

MODELING OF THIN-LAYER KINETICS AND COLOR CHANGES OF APPLE SLICES DURING FAR-INFRARED VACUUM DRYING

by

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In this study far infrared vacuum drying kinetics and change of color quality parameters of apple slices were analyzed. The experimental data set of drying kinetics was obtained on the experimental set-up designed to imitate an industrial far infrared vacuum dryer. For approximation of the experimental data with regard to the moisture ratio four well known thin-layers drying models from scientific and engineering literature and new developed model of Mitrevski et al., were used. The performed statistical analyzes show that the model of Mitrevski et al., has the best statistical performance than well-known thin-layer drying models. The estimated values of moisture diffusivity of apple obtained from this study are within the range from $2.80 \cdot 10^{-11}$ to $1.70 \cdot 10^{-10}$ m²/s. A negative effect on the total color change of far infrared vacuum dried apple slices was observed with increasing of temperature of infrared heaters and vacuum pressure.

Key words: far infrared vacuum drying, apple, color change

Introduction

In recent few decades the consumers' demand evolving in the direction of dry food materials that keep their original characteristics to a higher degree *i.e.* to dry materials with high sensorial and microbiological quality. Convective drying is the most used method for the production of dried fruits and vegetables. The main disadvantages of this classical method of drying are [1]: the material is exposed at high temperature for a long time during the contact with hot air which is the reason for decreases on nutritive values and color change, shrinkage, and low dehydration capacity of the dried material, structure and flavor changes during drying. In recent years, far infrared drying is popular method for thin-layer drying of various food materials [2-4]. In comparison with convective drying the method of far infrared drying has more advantage as: high energy efficiency, uniform heating of material, acceleration of drying time and improved dried product quality [5], minimization of color change and shrinkage of dried materials [6]. According to Nimmol fact is that infrared radiation accelerates the drying process, but heat sensitive materials as agricultural and foods materials could be damaged or degraded along with the quality decreasing, if radiation intensity is not properly applied [7].

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The effects of far infrared drying method can improve the quality and nutritional value of dried materials if was used in conjunction with vacuum drying. With combination on the advantages of both drying methods, energy efficiency of the drying processes is enhanced and degradation of dried product quality is reduced [8]. In scientific and engineering literature, several researchers investigated far infrared vacuum drying of various fruits and vegetables [9-15]. But, limited study of drying kinetics and change of color parameters of far infrared vacuum dried materials at high value of temperature of infrared heaters from 120-200 °C and vacuum pressure from 20-80 kPa were conducted. So, the objectives of this study were:

- research drying kinetics of far infrared vacuum drying apple slices and development of new thin-layer drying model,
- estimate to moisture diffusivity of apple slices and compared estimated values with the values published in scientific and engineering literature by other authors, and
- research of the influence of boundary conditions on total color changes of dried apple slices.

Material and methods

Sample preparation

Fresh apples variety Golden Delicious was used as raw material in the experimental part of the research. Prior to processing, the apples were stored in a cold chamber at a temperature of 4 °C and a relative air humidity of 75%. The apples were washed, peeled and sliced with a slicer machine in order to obtain uniform samples. The spherical samples with diameter 43 ± 10^{-1} mm and thickness of 3 ± 10^{-1} mm, obtained from the central medulla region where the cell structure is more uniform, were used in the drying experiments. Several measurements were made using a caliper, and only the samples with a tolerance of $\pm 2\%$ were used in the experimental part of research.

The apple slices were dried in a far-infra red vacuum set-up [15]. The experimental conditions were chosen such as that of temperature of infrared heaters and vacuum pressure were in the range to be used on the industrial dryer. The effect of temperature of infrared heaters 120 °C, 140 °C, 160 °C, 180 °C, and 200 °C, and vacuum pressure 20 kPa, 40 kPa, 60 kPa, and 80 kPa on the drying kinetics of apple slices were investigated from [15]. After each experiment the dried samples were stored in an air tight paper packet for further analysis. The transient temperatures of drying samples were measured with three micro-thermocouples placed in each of the mid-plane of the drying samples. The measurement of samples mass changes with time was enabled with load cell type OMEGA LCL-040 (Omega, Inc., USA), which was connected to data acquisition system. The temperature and mass changes of dried samples were registered on the personal computer. The initial moisture content of the samples was obtained according to the AOAC method no. 934.06 (AOAC 1995). The experiments were carried out in triplicate and an arithmetic average value was used for data processing. The drying experiments were performed until obtaining the moisture content of dry apple samples of 0.04 kg/kg.

