LWT - Food Science and Technology 60 (2015) 1136–1142

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Effects of pretreatments on explosion puffing drying kinetics of apple chips☆

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A R T I C L E I N F O

Article history:
Received 7 May 2013
Received in revised form
11 September 2014
Accepted 1 October 2014
Available online 8 October 2014

Keywords:
Explosion puffing drying
Pretreatment
Kinetics
Effective moisture diffusivity

A B S T R A C T

In the present paper, explosion puffing drying kinetics of sliced apples affected by four different pretreatments, including freezing, maltose syrup, calcium chloride and standard pasteurized milk immersion at atmospheric pressure were investigated. Four thin-layer drying models were applied to describe the drying kinetics. The results indicated that a parabolic model was the best model to characterize the drying kinetics of apple slices. The average values of determination coefficient (r^2) varied between 0.9803 and 0.9933. The parabolic model had the lowest root mean square error (*RMSE*), mean bias error (*MBE*) and chi-square (χ^2), the highest modeling efficiency and regression coincident. The values of effective moisture diffusivity were ranged from $154.0650 \times 10^{-12} \mathrm{m}^2\ \mathrm{s}^{-1}$ to $397.6886 \times 10^{-12} \mathrm{m}^2 \mathrm{s}^{-1}$. Freezing pretreatment had the highest effective moisture diffusivity value and maltose syrup immersion treatment exhibited the lowest one.

1. Introduction

Apple is regarded as one of the most important raw material in the food industry, and is cultivated all over the world. China has the largest cultivated area and yield in the world producing 31.6 million tons in 2011. Most apples were supplied for fresh consumption, juice and jam processing. Unsuitable preservation and storage methods can induce loss of fresh fruits. During the past decades, dehydration has proven to be a good method to preserve fruits and vegetables by not only maintaining nutrients but also avoiding quality deterioration.

Drying is a complicated process which involves simultaneous heat and mass transfer. Water molecule transport has a close relationship with the drying process, including molecular diffusion, such as capillary motion, liquid diffusion, and vapor diffusion, and hydrodynamic flow. Mathematical models have been widely used to represent drying kinetics for fruits and vegetables and describe thin-layer drying characteristics (Kaya, Aydın, & Demirtas, 2007; Menges & Ertekin, 2006). For example, thin-layer drying investigation was conducted on red bell-pepper (Arslan & Özcan, 2011), peach (Kingsly, Goyal, Manikantan, & Ilyas, 2007), bamboo (Kumar, Kanwat, & Choudhary, 2013), garlic (Sharma, Prasad, & Chahar, 2009), potato (Doymaz, 2012) and mango (Nieto, Castro, & Alzamora, 2001). Mathematical models and simulation of drying curves are important tools to control processing and product quality. Mathematical modeling for drying processes in fruits and vegetables has recently drawn researchers' attention.

As previous studies have reported, pretreatments before drying could shorten the drying time and improve final chips' structure and taste, including maintaining nutrition and flavor of fruits and vegetables. Blanching can strongly affect the effective diffusion coefficient of moisture during air dehydration process of fruits, and can separate cells, change fruit structure, and lead easier mass transfer than untreated samples (González-Fésler, Salvatorib, Gómeza, & Alzamora, 2008; Tunde-Akintunde, 2010). It is also known that calcium and iron can be used for fortification of apple slices. Iron ion immersion with low concentrations had no significant effect on moisture transfer during the drying process. Calcium ion immersion significantly reduced effective diffusivity values (Barrera, Betoret, & Fito, 2004). The phenomenon could be

☆ This manuscript was presented in the international conference of "Food Innova-2012" Hangzhou, China, December 12–14, 2012.

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http://dx.doi.org/10.1016/j.lwt.2014.10.006

attributed to the interactions between calcium ion and pectin or other cellular wall components (Andres, Bilbao, & Fito, 2004; Brett & Waldron, 1990), which form firm structures after heating. Freezing treatment prior to drying can improve mass transfer during the dehydration process (Eshtiaghi, Stute, & Knorr, 1994). Immersion in a sugar solution could remove part of moisture of raw materials before the drying process (Aktas, Fujii, Kawano, & Yamamoto, 2007; Rastogi, Nayak, & Raghavarao, 2004). Milk protein has been used as pretreatment method before drying of mushroom, results showed that whey treated dried mushroom displayed higher diffusion coefficient (Walde, Velu, Jyothirmayi, & Math, 2006). Furthermore, enzymatic browning of apple slices coated with milk protein was delayed (Letien, Vachon, Mateescu, & Lacroix, 2001). It indicated that milk immersion would be a promising pretreatment method.

Apple chips dehydrated by explosion puffing drying are regarded as prospective market valued snacks. These crisp apple chips have a high fiber content and are free of fat. These characteristics may make them highly desirable by consumers. Explosion puffing drying of apple chips can retain the most natural quality and consume less time and energy when compared to freeze-drying. This process can overcome the disadvantages of non-crispy sponge-like structure, undesirable colors, flavors and textures, which may be caused by oil frying or hot air drying. Consequently, explosion puffing drying offers an alternative way to maintain the quality of apple products that are used as crisp snacks, instant apple sauce, and ingredients for pies, tarts, and cobblers (Sullivan, Craig, Konstance, Egoville, & Aceto, 1980).

