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Research paper

Mathematical modeling and experimental analysis of potato thin-layer drying in an infrared-convective dryer

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A R T I C L E I N F O

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A B S T R A C T

In this paper, the thin layer potato drying process by a laboratory scale infrared-convective dryer is investigated. The experiments were accomplished in three levels of slice thickness; 3, 5 and 7 mm, and three levels of infrared power; 500, 700 and 900 W. Drying took place entirely in the falling rate period. The results show that increasing the infrared power leads to a decrease in the moisture content, and drying time of samples, but increased the drying rate, shrinkage, and effective moisture diffusivity. The results also indicated that by increasing the thickness, the effective moisture diffusivity and drying time increased while the drying rate and shrinkage decreased. Eight thin-layer drying models were fitted on the experimental data. The models were compared according to three statistical parameters of the correlation coefficient (R^2), root mean square error (RMSE), and reduced chi-square (χ^2). The obtained results indicated that the page model could satisfactorily describe the drying curve of potato slices with $R^2 = 0.9991{-}0.9997$, RMSE $= 0.0050{-}0.0095$, and $\chi^2 = 1.3\text{E-}05\text{-}9.6\text{E-}05$ under different operational conditions.

1. Introduction

Potatoes are major crops in the world after wheat, maize, and rice with an annual production of 300 million tons (Duran et al., 2007; Pedreschi, 2012). The dehydrated potato is an important food product, and is extensively used in ready-to-eat foods. Food problem arises in most developing countries mainly due to the inability to preserve food surpluses rather than due to low production (Jairaj et al., 2009). Potato is one of the products, which is highly wasted in developing countries because of poor harvest and storage methods, therefore, the production of dried potato products may be necessary to increase their shelf time, and decrease wastage. Of course other facilities, such as proper packaging, appropriate shipping, and sufficient processing may also lower the amount of the wasted products (Steinfeld and Segal, 1986). Drying is considered as one of the oldest food preservation methods, and a very important modern technology for preservation of food crops (Maskan, 2000). Dried food is preserved by reducing the water content due to simultaneous heat and mass transfer processes (Sagar and Kumar, 2010). Drying provides not only a longer shelf-life to the food due to the limitation of microbial growth and enzyme, and minimizes the physical and chemical changes during its storage, but also lowers the product mass and volume. The reduction in mass and volume improves the efficiency of packaging, storing, and transportation (Ansari and Datta, 2003; Mayor and Sereno, 2004; Jayaraman and Gupta, 2006; Raitio et al., 2011). Producing dehydrated products are still common with traditional methods especially in developing countries, but there are many main disadvantages, such as the long drying time, chance of microbial contamination of foods due to moisture, and the undesirable final product quality that can be prevented by using the new industrial dryers, which have to be designed under the guide lines of exact mathematical models and extensive experimental studies. Drying by infrared radiation is a new and innovative technique, gaining popularity because of its inherent advantages over conventional heating (Mongpraneet et al., 2002). The use of infrared radiation technology in dehydrating foods has several advantages. These may include decreased drying time, high energy efficiency, high quality of finished products, uniform temperature in the product

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while drying, and a reduced necessity for air flow across the product (Mongpraneet et al., 2002; Sharma et al., 2005). Infrared radiation is also advantageous in that it can be combined with conventional convection drying to dehydrate products, and combined infrared and convective drying has also been reported as a promising drying technique (Abe and Afzal, 1997). It is a well-known fact that drying the food materials in form of thin layers may lead to lower processing times and higher product quality. Also, many drying models have been used to describe the drying process of thin-layers. Wang and Brennan, (1995), Rovedo et al. (1998), Iyota et al. (2000), and Youcef-Ali et al. (2001) have studied the behavior of the potato during thin-layer drying. Hasan et al. (2014) used five thin-layer drying models for drying hybrid rice seed. They found that the Midilli equation was best fitted to experimental data followed by the Two term exponential equation, Page equation, Henderson and Pabis equation, and Newton model. Karathanos and Belessiotis (1999) also used certain agricultural products, such as black currant, seedless grapes, figs, and plums. The page model was found to be the best fitted empirical correlation. Ruiz Celma et al., (2009) studied the thin-layer infrared drying of grapes by using nonlinear regression analysis (Margaret method). When the drying process is controlled by the internal mass transfer, especially in the falling rate period, molecular diffusion is the main water transport mechanism, so the modeling of the drying process may be based on Fick's second law proposed by Crank (1975). All of the possible moisture transport mechanisms within the foods, such as liquid diffusion, vapor diffusion, surface diffusion, capillary flow, and hydrodynamic flow may be described in terms of effective moisture diffusivity. Therefore, determination of the effective moisture diffusivity is necessary for the design and modeling of the mass-transfer processes, such as drying (Midilli and Kucuk, 2003; Wang et al., 2007; Sarimeseli, 2011). Shrinkage of food materials is so common during the drying process due to water loss and heat stress in the cellular structure of the product, leading to product deformation and dimension reduction (Mayor and Sereno, 2004; Ratti, 1994). The aim of this study was to investigate the effect of infrared power and sample thickness on the shrinkage, effective moisture diffusivity, and drying behavior of potato slices in the infrared-convective laboratory scale dryer.