Drying kinetics

The experimental moisture content data obtained at different temperature of infrared heaters and vacuum pressure were converted to the moisture ratio (MR) using:

$$MR = \frac{u_{\tau} - u_{eq}}{u_0 - u_{eq}} \quad (1)$$

were MR is the dimensionless moisture ratio and u_τ , u_0 , and u_{eq} are moisture content at any time, initial moisture content and equilibrium moisture content. Because of the values of equilibrium moisture content, u_{eq} are relatively small compared to those of moisture content of material, u_τ or initial moisture content, u_0 the error involved in the simplification is negligible. Thus MR was then calculated:

$$MR = \frac{u_\tau}{u_0} \quad (2)$$

Calculation of moisture diffusivity

The moisture diffusivity of foods is very often considered as an Arrhenius-type temperature function [16, 17]:

$$a_m = a_{m0} \exp\left(-\frac{E_0}{RT}\right) \quad (3)$$

where a_{m0} is the Arrhenius factor, E_0 – the activation energy for moisture diffusion, R – the ideal gas constant, and T – the absolute temperature. In this study the values of moisture diffusivity were estimated on the basis of an accurate and easy to perform single thermocouple temperature measurement by using an inverse approach [16, 17]. An arithmetical mean of the readings from the three thermocouples inserted in the mid-palate position separately of each of the three drying slices of apple was used as a transient temperature reading [16, 17].

The estimation methodology is based on the minimization of the ordinary least square norm:

$$E(\mathbf{P}) = [\mathbf{Y} - \mathbf{T}(\mathbf{P})]^T [\mathbf{Y} - \mathbf{T}(\mathbf{P})] \quad (4)$$

where, $\mathbf{Y}^T = [Y_1, Y_2, \dots, Y_{imax}]$ is the vector of measured temperatures, $\mathbf{T}^T = [T_1(\mathbf{P}), T_2(\mathbf{P}), \dots, T_{imax}(\mathbf{P})]$ is the vector of estimated temperatures at time τ_i ($i = 1, 2, \dots, imax$), $\mathbf{P}^T = [P_1, P_2, \dots, P_N]$ is the vector of unknown parameters, $imax$ is the total number of measurements, and N is the total number of unknown parameters ($imax \geq N$). For the minimization of $E(\mathbf{P})$ representing the solution of the present parameter estimation problem the Levenberg-Marquardt method were utilized [16, 17].

Color measurement and kinetics on color changes

The colour changes in food materials during drying are due to degradation of pigments (chlorophylls, carotenoids, anthocyanins, and betalains), Maillard reactions or enzymatic browning [18]. In order to research the effect of temperature of infrared heaters and vacuum pressure on the color changes of dried apple, a three-filter colorimeter Konica Minolta CR-400 (Konica Minolta Sensing Americas, Inc., USA) was used. This instrument shows the quantitative parameters of color change in different systems. The measured values of the color parameters are represented in the CIE, L^* , a^* , b^* , color space. In this color space, L^* values are used as an indicator of lightness/darkness (ranges from 0 to 100), co-ordinate a^* to indicate chromaticity on a green (–) to red (+) axis (ranges from –120 to 120), and co-ordinate b^* to indicate chromaticity on a blue (–) to yellow (+) axis (ranges from –120 to 120). The color measurements were conducted before and after far infrared vacuum drying. Five measurements were performed for each sample which is selected randomly. The values used for total color change calculations encompassed the average values of L^* , a^* , and b^* of each sample. The total color change, ΔE is calculated on the basis of the equation [19]:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (5)$$

where L_0^* , a_0^* , b_0^* are initial values for lightness, redness, and yellowness.

