Applied Engineering Letters Vol. 1, No 2, 35-39 (2016) e-ISSN: 2466-4847

EXPERIMENTAL INVESTIGATION OF FAR-INFRARED VACUUM DRYING OF APPLE SLICES

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Abstract:
In this paper the experimental results of far-infrared vacuum drying of apple slices were presented. The investigation of far-infrared vacuum drying processes was conducted on the experimental set-up that was designed to imitate industrial batch dryer. Apple slices were dried at various vacuum pressures and temperatures of heaters which were kept constant during the single experiments. Five well known thin layer drying models from scientific literature were used to approximate the experimental data of drying kinetics in terms of moisture ratio. For each model and data set, the statistical performance index and chi-squared value were calculated and models were ranked afterwards. The performed statistical analysis shows that the model of Aghbashlo gives the best results for approximation of experimental drying data of apple slices.

ARTICLE HISTORY
Received 04 May 2016
Accepted 10 June 2016
Available online 30 June 2016

KEYWORDS
vacuum, far-infrared, apple, thin layer drying model

1. INTRODUCTION

Fruit informal in human diet and nutrition as sources of vitamins, minerals and dietary fibres. Apple is a fruit which is a good source of minerals such as potassium, magnesium and, iron, as well as vitamin C and B-6. According to the official data of FAOSTAT for 2013, annual world production of apples is 80822521 MT [1]. Countries with the largest production of apples are: China with 39682618 MT, USA, 4081608, Turkey, 3128450 MT, Poland, 3085074 MT and Italy, 2216963 MT [1].

Fresh apples having relatively high moisture contents are very sensitive to microbial spoilage even at refrigerated conditions and, hence, they must be consumed within a few weeks. The apples are consumed either fresh or in the form of various processed products such as juice, jam, marmalade and dried product. Drying is the most common form of food preservation. This process improves the food stability, since it reduces water considerably and microbiological activity of the material and minimizes physical and chemical changes during its storage [2].

Convective hot-air drying is the most widely used method for the production of dehydrated fruits and vegetables. The main disadvantages of this classical drying process are the low dehydration capacity of the dried materials and the material colour changes during drying [3]. For better quality of dried fruits and vegetables, vacuum freeze-drying technique is used. However, the freeze-drying process has two major disadvantages: large energy demand, lengthily drying time and consequently high production costs [3]. Increasing concern for product quality and the need for minimized processing and energy costs led to a more detailed study of food materials drying.

In recent years, far-infrared drying is very popular alternative method for drying various food materials. The use of infrared radiation in drying processes has more advantages compared to hot air

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convective drying, such as: high energy efficiency, uniform heating of material, acceleration of drying process or decreasing of drying time and improved dried product quality [4]. Although infrared radiation can accelerate drying process, heat-sensitive materials, such as agricultural materials and foods, could be damaged or degraded along with the quality decreasing, if radiation intensity is not properly applied [5].

Since most fruits and vegetables are heat-sensitive in nature and easily degrade at the presence of oxygen, it would be desirable to dry them at low temperature and low oxygen content to preserve the quality [6]. In vacuum drying of food, moisture within the product being dried evaporates at lower temperatures (lower than 100 °C) giving better product quality, especially in the cases of foods or agricultural products, which are heat-sensitive in nature [5]. Due to the high energy consumption in this method, vacuum drying can be used for highly sensitive and high value-added products [7]. With combined advantages of both drying methods, high-energy efficiency of the drying process is enhanced and degradation of dried product quality is also reduced [7].

In scientific literature, several researches experimentally investigated vacuum far-infrared drying of various food products: banana [8], carrot [5], mushrooms [9,10,3], onion [4], red pepper [11], potato [7,12].

