Mathematical Modeling of Thin Layer Drying Kinetics of Sliced Cucumbers

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Abstract: ***Thin layer drying behaviour of sliced raw cucumbers was studied in a laboratory model cabinet dryer. The samples were dried at 40, 50 and 60˚C air temperature. During drying, sample weights were measured every 20 minute. Four thin-layer drying models (Lewis, Page, Henderson and Pabis and logarithmic) were fitted to the moisture ratio data. Among the drying models investigated, the Page model satisfactorily described the drying behaviour of raw cucumber slices. Temperature dependence of the total weight to solid weight ratio followed an Arrhenius relationship. Activation energy deduced for this ratio was 5.35 kJ/mol.***

Keywords: Thin layer drying, Sliced cucumbers, Modeling, Activation energy

1. Introduction

The cucumber most likely originated in India (south foot of the Himalayas) and it has been in cultivation for at least 3000 years. The cucumber (Cucumis sativus L.) belongs to the Cucurbitaceae family, one of the more important plant families. The cucumber fruit, like that of other Cucurbitaceae, is noted for its high water content, which is around 95% of its fresh weight. The nutritive value of 100 g of edible cucumber is as follows: energy 12 cal, protein 0.6 g, fat 0.1 g, carbohydrate 2.2 g, vitamin A 45 IU, vitamin B1 0.03 g, vitamin B2 0.02 g, niacin 0.3 g, vitamin C 12 g, calcium 12 mg, iron 0.3 mg, magnesium 15 mg, and phosphorus 24 mg (Papadopoulos, 1902).

Dried cucumber slices are good for snacks as well as other fruit chips. They can also be used directly or powdered as seasoning in soups, desserts and yogurt. It could be tasted by adding some salt to the slices before drying.

Preservation of fruits, vegetables and similar products by dehydration method requires special skills. Due to the structure of this kind of products, moisture removal must be done in a manner that will have minimal impact on its quality. During drying, simultaneous heat and mass transfer occurs, causing the material to dehydrate. Those transport phenomena are highly linked to material properties like moisture content, density ,shrinkage and porosity (Luikov, 1975; Martynenko, 2008). Thus ,real-time evaluation of these properties is crucial to the design and optimisation of cucumber drying (Mercier et al., 2011).

The most common drying method employed for food materials to date was hot air drying (Maskan, 2001).

Cabinet dryers are the most favorite equipment used in farms for fruit drying. These dryers are simple in structure, low in cost installation and can be employed in almost any environmental conditions. In conventional cabinet dryers, hot air is usually introduced under first tray (bottom tray) and passes through the other trays normally. (Amanlou & Zomorodian, 2010).

The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behaviour, and for optimising the drying parameters. Recently, studies have been done on drying kinetics of fruits and vegetables (Sabarez & Price, 1999; Togrul & Pehlivan, 2002; Soysal, 2004; Doymaz, 2004; Cao et al., 2004; Jain & Pathare, 2004). However, no detailed studies were found in literature on drying kinetics of raw cucumber. The objectives of this study were: (a) to study the effect of temperature on drying behaviour of raw cucumber; (b) to evaluate a suitable thin-layer drying model and (c) to calculate activation energy of the total weight to solid weight ratio of sliced cucumbers.

2. Materials and Methods

2.1 Materials

Raw cucumbers used for the drying experiments were purchased from local market, Isfahan, Iran. Prior to drying, samples were washed and then peeled with a sharp vegetable peeler. The cucumbers were sliced uniformly (average thickness 5±0.2 mm) and was dried on the same day. The initial moisture content of cucumber was 96% (w.b.) based on vacuum-oven drying (AOAC, 2006).

2.2 Drying procedure

Experiments were conducted at 40, 50 and 60 ˚C in an experimental cabinet dryer. After the dryer reached the set conditions, sliced raw cucumber samples (5 g) were uniformly spread in rectangular aluminum trays and kept in the cabinet for drying. Moisture loss was recorded in 20 min intervals by a digital balance of 0.01 g accuracy (Scaltec instruments, Germany). The drying was continued until there was no large variation in the moisture loss. It was assumed that all weight loss was due to water loss. Experiments were replicated three times.

2.3 Mathematical modeling

Moisture ratio of samples during drying was expressed by the following equation:

$$M_R = (M_t - M_e) / (M_0 - M_e) \quad (1)$$

Where: M_R is the dimensionless moisture ratio; and M_t, M_0 and M_e are the moisture content at any given time, the initial moisture content and equilibrium moisture content, respectively.