In order to determine the rate of color changes during drying of far infrared vacuum drying, the kinetics of the parameters of lightness, L^* , redness, a^* , and yellowness, b^* , were investigated. For approximation of the total color changes, ΔE data during far infrared vacuum drying process new developed model were used:

$$\Delta E = A + \frac{B}{t_h} + Cp^2 \quad (6)$$

where A , B , C , are parameters, t_h , – the temperature of infrared heaters, and p – the vacuum pressure. In this study multiple regression relationship between dependent variable, ΔE and independent variables, temperature of infrared heaters and vacuum pressure were used.

Results and discussion

Fitting of drying curves

In the most number existing thin-layer drying models which is used to for approximation experimental data of drying kinetics the effect of boundary conditions on the empirical parameters it is not take into account. It that reasons in this study the new generalized thin-layer drying model was developed. For approximation of experimental data on the drying kinetics of apple slices five thin-layer mathematical models from scientific literature and new developed model of Mitrevski *et al.* were used, tab. 1.

Table 1. Thin-layer drying models

| Model | Equation | Name of model | References |
|-------|--|-------------------------|------------|
| M01 | $MR = A \exp(-k_1 \tau^m) + B\tau$ | Midilli | [20] |
| M02 | $MR = A \exp(-k_1 \tau) + (1 - A) \exp(-k_1 B\tau)$ | Diffusion approach | [21] |
| M03 | $MR = A \exp(-k_1 \tau) + (1 - A) \exp(-B\tau)$ | Verma | [22] |
| M04 | $MR = A \exp(-k_1 \tau + B\tau^{0.5}) + C$ | Jena and Das | [23] |
| M05 | $MR = A \exp(-k_1 B\tau) / \left(\frac{1}{p^C} \right) \left(\frac{1}{t_h^D} \right) + (1 - A) \exp(-k_1 B\tau) ** \left(\frac{1}{p^E} \frac{1}{t_h^F} \right)$ | Mitrevski <i>et al.</i> | This study |

$MR = M/M_0$ is the moisture ratio, A , B , C , D , E , F – the parameters, k_1 [min^{-1}] – drying rate constant, τ [min] – drying time, t_h [$^{\circ}\text{C}$] – the temperature of infrared heaters, and p [kPa] – the vacuum pressure

The method of multiple 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 to for calculation of the statistical parameters and estimate the parameters in the given models. 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 [24], a large number of numerical experiments were performed. On the basis of thin-layer data and each model from, tab. 1, the values of: coefficient of determina-

tion, R^2 , root mean squared error, RMSE, and mean relative deviation, MRD, were calculated. When the value for coefficient of determination obtained from different estimation methods was different, the greatest value was accepted as relevant. In order to estimate and select the best thin-layer drying model the value of performance index, ϕ , and chi-squared, χ^2 were calculated:

$$\phi = \frac{R^2}{RMSE \cdot MRD} \quad (7)$$

$$\chi^2 = z_1^2 + z_2^2 \quad (8)$$

where z_1 and z_2 are individual statistics for testing of the population of skewness and kurtosis [25].

The best model that is describing the thin-layer drying characteristics apple slices has to be chosen on the basis of higher, ϕ and χ^2 the value lower than tabled critical 0.05 chi-square value $\chi_{0.05}^2 = 5.99$ for degrees of freedom, Dof = 2, tab. 2.