The objectives of this paper were:

a) Experimental investigation of the drying kinetics of apple slices under different vacuum pressures and temperatures of heaters in vacuum chamber, and

b) Evaluation of suitability of some thin-layer drying models for approximation of experimental drying data and comparison of their goodness of fit based on calculated value of performance index, ϕ, and chi-squared, χ^2 value.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1. Experimental setup

The obtained experimental data set for thin-layer drying kinetics of apple slices were hanged experimental setup, Fig. 1, designed to imitate industrial dryer [12]. The experimental setup consisted of two basic units. The first unit was composed of vacuum pump (1) with separator (2), and vacuum chamber (3) with vacuum meter (4), temperature controller (5) and vacuum regulator (6). The second unit contained microthermo-couples (8), load cell (9), data acquisition system (12) and personal computer (14). The required temperature in the vacuum chamber was maintained by regulation of heaters (11) with 28-segment programmable temperature controller in which over-temperature protection is incorporated with included PID precise temperature control with temperature fluctuation of ±1 °C. The required temperature in the chamber and drying time were set by this controller. The temperature in the vacuum chamber was measured by microthermocouple incorporated in the chamber, and observed from the display. When the temperature was achieved, the samples (7) were put on the support (10), in the vacuum chamber. The vacuum in the chamber was achieved by single step rotary vane vacuum pump, type EQ-2XZ. The vacuum in vacuum chamber was kept constant during single experiments, and was regulated with vacuum regulator (6). The transient temperatures of drying samples were measured with three microthermocouples (8) placed in the mid-plane of the drying samples. The micro-thermocouples were connected to data acquisition system contained of computer interface (12), type IDRN-ST, 24-bit A/D converter (13), type OMB-DAQ-2408 and data acquisition software. The measurement of sample's mass changes with time was enabled with load cell type OMEGA LCL 040, which was connected to data acquisition system. The temperature and mass changes were registered on personal computer.

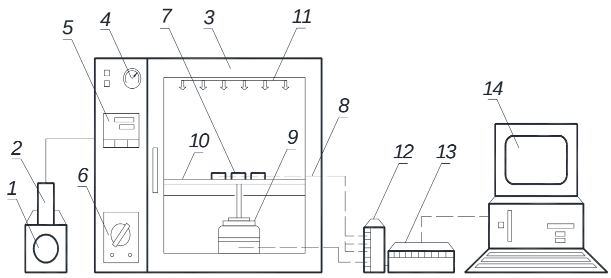

Fig. 1. Experimental vacuum far-infrared setup

1-vacuum pump, 2-separator, 3-vacuum chamber, 4-vacuum meter, 5-temperature controller, 6-vacuum regulator, 7-samples, 8-microthermocouples, 9-load cell, 10-shelf, 11-heaters, 12-data acquisition system, 13-24 bit A/D converter, 14-personal computer

2.2. Procedures

Apple variety "Golden Delicious" was used in the experimental part of the research. The samples were stored in a refrigerator at 4 °C until usage. To prepare samples, the apples were washed, peeled and sliced in order to obtain uniform samples with thickness of 3 ± 10^{-1} mm, before being reduced to a cylinder form with diameter of 43 ± 10^{-1} mm.

On the experimental setup, the series of experiments were conducted. The experimental conditions have been chosen so that heaters' temperature and vacuum chambers' pressure have been rephrase.

The initial moisture content, M_0, and the initial slices thickness, $2L_0$, were measured for each of the experiments. The initial moisture content of fresh slices and the final moisture content of dried samples were determined gravimetrically by hot air oven method at 105 °C for 24 h. The drying experiments were performed until the sample moisture content of 0.072 kg·kg^{-1} d.m. was obtained.

3. MATHEMATICAL MODELLING OF DRYING CURVES

Five thin-layer mathematical models given in Table 1 were used to approximate experimental data of the drying kinetics of apple slices.