To select a suitable model for describing the drying process of cucumber slices, drying curves of moisture loss (M_R $vs. t$) that is shown in figure 1 were fitted with four thin-layer drying equations. The moisture ratio models are presented in Table 1. In the models, y=M_R and t is time (s). Curve Expert (version 1.5) software (Microsoft Corporation, Mississippi, USA) was used to fit the mathematical models to experimental data. The coefficient of determination R^2 was one of the main criteria for selecting the best equation. In addition to the coefficient of determination, the goodness of fit was determined root mean square error ERMS. For quality fit, R^2 value should be higher and ERMS value should be lower (Pangavhane et al., 1999; Sarsavadia et al., 1999; Togrul & Pehlivan, 2002; Erenturk et al., 2004; Demir et al., 2004). The ERMS parameter can be calculated as follows:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(M_{R,pre,i} - M_{R,exp,i})^2\right]^{1/2} \quad (2)$$

Where: $M_{R,pre,i}$ and $M_{R,exp,i}$ are the experimental and predicted dimensionless moisture ratios, respectively; N is the number of observations (Goyal et al., 2006).

Table 1: Thin-layer drying models

Model	Expression	Reference
Lewis	M_R = exp(-kt)	Lwis (1921)
Page	M_R = exp(-kt^n)	Page (1949)
Henderson and Pabis	M_R = a exp(-kt)	Henderson and Pabis (1961)
Logarithmic	M_R = a exp(-kt)+b	Yaldiz et al., (2001)

M_R, moisture ratio; k, drying constant; t, drying time; n, drying exponent; a, b drying coefficients specific to individual equations.

2.4 Calculation of activation energy

The total weight to total solid ration was measured for all the samples in each time interval (Equation 3). If the temperature dependence of this ratio follows the Arrhenius- type behaviour (Equation 4), activation energy of k ratio can calculated by equation (4).

$$k = \frac{total\ weight}{solid\ weight} \quad (3)$$

Where $total\ weight$ is the sample weight (g) in each time and $solid\ weight$ is dried sample weight (g).

$$k = A \exp\left(\frac{-Ea}{RT}\right) \quad (4)$$

In this equation: k is the ration mentioned in equation (3), A is Arrhenius factor ($m^2\ s^{-1}$), Ea the activation energy (kJ/mol), T the temperature (k) and R is the perfect gas constant (R = 8.3143×10^{-3} kJ/mol k).

To prove that the temperature-dependence of k ratio follows the Arrhenius-type behaviour, Arrhenius equation was lineared in time scale (Equation 5) and then the graph of the average of calculated ln(k) for different times versus (1/T) was plotted. The linear regression equation was calculated by Excel 2007 software (Figure 2). The criterion to prove that the temperature-dependence of k ratio follows the Arrhenius-type behaviour is the constant slope of the obtained equation.

$$ln(k) = ln(A) + \left(\frac{-Ea}{RT}\right) \quad (5)$$

Notation

wb	Wet basis
Ea	Activation energy (kJ/mol)
M_R	Dimensionless moisture ratio
M_e	Equilibrium moisture content (dry basis), kgH2O/kg dry solid
M_t	Moisture content (dry basis), kgH2O/kg dry solid
M_0	Initial moisture content (dry basis), kgH2O/kg dry solid
t	time (second)
$RMSE$	root mean squared error
Exp	experimental
Pre	predicted
N	number of observations
k	Dimensionless total weight / solid weight
R	Gas constant 8.3143×10^{-3} kJ/mol k
T	Temperature (k)

3. Results and Discussion

3.1 Drying behaviour of raw calcucumber slices

The moisture ratio curves verses time is shown in figure 1. The drying curves show that moisture ratio decreases continuously with drying time. Drying of raw cucumber slices occurred in falling rate period and no constant rate period was observed. The drying in falling rate period indicates that, internal mass transfer has occurred by diffusion. Similar results have been reported for the drying studies on onion slices (Rapusas & Driscoll, 1995) and apricots (Doymaz, 2004).

3.2 Mathematical modelling of drying curves

The moisture ratio data of raw cucumber slices dried at different temperature were fitted into the thin-layer drying models listed in Table 1. The M_R data in 40 ˚C and its fitted models are shown in figure 3 as an example of fitting results. For the better description of fitting with experimental models, the dotted line sector in figure (2-a) is magnitude in figure (2-b). The values of $RMSE$ for the Page, logarithmic, Lewis and Henderson models were 0.131, 0.156, 0.163 and 0.164 respectively. Although these values show appropriate fitting, but the Page model gave comparatively lower $RMSE$ value; hence, the Page model may be assumed to represent the thin-layer drying behaviour of raw mango slices. Demir et al. (2004) reported a similar result for air-drying of bay leaves. These results are in agreement with the study of Goyal et al. (2006) for thin-layer drying kenetics of raw mango slices. Doymaz (2005) and Ertekin et al. (2004) reported similar results for drying characteristics of okra and eggplant, respectively.