Table 2. Statistic summary of the regression analysis

| Model | R^2 | RMSE | MRD | ϕ | χ^2 | Rank |
|-------|--------|--------|--------|--------|----------|------|
| M01 | 0.9393 | 0.1170 | 1.8162 | 4.4197 | 4.6435 | 5 |
| M02 | 0.9394 | 0.1166 | 1.7277 | 4.6620 | 4.5585 | 3 |
| M03 | 0.9394 | 0.1166 | 1.7197 | 4.6836 | 4.5413 | 2 |
| M04 | 0.9394 | 0.1166 | 1.8089 | 4.4512 | 4.6225 | 4 |
| M05 | 0.9942 | 0.0363 | 0.8602 | 31.869 | 1.1539 | 1 |

From tab. 2 it is evident that model M05 *i.e.* new developed model, has the highest value of performance index, $\phi = 31.869$, (Rank 1) in comparison with the other models. Also it can be seen that all models have smaller average value of, χ^2 than tabled critical chi-square value. In accordance with statistical criteria, the new developed model of Mitrevski *et al.*, is able to correlate the experimental values of drying kinetics of apple slices with 3.63% root mean squared error. The estimated values of parameters in new generated model of Mitrevski *et al.*, are presented in tab. 3.

Table 3. The values of estimated parameters

| A | K1 | B | C | D | E | F |
|---------|--------|--------|---------|--------|--------|---------|
| -0.0004 | 0.0054 | 0.0052 | -0.0872 | 1.3645 | 0.0253 | -1.2991 |

The analysis of variance (ANOVA) results indicated that the temperature of heaters ($p \leq 0.001$), vacuum pressure ($p \leq 0.05$), and the interaction of the temperature of heaters and vacuum pressure ($p \leq 0.05$) significantly affected the drying time of apple slices.

In fig. 1, the experimental and predicted values of MR with drying time at temperature of infrared heaters 120 °C, 140 °C, 160 °C, 180 °C, and 200 °C for apple slices at vacuum pressure of 20 kPa are shown.

From fig. 1 is evident that has a good agreement between the experimental and predicted values of moisture data of apple slices.

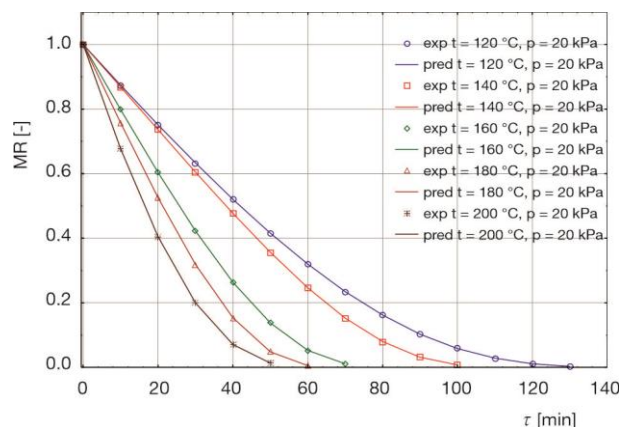


Figure 1. Experimental and predicted MR values by the Mitrevski *et al.* model for different temperatures of infrared heaters at vacuum pressure 20 kPa

Moisture diffusivity

The values of the parameters of effective moisture diffusivity, a_{m0} , and activation energy E_0 are determined by application of inverse approach. In tab. 4 the initial guesses of parameters and computationally obtained values of parameters using the Levenberg-Marquardt method and RMS-error for the one of real realized experiment E17 ($t_h = 180$ °C, $p = 40$ kPa, $2L_0 = 3$ mm, $u_0 = 5.24$ kg/kg, and $t_0 = 24.82$ °C), [26] are shown.

Table 4. Estimated values of unknown parameters and RMS-error

| | $a_{m0} \cdot 10^3$ [m ² s ⁻¹] | E_0 [kJmol ⁻¹] | RMSE |
|------------------|---|------------------------------|-------|
| Initial guess | 0.274 | 38.50 | 7.660 |
| Estimated values | 0.085 | 36.40 | 0.710 |

a_{m0} – the Arrhenius factor, E_0 – the activation energy, and RMSE – the root mean squared error

The estimated values of moisture diffusivity of apple obtained from this study are within the range from $2.80 \cdot 10^{-11}$ to $1.70 \cdot 10^{-10}$ m²/s. These values are comparable with values for other dried food materials which values generally were reported in scientific literature, from 10^{-13} to 10^{-6} m²/s [27, 28]. The determined values of moisture diffusivity in this study showed that the higher values of temperature of infrared heaters and lower value of vacuum pressure is better to dry the apple slices in the selected experimental domain, because the obtained values of moisture diffusivity are relatively higher.

