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Extended Abstract

Modeling of Mass Transfer in the Drying Process of Apple Slices Using Infrared Irradiation with Intermittent Heating Method

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Abstract

Infrared radiation by intermittent heating is a novel method in which the surface temperature of the product is maintained at a constant value. This method is widely used in simultaneous blanching and drying process. The main advantages of intermittent IR-radiation are energy saving and preventing undesirable quality changes in the final product. The calculations of mass transfer in this process can be used to estimate the temperature and time conditions in the process. For this purpose, drying behavior of apples slices (Golden Delicious variety) was investigated with slab shape in three different sizes: thickness of 5, 9 and 13 mm and length and width was 20 mm. Heating operation performed by infrared dryer that was equipped with controller of product surface temperatures at 70, 75 and 80 °C. Kinetic models such as Newton, Page, Modified Page, Henderson-Pabis and parabolic were fitted on experimental data of dimensionless moisture ratio using MATLAB software. The adjusted correlation coefficient (Adj.R^2) and root mean square error (RMSE) were used to compare the models. The evaluation of effective moisture diffusivity (D_{eff}) performed during drying of slices and its dependency with temperature investigated using Arrhenius equation. The results showed that models of page and parabolic presented a good fit on experimental data, respectively (higher Adj.R^2 and lower RMSE). The effective diffusion coefficient significantly elevated with an increase in surface temperature and thickness. This parameter showed higher energy activation for lower thicknesses that indicated a greater irradiation temperature dependence of effective diffusion coefficient through the decreasing of thickness.

Keywords: Drying, Infrared, Intermittent Heating, Kinetic Model, Mass Transfer

Introduction

Simultaneous infrared dry-blanching and dehydration (SIRDBD) can be operated in two heating modes, continuous and intermittent heating. During continuous heating, the radiation intensity is maintained constant (Zhu & Pan, 2009). Infrared radiation by intermittent heating is a novel method in which the surface temperature of the product is maintained at a constant value. The main advantages of intermittent IR-radiation are energy saving and preventing undesirable quality changes in final product (Zhu *et al.*, 2010). The current study was designed to better understand the mass transfer behavior of apple slice in intermittent heating mode.

The calculations of mass transfer parameters in this process can be used to estimate the temperature and time conditions in process. Therefore, the aim of this study was: (a) to study the effect of irradiation temperature on the drying times and dehydration of apple slice, (b) to fit the experimental data to five simple mathematical models available in the literature, and (c) to compute effective moisture diffusivity and activation energy of various thickness of samples.

Material and methods

Apple slices *(Golden Delicious* variety*)* were prepared in thickness of 5, 9, and 13 mm and then dried using infrared irradiation by intermittent heating at constant surface temperature of 70, 75, and 80 °C. According to Toğrul (2005), The moisture content of drying sample at time t can be transformed to be moisture ratio (MR). Similar to Doymaz (2010) selected simple drying models, detailed in Table (1), were fitted to the drying curves (MR:dimensionless versus time:secounds) using MATLAB 2009 software. The adjusted correlation coefficient (Adj.R^2) and root mean square error (RMSE) were used to compare the models. According to Doymaz (2010) For long drying times, Evaluation of effective moisture diffusivity (D_{eff}) performed using Eq. (1). D_{eff} is the effective moisture diffusivity (m^2/s), t is the time (s), L is the half-thickness of samples (m). The dependence of the effective diffusivity on the temperature is generally described by the Arrhenius equation. Statistical analysis of the effect of temperature and thickness on the parameter of effective diffusivity coefficient performed using SPSS 19 by completely randomized design in form of factorial (3^2) and multiple mean comparison of Duncan test (P<0.05).

Table 1. Mathematical Models applied on drying curves

Model Name	Equation
Newton	$MR= \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified page	$MR=\exp(-(kt)^n)$
Henderson-Pabis	$MR= a.\exp(-kt)$
Parabolic	$MR= a + bt + ct^2$

*model parameters (k, a, b, c), time (t)

$$LnMR = Ln\left(\frac{8}{\pi^2}\right) - \left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \qquad (1)$$

Results and discussion

Results showed that models of page and parabolic presented a good fit on experimental data, respectively (higher Adj.R^2 and lower RMSE). Figure (1) shows the predicted moisture ratio (MR) against the actual value for the page model (R^2=0.9868). Madamba (2003) stated that the page model provides a more favorable prediction compared to other one or more parametric models.