2. Materials and methods

2.1. Sample preparation

The potato drying process includes washing, peeling, cutting, blanching using a hot solution of calcium chloride in water, treating with ascorbic acid, and drying. Potatoes used for the drying experiments were purchased from a local market (Babol, Iran) and stored in a refrigerator at 4 ± 0.5 °C for 48 h, to reduce the intensity of respiration, and physiological and chemical changes until the start of the experiments. Prior to drying, each sample was placed outside of the refrigerator for an hour to reach room temperature and then, they were peeled, washed in clean water, and sliced into slabs of 3, 5 and 7 mm on a cutting board made of polyethylene. Then, the potato samples were blanched in a solution of calcium chloride 0.4% for 2 min at 98 °C. Calcium chloride concentration was determined according to Lisinsca and Plisga (1992), and the blanching time was determined according to Kyung and Wan (1992). After blanching, the samples were washed immediately with cold water to remove the starch on their surface. Then, the samples were poured into a 5 ppm solution of ascorbic acid to avoid the undesirable changes during the drying process and preserve the quality of the dried products during storage (Talburt and Smith, 1975). After five minutes, the samples were removed from the solution and were drained off, before being dried under 500, 700 and 900 W of infrared power. All samples were dried to reach the equilibrium moisture. The initial moisture content of the potato was measured by a moisture analyzer prior to drying. The initial moisture content of the potato samples were found to be around 78–80% (wet basis).

2.2. The experimental equipment and procedures

Experiments were carried out at different infrared power levels (500,700 and 900 W) and slice thicknesses (3, 5 and 7 mm) in a laboratory scale infrared-convective dryer containing two trays that were designed and made at the Babol University of technology, Iran. A laboratory scale infrared-convective dryer was developed and thin-layer drying of potato slices was carried out under different infrared power levels (500, 700 and 900 W), and slice thicknesses (3, 5 and 7 mm). The drying chamber is fitted with two aluminum trays. A door is provided at the rear end of the drying chamber for loading and unloading the trays. In this dryer, air enters by natural convection through holes at the bottom of the dryer. The two opposite walls of dryer also have some holes for easy air flow. Prepared samples were uniformly spread in thin layers on the aluminum trays and get heated due to high temperature in the enclosure and then air escapes with moisture vapors through the side ventilation holes. Samples dried until a constant weight was observed.

During the drying process, moisture loss was continuously recorded in 60 s intervals by a digital electronic balance of ±0.01 g accuracy. The infrared-convective dryer was running empty for about 30 min to achieve the steady state before each drying run. Potato slices were uniformly distributed on the trays and dried until a constant weight was observed.

2.3. Modeling of the drying process

The empirical models usually predict the variation of the moisture ratio with time. The moisture ratio is defined by the following equation:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \tag{1}$$

The drying rate, D_t, is defined as the amount of the evaporated moisture over time and can be calculated by the following equation:

$$D_t = \frac{X_{t+dt} - X_t}{dt} \tag{2}$$

where MR is the dimensionless moisture ratio, X_t, X_{t+dt}, X_e, X_0 are the moisture content at time t, t + dt, equilibrium, and initial condition (dry basis), respectively. D_t is the drying rate (g moisture/g dry solid. min) and dt is the time interval between two consecutive moisture (minute).

The moisture content data at different infrared power and thickness of the potato samples was converted into moisture ratio according to Eq. (1), and then, fitted against the drying time, using the various standard models of thin-layer drying of agricultural products collected in Table 1. Several criteria are available to compare the different empirical correlations. The correlation coefficient (R^2) was used to determine the appropriateness of the model while the accuracy of the fits was assessed using a reduced chi-square (χ^2) and root mean square error (RMSE). A model is considered to be good when the R^2 value is close to one while χ^2