Color change

In tab. 5 the average value changes in lightness, L^* , redness, a^* , yellowness, b^* , and total color changes, ΔE , of apple slices for different value of temperature of infrared heaters and vacuum pressure were presented.

From tab. 5 it is evident that, the L^* value of dried apple slices decreased during drying. The, L^* decreased from initial value $Lo^* = 83.32$ to $L^* = 63.32$, when apple slices are dried at 200 °C and 80 kPa. The changes in L^* parameter value was less at lower temperature of infrared heaters and lower vacuum pressure. As temperature of infrared heaters increased from 120-200 °C and vacuum pressure changes from 20-80 kPa the lightness of apple slices

decreased from 81.07 to 63.32. The decrease in L^* value was in correlation with non-enzymatic browning reactions which accelerates at high temperatures. The reduction in L^* value may be attributed to intense browning reaction and increase crust formation due to exposure to high temperature [29]. Because the lightness is a very important color quality parameter, lower temperature of infrared heaters and lower vacuum pressure are preferable to preserve of dried apple slices. The temperature of infrared heaters and vacuum pressure also have an effect on the redness parameter, a^* . From instance, a^* value increased from initial value $a_0^* = -6.16$ to $a^* = 6.67$ at the end point when apple slices were dried at 200 °C and 80 kPa. As shown in tab. 5 the yellowness of dried slices increased during drying from 2.41 to 6.67. The values of yellowness, b^* increased from initial value $b_0^* = 21.86$ to $b^* = 25.67$ when apple slices were dried at 200 °C and 80 kPa. As the temperature of infrared heaters increased from 120-200 °C and value of vacuum pressure varied between 20 to 80 kPa the yellowness of apple slices increased from 22.23 to 25.67. Similar effects on the drying kinetics on changes of color parameters were reported for banana [10].

Table 5. The effect on drying conditions on changes of color parameters

| t_h | p | a^* | b^* | L^* | ΔE |
|-------|-----|------------|--------------|-------------|------------|
| 120 | 20 | 2.41 ±3.81 | 22.23 ±9.36 | 81.07 ±2.09 | 8.67 |
| 140 | 20 | 2.98 ±3.84 | 22.29 ±9.78 | 73.01 ±3.26 | 13.10 |
| 160 | 20 | 4.14 ±3.60 | 23.40 ±10.66 | 71.73 ±3.09 | 14.85 |
| 180 | 20 | 4.98 ±3.84 | 23.50 ±19.40 | 70.03 ±3.26 | 16.67 |
| 200 | 20 | 5.56 ±4.16 | 23.95 ±11.36 | 68.99 ±3.19 | 17.87 |
| 120 | 40 | 2.87 ±3.76 | 22.66 ±9.40 | 80.15 ±3.26 | 9.32 |
| 140 | 40 | 3.41 ±3.60 | 23.11 ±10.36 | 71.12 ±3.39 | 14.78 |
| 160 | 40 | 4.61 ±3.84 | 23.67 ±10.78 | 70.66 ±3.56 | 15.98 |
| 180 | 40 | 5.33 ±3.94 | 24.41 ±11.32 | 69.16 ±3.36 | 17.66 |
| 200 | 40 | 5.99 ±4.60 | 24.89 ±11.56 | 67.22 ±3.89 | 19.62 |
| 120 | 60 | 3.13 ±3.92 | 22.91 ±10.36 | 77.42 ±3.09 | 10.56 |
| 140 | 60 | 3.89 ±3.84 | 23.35 ±11.40 | 69.68 ±3.26 | 16.22 |
| 160 | 60 | 4.98 ±3.60 | 23.97 ±11.36 | 68.09 ±3.49 | 18.19 |
| 180 | 60 | 5.88 ±4.84 | 24.59 ±11.40 | 67.30 ±3.56 | 19.44 |
| 200 | 60 | 6.34 ±3.73 | 25.32 ±11.66 | 66.34 ±4.09 | 20.58 |
| 120 | 80 | 3.41 ±3.64 | 23.22 ±10.40 | 73.44 ±3.26 | 13.13 |
| 140 | 80 | 4.24 ±3.60 | 23.66 ±11.36 | 66.32 ±3.39 | 19.17 |
| 160 | 80 | 5.21 ±3.84 | 24.44 ±12.40 | 65.21 ±3.46 | 20.70 |
| 180 | 80 | 6.11 ±4.14 | 25.24 ±13.40 | 64.89 ±3.66 | 21.58 |
| 200 | 80 | 6.67 ±4.60 | 25.67 ±13.56 | 63.32 ±4.49 | 23.32 |