In previous researches, the optimal processing parameters of explosion puffing drying had been investigated, including apple, hami melon, potato, mushrooms, pineapples (Bi, Wei, Wang, & Zhang, 2008; Kozempel, Sullivan, Craig, & Konstance, 1989; Nath, Chattopadhyay, & Majumdar, 2007; Sullivan et al., 1980). However, there are few reports of explosion puffing drying of apple chips combined with different pretreatments. The objective of the present work is to investigate the effect of pretreatments on the explosion puffing drying process of apple chips by various drying models. Effective moisture diffusivities were estimated from the models and compared to describe the drying process. The effects of pretreatments on the texture properties of apple chips were also investigated. The present study would not only provide the guideline for optimal design of drying process of apple slices, but also important for industrializing apple slices processing.

2. Materials and methods

2.1. Materials and sample preparation

Fresh apples (*Malus domestica Borkh. CV. Red Fuji*), were purchased from a local market. The apples were stored in a refrigerator at 4 ± 0.5 °C, and were equilibrated at room temperature before each trial. Initial moisture content of the fresh apples was determined with a microwave moisture tester (LMA200PM-000EU, Sartorius Company, Goettingen, Gemany), which indicated about 8.01 ± 0.1 kg water/kg dry basis (d.b.).

Food grade calcium chloride (98 g/100 g) and maltose syrup (76 g/100 g) were provided by Shandong Luzhou Group Corporation (Linyi, China). Standard pasteurized milk (protein content of 3.1 g/100 g; fat content of 3.7 g/100 g; carbohydrate content of 4.7 g/100 g), produced by Sanyuan Foods Co. Ltd. (Beijing, China), was purchased from a local supermarket.

The apples were peeled and sliced uniformly at an average thickness of 5 mm and diameter of 62.0 ± 0.3 mm. The diameter of the apple slices was considerably larger than the thickness (The ratio of thickness-diameter was 5 mm/62.0 ± 0.3 mm < 0.1) (Ramírez, Troncoso, Muñoz, & Aguilera, 2011). The shape of the sliced apple could be considered as an infinite plate assuming mass transfer occurred only in the axial direction.

The sliced apples were pretreated with four different methods, including freezing and immersing with three solutions (0.05 mol/L calcium chloride, 30 g/100 g maltose syrup and 100% milk) for 30 min. The immersion ratio between apples slices and solution was 1:5 (w/w). The immersion treatments were conducted at room temperature (25 °C). After immersion, the samples were allowed to drain on a stainless steel mesh at room temperature (25 °C) for 5 min. The final moisture content of the immersed apple slices in calcium chloride, malt syrup and milk was 6.5 ± 0.1 g water/g d.b., 6.2 ± 0.1 g water/g d.b. and 5.8 ± 0.1 g water/g d.b. The freezing treatment was conducted by placing apple slices in a freezer (ULT 1386-3-U41, Thermo Fisher Scientific, Asheville, USA) at −80 ± 1 °C for 12 h, and then thawed at room temperature (25 °C) for 1 h. The final moisture of apple slices treated by freezing was 4.9 ± 0.1 g water/g d.b.

2.2. Explosion puffing drying process

The explosion puffing drying process was carried out by the equipment shown in Fig. 1 (Tianjin Qin-de New Material Scientific Development Co. Ltd., Tianjin, China). Before the explosion puffing drying process, the apple slices were dried for 2 h by hot air (DHG-9030, Jing Hong Laboratory Instrument Co., Ltd., Shanghai, China), then placed on a plate in the explosion puffing chamber for 15 min under an elevated pressure of 0.2 MPa by air compressor and an explosion temperature of 80 °C by steam. Then the cooling water valve, pressure valve and vacuum pump were unlocked to obtain a sudden pressure drop to vacuum (−0.1 MPa) for the chamber. During the above process, water in the samples was brought to a temperature above its boiling point, which turns to steam rapidly. A sudden decrease in pressure caused the water in the cells of the material to vaporize and expand. The depressurizing treatments, involves the release vapor of water in the samples, and creates a porous structure. After explosion puffing, the apple slices were dried under continuous vacuum at 60 °C for about 2 h. The weights of the samples were measured every 3 min during the puffing drying process and every 5 min during the vacuum drying process by using an automatic digital balance. The sample plate was connected to the balance by a weight sensor. The digital balance was inserted in the drying chamber so that the weight can be read during the drying process without removing the samples out. All experiments were conducted in triplicate.

2.3. Texture analysis

The hardness and crispness of apple chips dried by explosion puffing combined with different pretreatments was determined by TA-XT2i Texture Analyzer (Stable Micro Systems Ltd., Surrey, UK). A stainless steel ball probe (0.25 S) was selected and the pre-speed, post-speed and test speed were set at 2 mm/s, 2 mm/s and 1 mm/s, respectively (Huang, Zhang, Wang, Mujumdar, & Sun, 2012). During penetration tests, the hardness value was expressed as the maximum force (g) to break the chips, and the crispness value was expressed as the time (s) required for sample fracture. Each measurement was repeated ten times and the average value was calculated.

2.4. Mathematical modeling of drying curves

Statistical analysis was conducted to test the fitness of different models for describing the explosion puffing drying process of apple slices combined with different pretreatments, and the moisture