Table 1. Thin-layer drying models

Model	Equation	Name of model	References
M01	$MR = 1+A\tau+B\tau^2$	Wang and Singh	Erbay and Icer, 2009
M02	$MR = \exp(-k_1\tau/(1+k_2\tau))$	Aghbashlo	Aghbashlo et al., 2009
M03	$MR = A+B\tau+C\tau^2$	Parabolic	Doymaz, 2011
M04	$MR = (A+k_1\tau)^2$	Vega and Lemus	Cruz et al., 2012
M05	$MR = A\exp(-k_1\tau+B\tau^{0.5})+C$	Jena and Das	Jena et al., 2007

In these models, the moisture ratio, MR was defined by the following equation:

$$MR = \frac{M - M_{eq}}{M_0 - M_{eq}} \tag{1}$$

The values of, M_{eq} were relatively small compared to those of, M or M_0, so the error involved in the simplification was negligible. Thus, moisture ratio was calculated as:

$$MR = M / M_0 \tag{2}$$

In order to estimate and select the best thin-layer drying model, the performance index, ϕ was calculated. The value of performance index, ϕ was calculated on the basis of calculated values for coefficient of determination, R^2, the root mean squared error, $RMSE$ and the mean relative deviation, MRD [13]:

$$\phi = \frac{R^2}{RMSE \cdot MRD} \tag{3}$$

Higher values of performance index, ϕ indicated that thin-layer model better approximates the experimental data.

The D'Agostino-Pearson's test of normality is the most effective procedure for assessing a goodness of fit for a normal distribution [14]. This test is based on the individual statistics for testing of the population of skewness, z_1 and kurtosis, z_2. The test statistic for the D'Agostino-Pearson test of normality is computed with equation [14]:

$$\chi^2 = z_1^2 + z_2^2 \tag{4}$$

The, χ^2 statistics has a chi-squared distribution with 2 degrees of freedom (df). The tabled critical 0.05 chi-square value for df = 2 is $\chi^2_{0.05}$ = 5.99. Therefore, if the computed value of chi-square is equal to or greater than either of the aforementioned values, the null hypothesis can be rejected at the appropriate level of significance, i.e. the thin-layer model should be rejected.

The best model that is describing the thin-layer drying characteristics of apple slices has to be chosen on the basis of higher, ϕ, and lower, χ^2 value.

4. RESULTS AND DISCUSIONS

The experimental moisture content data obtained at different heater temperatures, 120, 140, 160, 180 and 200 °C and different absolute vacuum pressures, 20, 40, 60 and 80 kPa were converted to the moisture ratio, MR, and then fitted to the five thin-layer drying models given in Table 1. Because the regression method, estimation method, the initial step size, the start values of parameters, convergence criterion and form of the function have significant influence on accuracy of estimated parameters, a large number of numerical experiments were performed [15].

The method of indirect non-linear regression and estimation methods of Quasi-Newton, Simplex, Simplex and quasi-Newton, Hooke-Jeeves pattern moves, Hooke-Jeeves pattern moves and quasi-Newton, Rosenbrock pattern search, Rosenbrock pattern search and quasi-Newton, Gauss-Newton and Levenberg-Marquardt from computer program StatSoft Statistica (Statsoft Inc., Tulsa, OK, (http://www.statsoft.com) were used in numerical experiments. On the basis of thin-layer data of apple and each model from Table 1, the average value of: coefficient of determination, R^2, root mean squared error, $RMSE$, mean relative deviation, MRD, performance index, ϕ and χ^2, were calculated. When the value for coefficient of determination obtained from different estimation methods was different, the greatest value was accepted as relevant. After that, the thin layer models were ranked on the basis of average value of performance index, ϕ.

Table 2. Statistic summary of the regression analysis

Model	R^2	*RMSE*	*MRD*	ϕ	χ^2
M01	0.9989	0.0163	0.3736	491.70	2.1042
M02	0.9999	0.0048	0.0690	6613.7	1.1219
M03	0.9992	0.0189	0.2823	487.05	1.2281
M04	0.9978	0.0155	0.1575	521.10	1.2265
M05	0.9986	0.0190	0.5774	174.50	1.1932

Average values were calculated for five temperature of heaters and four absolute vacuum pressures

From Table 2, it is evident that the model of Aghbashlo, M02 had the highest average value of performance index, ϕ = 6613.7, while the Jena and Das model, M05 had the smallest average value of performance index, ϕ = 174.50. From Table 2 that all the models had lower average value of, χ^2, than tabled critical value (the lowest model of Aghbashlo, M02). In accordance with statistical criteria, this model was able to correlate the experimental values of drying kinetics of apple slices with 0.48÷1.90% root mean squared error. In Table 3 the estimated values of parameters for the Aghbashlo model at different heater temperatures and different absolute vacuum pressure are given.