t_h – heaters temperature, p – vacuum pressure, a^* – redness, b^* – yellowness, L^* – lightness, ΔE – total color change, mean ± standard deviation

From tab. 5 obviously that ΔE values, increased during drying apple slices and color changes intensity is more intense at higher temperature of infrared heaters and higher vacuum pressure. The total color change, ΔE values increased from 8.67 to 23.32, when apple slice are dried at temperature of heaters from 120-200 °C and vacuum pressure from 20-80 kPa. Similar results were reported from far infrared vacuum drying of peach [6] and kiwi [12].

For estimation of the statistical parameters in the model of total color change, eq. (5), the method of multiple indirect non-linear regression and estimation method of Quasi-Newton, from computer program StatSoft Statistica (Statsoft Inc., Tulsa, OK, <http://www.statsoft.com>), were used. In tab. 6 the estimated values of parameters from the mathematical model with eq. (5) are presented.

Table 6. The values of estimated parameters (eq.5)

| A | B | C |
|--------|----------|--------|
| 32.264 | -2.838.4 | 0.0009 |

In fig. 2 the total colour change as functions of temperature of infrared heaters at different vacuum pressure was presented. The high value of coefficient of determination, $R^2 = 0.9821$ and small value of root mean squared error, $RMSE = 0.062$ showed that the total color change, ΔE during far infrared vacuum drying apple slices could be modeled by new generated model of Mitrevski *et al.*

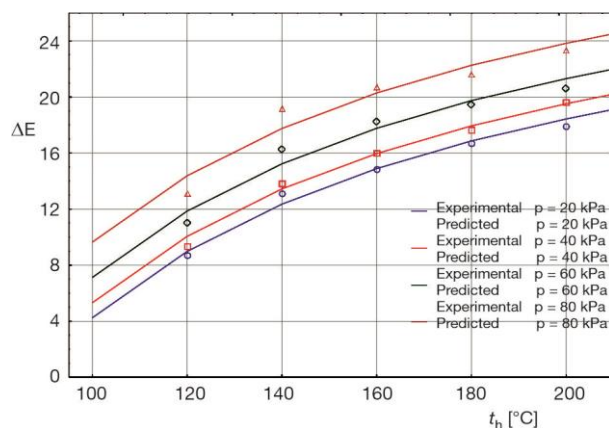


Figure 2. Effect of temperature of infrared heaters on total color change at different vacuum pressure

Conclusions

In the present study the effects of temperature of infrared heaters and vacuum pressure on the drying kinetics and color quality of apple slices were examined. The experimental drying data in terms of MR were approximated with four thin-layer drying models from scientific literature and new generated model of Mitrevski *et al.* According to the statistical evaluation, the new developed model of Mitrevski *et al.*, has the best statistical performances than other literature thin-layer drying models. The estimated values of moisture diffusivity for apple obtained by inverse approach are in the range from $2.80 \cdot 10^{-11}$ to $1.70 \cdot 10^{-10}$ m^2/s and are comparable with values for other dried food materials. This study verified that the boundary conditions on the surface of dried apple slices (the temperature of infrared heaters and vacuum pressure) have a strong effect on the change of color parameters (L^* , a^* , b^* , and ΔE). The high temperature of infrared heaters and high value of vacuum pressure has a negative effect on the total color change of dried apple slices. For the preserved nutritional values of dried apple slices the optimum drying conditions for combined far infrared vacuum drying is 120 °C and 20 kPa. The new developed thin-layer drying model and the results of kinetics on color

changes presented in this study will find the technological application on far infrared vacuum drying for preservation of other food materials.

