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Microwave and ultrasound enhancement of convective drying of strawberries: Experimental and modeling efficiency

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ABSTRACT

This article presents the results of convective drying of strawberries enhanced with microwaves and ultrasound acting together or separately. Five drying programs applied for this biological product with different application of microwaves and ultrasounds and pure convective drying as a reference test were carried out. The purpose of the studies was to analyze the effect of hybrid drying with respect to drying kinetics, total energy consumption, and the quality of this dried product. It was proved that convective drying assisted with microwaves and ultrasounds significantly improves the efficiency of heat and mass transfer in strawberries. However, microwave and ultrasound as different energy sources affect the energy consumption and the product quality in different way. The microwaves generate at most the "heating effect" and the ultrasound reveal significantly the "vibration effect". Both these energy sources acting together accelerate the drying rate due to "synergistic effect". The model of drying kinetics used in this article illustrate the mentioned above effects.

1. Introduction

Fresh fruits like strawberries belong to a group of materials with low microbial stability due to high moisture content. Drying is one of the most popular processing methods to prevent such phenomena as food spoilage and decay. Dehydration of strawberries reduces its water activity, which results in a protection against bacteria, yeasts and molds, and thus safes the products enabling their storage at ambient temperature [2]. The main advantages of the drying process is that it enhances shelf life of fruits and vegetables, reduces their volume and weight, and thus decreases the costs of storage and transportation [14]. Processed food by drying has a wide range of applications, e.g. as a spice, addition to herbal teas, instant products and muesli, as well as a healthy snack in the form of bars or fruit and vegetable chips [13].

However, there are still some disadvantages related to convective drying process. This operation is extremely time and energy consuming, and both of these factors affect the high cost of this process [23]. Another important factor is the effect of long term exposure to high temperature, which directly influences the quality. The value of color, shape, taste, flavor, nutrient content and many other quality parameters are subjected to change [21,44,27,34]. In view of the problems highlighted above, it seems necessary to search for new and innovative drying methods that will allow to obtain good quality dried products, while reducing the drying time and energy consumption.

The conventional drying techniques like convective drying are still extensively employed as hot air drying is commonly used due to unquestionable advantages such as simple apparatus and a very well-known drying mechanism. Convective dryers can be also operated under milder conditions by processing heat-sensitive biological products, in order to protect these materials against the over-heating, shrinkage, discoloration and case hardening. But, on the other hand, a long-lasting hot air drying gives rise to low drying performance and high operating costs [29]. Thus, overcoming limitations of conventional dryers gives rise to some emerging drying technologies and a new advancement in drying technology like hybrid drying.

Hybrid mode combines different drying techniques such as convective (CV), microwave (MW), ultrasound (UD) drying etc. These methods are characterized by different mechanisms of energy supply [24]. In convective drying, the heat transferred by a drying agent (air) is used to evaporate the moisture from the material surface, and then for moisture diffusion from the material core to the surface [28]. In turn, the absorption of microwave radiation causes heat generation in the entire volume of the material ("heating effect"). Thus, the body temperature becomes greater inside the material than on its surface, which intensifies the heat and mass

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Nomenclature

A_m	surface of mass exchange [m^2]
A_T	surface of heat exchange [m^2]
a^*	color parameter from red to green
a_w	water activity
b^*	color parameter from yellow to blue
c_s	specific heat for solid [J/kg·K]
c_l	specific heat for liquid [J/kg·K]
db	dry basis
h_m	coefficient of convective vapor transfer [kg/m^2·s]
h_T	coefficient of heat transfer [W/m·K]
J_m	moisture flux [kg/m·s]
J_T	heat flux [J/m^2·s]
L^*	lightness
l	latent heat of evaporation [J/kg]
m_s	mass of dry body [kg]
m_t	mass of fresh strawberry with OD [kg]
t	time [s]
p_w	partial vapor pressure [Pa]
p_{ws}	partial vapor pressure in saturated state [Pa]
T	temperature of the material [K]
T_a	temperature of drying air [K]
wb	wet basis
X	moisture content (db) [kg/kg]

Greek letters

φ	relative air humidity [%]

