the direction of low temperature (evaporation with ultrasound is very intense on the herb surface). Thus, the main difficulty in implementing an integrated drying process is moving moisture to the surface.

The author proposes an original experimental setup based on a steam convection oven for drying herbs and leafy greens, and presents the results of experimental studies on ultrasonic convective drying of raw materials published in [9,10].

3. Results and discussions
The formulated mathematical models and numerical calculations should be carried out based on Lagrange variables. The model is developed and presented below. To study the drying process mathematical modeling is used. For convective dryers, the driving force of the process is expressed as the temperature difference between the air and the surface of the material, using the effective heat transfer coefficient from air to material, determined from experimental data [7]. The heat balance of the convective drying process is written in the form of (1):

\[ c_B G_B \frac{dt_B}{dl} - \alpha F_M (t_B - t_n) = \chi G_c \frac{dD}{dl} , \]  

where:
- \( c_B \) is the airhead capacity of, J / (kg \( \cdot \) °C);
- \( G_B \) is air consumption, kg / s;
- \( \frac{dt_B}{dl} \) is the change of air temperature along the length of the dryer, °C / m;
- \( \alpha \) is the effective heat transfer coefficient, J / (m² • s • °C);
- \( F_M \) is the heat transfer surface of the material per unit length of the dryer, m;
- \( t_B \) is air temperature, °C;
- \( t_n \) is material surface temperature, °C;
- \( G_c \) is consumption of absolutely dry material, kg / s;
- \( \alpha \) is the heat of pure liquid vaporization, J / kg;
- \( D \) is the moisture content of the material, kg / kg;
- \( l \) is the coordinate along the length of the dryer, m;
- \( L \) is the length of the dryer in the AHP, m;
- \( \chi = H/r \) is a coefficient taking into account the increase in heat consumption for moisture evaporation from the dried material compared to pure liquid.

For the first drying period \( \chi = 1 \) and \( t_n \) is a constant, then from (1) it follows (2):

\[ \frac{dt_B}{t_B - t_n} = \frac{\alpha F_M}{c_B G_B} dl \ dD = \frac{c_B G_B}{\rho G_c} d(t_B - t_n) \]  

Integration of equations (2) is

\[ t_B = t_n + (t_B - t_n)_H \times e^{-al} \]  

\[ D_H - D = b[(t_B - t_n)_H - (t_B - t_n)] = b(t_B - t_n)_H[1 - e^{-al}] \]  

where:
- \( D_H \) is the moisture content in material in the beginning of the first drying zone, kg / kg;
- \( t_B \) is the difference in air temperature and surface temperature of the material in the beginning of the first drying zone, °C;

\[ a = \frac{\alpha F_M}{c_B L}; b = \frac{c_B L}{\rho G_c} \]

In the second drying period, the process speed decreases due to decrease in temperature difference and increase in heat consumption for heating the material and moisture evaporation. Assumed that the last two factors are taken into account by the coefficient \( \chi \), then equation (2) can be used for the second drying period. Then, with using (3), we get the equations:
Using the developed mathematical model, simulation studies were carried out, and static characteristics of the drying process are shown in figure 1.

\[
\frac{dU}{U^n \left(t-t_0\right)k \rho_0 \frac{k}{\rho}(1-U)} = adl
\]  

Figure 1. Dependence of moisture (%) of spicy herbs (thyme) on drying time (minutes) with ultrasound at air flow temperature in steam convection oven 500C.

The acoustic exposure process at the first stage of drying starts with a certain threshold value of sound pressure (130-140 dB). It depends on body configuration, the type of acoustic flows on the material surface and in the environment. There is a rapid decrease in the mass of the product and there is no sharp decrease in the size of the leaves, although high sponginess of leaves is saved. The second stage of drying is characterized in the form of downward speed, a slow decrease in moisture content in the material. Acoustic vibrations increase the diffusion coefficient of a liquid as a result of heating absorption of ultrasound in macro capillaries and pores.

However, water heating in the sound field is negligible and the increase in the diffusion coefficient does not exceed 150-180%, and there is no significant acceleration of drying process at this stage.

4. Conclusions
Fundamental feature of the method is based on the fact that the acceleration (2-6 times) of the drying process of products is provided almost without temperature increase. Thus, principle of cold drying is implemented, which eliminates the thermal effect on greens, excessive removal of aromatic substances and oxidation of fats, and therefore eliminates smack and off-odors.

Thus, the advantages of drying method in high-intensive acoustic fields are:

- high intensity of the drying process (for example, when drying the leaves of spicy herbs, it increases by 5 times);
- the possibility of high-quality and effective drying at low temperatures and with practically no temperature increase (which eliminates the destruction of vitamins and rapid removal of essential oils);
- less energy consumption (experiments suggest that energy consumption can be reduced by 1.3–2 times, and the drying rate by 2–6 times);
- the possibility of drying almost all materials without a significant change in design of the dryer;
environmentally friendly technology due to the absence of fuel combustion products and low drying temperatures.

This mathematical model of the drying process with ultrasound at atmospheric pressure allows one to describe the heat and mass transfer processes under conditions of combined energy supply, introduce changes in product temperature and moisture, calculate the drying time under given conditions, and control the drying process of spicy herbs without using a preliminary expensive experiment. The results of the experiments show the perspective and benefits of creating combined drying units (ultrasound - convection) with optimal ratio of thermal and acoustic energy.

Conflict of Interest
The authors have no conflict of interest to declare.

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