Nomenclature

| | | | |
|--------------------|--|----------------------|--|
| A, B, C, D, E, F | – parameters | \mathbf{T} | – vector of estimated temperature, [°C] |
| a^* | – redness | \mathbf{Y} | – vector of measured temperature, [°C] |
| a_m | – moisture diffusivity, [m ² s ⁻¹] | u | – moisture content, [kg ⁻¹ kg ⁻¹ db] |
| a_{m0} | – Arrhenius factor, [m ² s ⁻¹] | z_1, z_2 | – individual statistics for testing of the population of skewness and kurtosis |
| b^* | – yellowness | | |
| E_0 | – activation energy, [Jkg ⁻¹] | | |
| k_1 | – drying rate constant, [min ⁻¹] | | |
| L^* | – lightness | | |
| MR | – moisture ratio [–] | | |
| MRD | – mean relative deviation | | |
| P | – vector of unknown parameter | | |
| R | – absolute gas constant, [JK ⁻¹ mol ⁻¹] | | |
| R^2 | – coefficient of determination | | |
| $RMSE$ | – root mean squared error | | |
| p | – pressure, [Pa] | | |
| t | – temperature, [°C] | | |
| T_k | – temperature, [K] | | |
| | | <i>Greek symbols</i> | |
| | | ΔE | – total color change |
| | | ϕ | – performance index |
| | | τ | – time, [minute] |
| | | χ^2 | – chi-squared value |
| | | <i>Subscripts</i> | |
| | | eq | – equilibrium |
| | | h | – heater |
| | | 0 | – initial |

References

- [1] Kanevce, G., et al., Vacuum Drying of Mushrooms, *Proceedings*, 14th International Drying Symposium of Tehnologist for Drying and Storing, Stubicke Toplice, Croatia, 1998, Vol. 1, pp. 220-229
- [2] Doymaz, I., Infrared Drying Characteristics of Bean Seeds, *J. of Food Process. Preserv.*, 39 (2015), 6, pp. 933-939
- [3] Pawar, S. P., Pratape, V. M., Fundamentals of Infrared Heating and its Application in Drying of Food Materials: A review, *J. Food Process. Eng.*, 40 (2017), 1, e12308
- [4] Riadh, M. H., et al., Infrared Heating in Food Drying: An overview, *Dry. Technol.*, 33 (2015), 3, pp. 322-335
- [5] Mongpraneet, S., et al., Accelerated Drying of Welsh Onion by Far Infrared Radiation under Vacuum Conditions, *J. Food Eng.*, 55 (2002), 2, pp. 147-156
- [6] Alaei, B., Chyjan, R. Z., Modelling of Nectarine Drying near Infrared-Vacuum Conditions, *Acta Sci.Pol.Techol.Aliment.*, 14 (2015), 1, pp. 15-27
- [7] Nimmol, C., Vacuum Far-Infra Red Drying of Foods and Agricultural Materials, *King Mong Univ.tehnoI.north Bang.*, 20 (2010), 1, pp. 37-44
- [8] Hafezi, N., et al., Evaluation of Energy Consumption of Potato Slices Drying Using Vacuum-Infrared Method, *Int. J. Adv. Biol. Biomed. Res.*, 2 (2014), 10, pp. 2651-2658
- [9] Pliestic, S., Mitrevski, V., The Observation of Red Pepper in Vacuum by Measurement Temperature, *Strojarsvo*, 45 (2003), 1, pp. 47-54
- [10] Swasdisevi, T., et al., Optimization of a Drying Processes Using Infrared-Vacuum Drying of Cavendish Banana Slices, *Songklanakarın J. Sci. Technol.*, 29 (2007), 3, pp. 809-816
- [11] Liu, Y., et al., Drying Characteristics and Modeling of Vacuum Far-Infrared Radiation Drying of Flos Lonicerae, *J. of Food Process. Preserv.*, 39 (2015), 4, pp. 338-348
- [12] Aidani, E., et al., Experimental and Modeling Investigation of Mass Transfer During Combined Infrared-Vacuum Drying of Hayward Kiwifruits, *Food Sci. Nutr.*, 5 (2016), 3, pp. 596-601
- [13] Salehi, F., Kashaninejad, M., Modeling of Moisture Loss Kinetics and Color Changes in the Surface of Lemon Slice During the Combined Infrared-Vacuum Drying, *Inf. Process. Agric.* 5 (2018), 4, pp. 616-523
- [14] Mitrevski, V., et al., Vacuum Far-Infrared Drying of Apple, *J. Process. Energy in Agr.*, 20 (2016), 1, pp. 1-3
- [15] Mitrevski, V., et al., Mathematical Modelling of Far Infrared Vacuum Drying of Apple Slices, *Thermal Sciences*, 23 (2019), 1, pp. 393-400