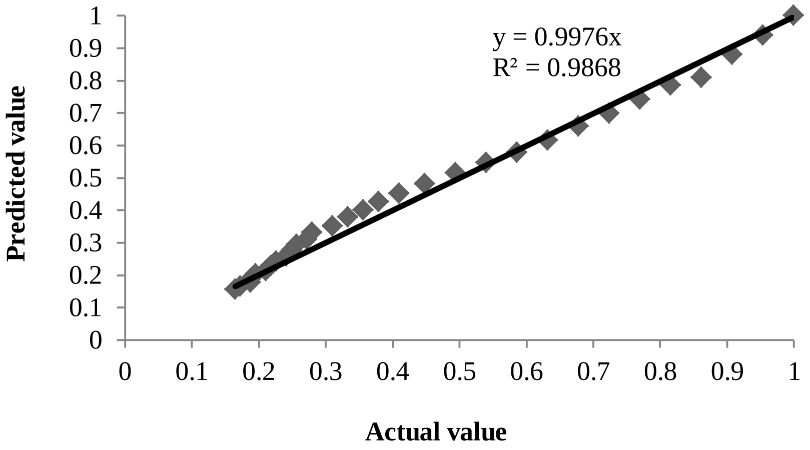

Figure 1. The predicted moisture ratio (MR) value versus actual value for the page model

Generally, with increasing the process temperature, the effective diffusivity coefficient of moisture always increased significantly and was significantly higher for larger thicknesses (Figure 2). Nowak & Lewicki (2004) noted that increasing the overall surface of apple slices in infrared drying will result in more mass flux of water during evaporation. In fact, with decreasing the thickness of the sample, it seems that dry layers are created at the product surface, which reduces the amount of moisture penetration (lower D_{eff}).

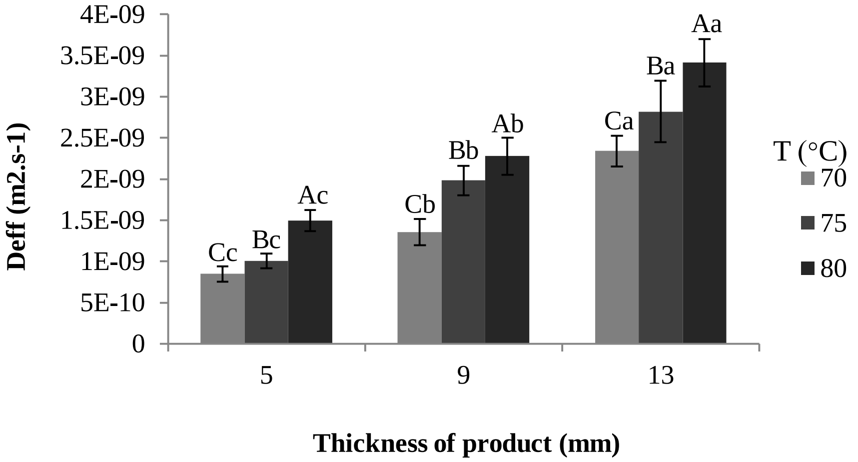

Figure 2. Variation of effective diffusivity with drying temperature and thickness of slices, upper case letters shows the comparison between temperatures and lower case letters shows the comparison between thicknesses (P<0.05)

The information of Arrhenius equation fitting for various apple slice thicknesses is presented in Table 2. As it is known, by decreasing the apple slices thickness, the parameters of (D_0) and (E_a) increased. For the lower thickness, higher activation energy (E_a) indicates a greater temperature dependency of the diffusion coefficient (Marfil *et al*., 2008).

Table 2. Information of the fitting of Arrhenius's equation in different apple slice thicknesses

Thickness (mm)	D_0	E_a (j.mol^{-1})	Adj.R^2	RMSE
5	0.38125	56916.65	0.8901	0.09639
9	0.24195	54141.44	0.8654	0.099
13	0.00146	38055.22	0.9996	0.00385

Conclusion

Due to the fact that in the infrared heating methods for vegetables, the blanching is always an integral part of the process, it is possible to consider the low temperature or higher thickness as the suitable treatment with minimum changes in weight at the beginning of the process. Because of severe weight changes will result in adverse chemical reactions in the product.

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