Subscripts

0	initial
∂B	near the material surface
a	air
cr	critical
eq	equilibrium

Abbreviations

AD	air drying
AT	air temperature [°C]
CDRP	constant drying rate period
FDRP	falling drying rate period

transfer [37]. A completely different situation occurs during ultrasound drying. High power ultrasound (20–500 kHz) causes various phenomena in the dried material like "vibration effects". Absorption of acoustic energy contributes also to a moderate material temperature rise, which in turn may cause an increase in water vapor pressure in the dried body. High frequency vibration of the air causes a micro vibrations and air turbulences near the material surface, that enhance the heat and mass transfer process [19]. Moreover, when a high-intensity ultrasonic energy travels through the body, it causes a rapid series of contractions and expansions of the material tissue (sponge effect). The alternating stress creates microscopic channels through which moisture dehydration is easier [8].

Integration of various drying methods based on the theoretical and experimental knowledge, allows to eliminate defects and use the advantages of combined techniques. The synergistic effect of such action manifests itself most often by improving the quality, reduction of drying time and energy saving. Experimental investigations with over two decades have shown that appropriate and skillful use of convection and microwaves in one process significantly increases its efficiency [43]. As shown Kowalski and Mierzwa [15], application of non-conventional methods, e.g. convective-microwave drying accelerates the drying rate of bell pepper almost twenty-fold and shortens the drying time by 95%. Similar results were obtained by Bhattacharya et al. [1], who revealed that the drying rate as well as effective diffusivity at the same air velocity is higher in case of convective-microwave drying of oyster mushroom as compared to hot-air drying, and the drying time reduction is up to 75%.

MW-related drying improves also the final quality of dried products [41,26]. Air drying followed by a microwave final drying showed that total color change (ΔE) of banana is lower more than three times, compared to the pure hot air and microwave drying methods alone. As reported Workneh et al. [42], microwave assisted hot air ventilation drying at the lowest microwave power density maintains the superior quality of tomato slices in terms of color. Kowalski et al. [17], in hybrid drying of cherries observed also the lowest value of water activity after application of microwaves in the falling drying period. Another benefit of microwave-related drying is energy savings. Combination/hybrid drying as a cost effective alternate system has proven to minimize energy requirements [35]. Sharma and Prasad [38] showed by drying of garlic that microwave-convective technique resulted in about 70% energy saving as compared to pure convective method.

The first mention about intensification of heat and mass transfer by ultrasound (US) action appeared already a few decades ago. However, since recently the high power ultrasound has become an efficient tool for large scale commercial applications such as e.g. drying processes [32]. García-Pérez et al. [12] demonstrated that US application in air drying reduces the drying time of orange peel maximum up to 45%, and improves significantly both the effective moisture diffusivity and the mass transfer coefficient, as well as reduces the total energy consumption by 20%. Similarly, Sabarez et al. [36], found a reduced energy consumption and increased production throughput after application of ultrasonic energy in hot air drying process of apples. Moreover, as many other researchers [4,11,30,16], they showed that the ability of ultrasound to improve the drying efficiency is greater at low temperatures, high ultrasonic power level, as well as at lower air flow rate. Furthermore, there are a lot of reports on positive effects of ultrasound on the final product quality. As reported Frias et al. [6], power ultrasound may be considered a valuable tool to obtain high nutritive dehydrated products, due to its ability to retain a higher vitamin C and β-carotene content than in convective air drying. In turn, Gamboa-Santos et al. [9], showed that ultrasound-assisted convective drying is an adequate procedure to obtain dried strawberry samples with high quality and appropriate microbiological stability. Application of air-born ultrasound in convective drying has also revealed as a tool to reduce the total color change ΔE (up to 11%) in comparison to the air-dried product [20].

One of the important aspects of process engineering, including drying processes, is mathematical modeling. It reflects the actual processes carried out by experiment and facilitates their designing. Due to mathematical modeling it is possible to choose suitable drying technique for heat-sensitive fruits and vegetables and optimize (using computer simulation) the hybrid drying programs developed on the basis of experimental data.

Strawberry is a member of Rosaceae (Rose) family and Fragaria (F) genus. According to the FAO, the largest producer of strawberries in the world is the United States of America. However, Poland