Table 3. Non-linear regression parameters

t_h [°C]	p [kPa]	k_1 [min^{-1}]	k_2 [min^{-1}]
120	20	0.0127	- 0.0055
120	40	0.0121	- 0.0055
120	60	0.0116	- 0.0055
120	80	0.0110	- 0.0055
140	20	0.0131	- 0.0073
140	40	0.0131	- 0.0067
140	60	0.0130	- 0.0065
140	80	0.0130	- 0.0061
160	20	0.0203	- 0.0098
160	40	0.0194	- 0.0095
160	60	0.0188	- 0.0091
160	80	0.0178	- 0.0091
180	20	0.0245	- 0.0119
180	40	0.0240	- 0.0112
180	60	0.0240	- 0.0104
180	80	0.0239	-0.0097
200	20	0.0344	- 0.0120
200	40	0.0327	- 0.0115
200	60	0.0320	- 0.0108
200	80	0.0310	- 0.0103

As shown in Fig. 2, a good match was found between experimental and calculated values with the model of Aghbashlo.

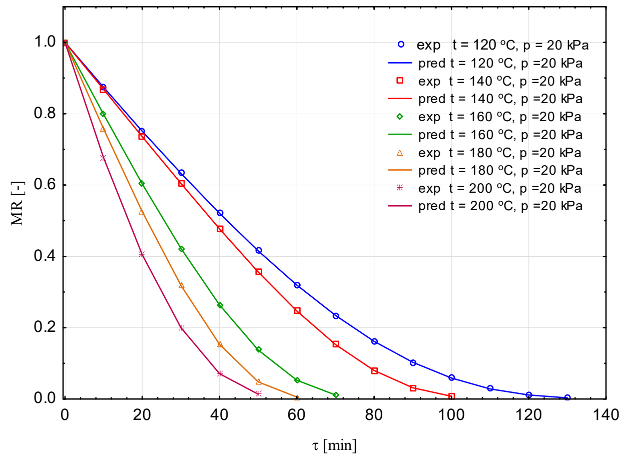

Fig. 2. Experimental and predicted moisture ratio for different temperature of heaters and different vacuum pressure

Analysing the residues of the model of Aghbashlo model, the plots of the residues against the moisture ratio did not indicate abnormal distribution for this model (not presented here).

5. CONCLUSIONS

In the presented study, the drying kinetics of apple slices under far-infrared vacuum drying was investigated. Experiments were carried out for five values of heaters temperature and four absolute vacuum pressures in the vacuum chamber. The experimental drying data in terms of moisture ratio were approximated with five well known thin layer drying models. The goodness of fit for those models was determined using performance index, ϕ and chi-squared value, χ^2. According to the results obtained from statistical analyses it was concluded that the model of Aghbashlo could adequately describe the thin layer drying behaviour of apple slices.

NOMENCLATURE

A, B, C	parameter
k_1, k_2	drying constants min^{-1}
L	slice thickness m
M	moisture content kg kg^{-1}
MR	moisture ratio
MRD	mean relative deviation
p	pressure Pa
R^2	coefficient of determination
RMSE	root mean squared error
t	temperature °C
z_1, z_2	statistic for testing the skewness and kurtosis of the residual population

Greek letters

χ^2 statistic for testing the normality of the moisture residuals
ϕ lumped measure for the goodness of fit
τ time min^{-1}

Subscripts

0 initial
eq equilibrium

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