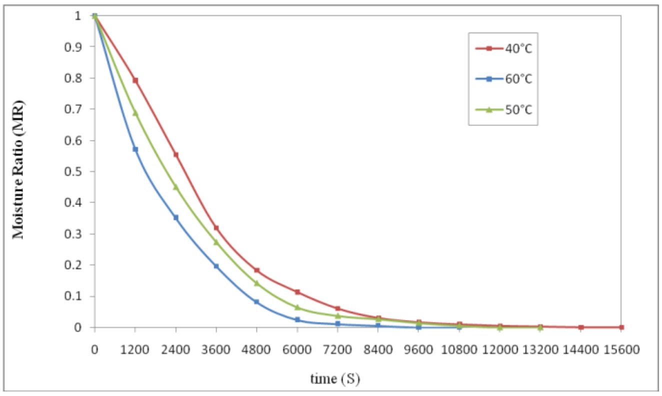

Figure 1: Drying curves for cucumber slices at three different temperatures

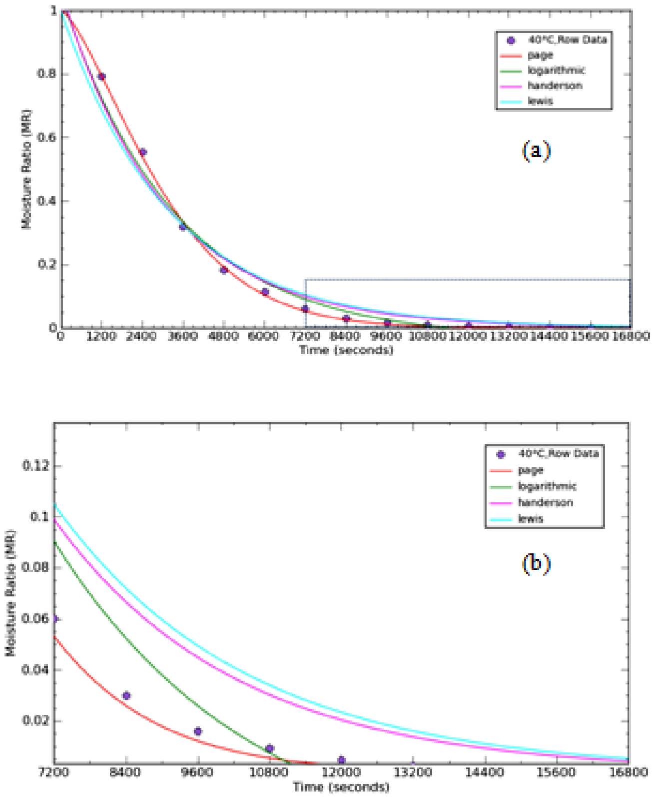

Figure 2: Values of moisture ratio in 40 ˚C fitted with four thin-layer drying models (a). Dotted line sector in figure (2-a) is magnitude in figure (2-b).

4. Changes of total weight to solid weigh ratio (k) verse temperature

By increasing temperature in Arrhenius equation, total weight to solid weigh ratio (k) was decreased. This is proven by the linear relation of ln (k) verses (1/T) in figure 3. The slope of this curve equals to (-Ea/R), so the activation energy was calculated 5.35 kJ/mol for total weight to solid weigh ratio (k).

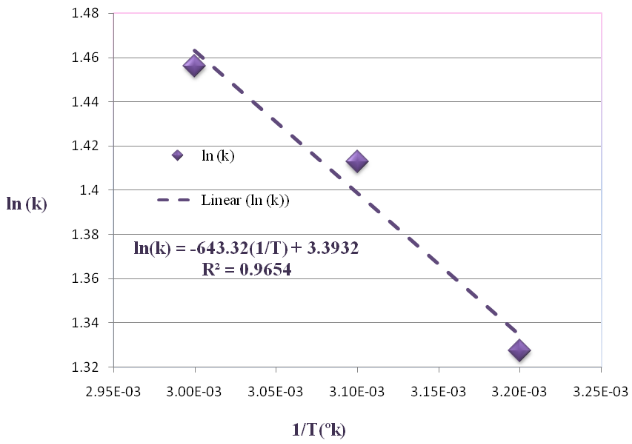

Figure 3: Arrhenius curve of total weight to solid weigh ratio (k) data at 40, 50 and 60 ˚C. Dotted line shows average values of total weight to solid weigh ratio in each experimental temperature.

5. Conclusions

Thin layer drying behaviour of sliced raw cucumbers was studied in a laboratory model cabinet dryer at three different air temperature. The total time of drying was reduced by increasing in drying temperature. This temperature-dependence follows the Arrhenius-type behaviour. The ability of four thin-layer drying models (Lewis, Page, Henderson and Pabis and logarithmic) to describing thin-layer drying of cucumber slices was evaluated. Among the drying models investigated, the Page model satisfactorily described the drying behaviour of raw cucumber slices. Janjai et al. (2011) reported a similar result for thin-layer drying of litchi (Litchi chinensis Sonn). Also Kianmehr et al. (2009) for thin-layer drying of potato slices, Zielinska et al. (2010) for evaluation of air drying characteristics and moisture diffusivity of carrots introduced Page model as the best model to describe drying behavior of the mentioned samples. Activation energy deduced for total weight to solid weight ratio was 5.35 kJ/mol.

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