- [16] Kanevce, G., et al., Inverse Approaches to Drying of Thin Bodies with Significant Shrinkage Effects, *Int. J. Heat Mass Transf.*, 129 (2007), 3, pp. 379-386
- [17] Mitrevski, V., et al., Estimation Thermophysical Properties of Far-Infrared Vacuum Drying Potato by Application of Inverse Approach, *Thermal Sciences*, 25 (2021), 1B, pp. 603-6111
- [18] Bonazzi, C., et al., Food Drying and Dewatering, *Dry.Technol.*, 14 (1996), 9, pp. 2135-2170
- [19] Ghaboos, S. H. H., et al., Combined Infrared-Vacuum Drying of Pumpkin Slices, *J.Food Sci.Technol*, 53 (2016), 5, pp. 2380-2388
- [20] Midilli, A., et al., A New Model for Single-Layer Drying, *Dry. Technol.*, 20 (2002), 7, pp. 1503-1513
- [21] Erbay, Z., Icier, F., A Review of Thin-Layer Drying of Foods: Theory, Modeling and Experimental Results, *Crit. Rev. Food Sci Nutr.*, 50 (2009), 5, pp. 441-464
- [22] Verma, L. R., et al., Effects of Drying Air Parameters on Rice Drying Models, *Trans. ASAE*, 28 (1985), 1, pp. 296-301
- [23] Jena, S., Das, H., Modelling for Vacuum Drying Characteristic of Coconut Presscake, *J. Food Eng.*, 79 (2007), 1, pp.92-99
- [24] Mitrevski, V., et al., Adsorption Isotherms of Pear at Several Temperatures, *Thermal Sciences*, 19 (2015), 3, pp. 1119-1129
- [25] Sheskin, D. J., *Handbook of Parametric and Nonparametric Statistical Procedures*, Champan and Hall CRC, London, UK, 2011
- [26] Bundalevski, S., Modelling of Far-Infrared Vacuum Drying Processes by Applying Inverse Approach, Ph. D. thesis, University St. Climent Ohridski, Bitola, Macedonia, 2015
- [27] Saravacos, G. D., Maroulis, Z. B., Moisture Diffusivity Compilation of Literature Data of Food Materials, in: *Transport Properties of Foods* (ed T.W. Fennema et al.), Marcel Dekker Inc., New York& Basel, USA, 2001, pp. 163-236
- [28] Panagiotou, N., et al., Moisture Diffusivity: Literature Data Dompilation for Foodstuffs, *Int. J.Food Prop.*, 2 (2004), 2, pp. 273-299
- [29] Mariscal, M., Bouchon, P., Comparison Between at Atmospheric and Vacuum Drying of Apple Slices, *Food Chem.*, 107 (2008), 4, pp. 1561-1569