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MATHEMATICAL MODELLING OF THIN LAYER DRYING OF PEAR

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Article Highlights

- We examined thin-layer drying of pear slices as a function of drying conditions
- The best model was determined numerically
- Effective moisture diffusivity values ranged from 6.49×10^{-9} to 3.29×10^{-8} m^2 s^{-1}
- The values of activation energy were in the range of 28.15-30.51 kJ mol^{-1}

Abstract

In this study, thin-layer drying of pear slices as a function of drying conditions was examined. The experimental data sets of thin-layer drying kinetics at five drying air temperatures (30, 40, 50, 60 and 70 °C) and three drying air velocities (1, 1.5 and 2 m s^{-1}*) were obtained from an experimental setup designed to emulate industrial convective dryer conditions. Five well-known thin-layer drying models from scientific literature were used to approximate the experimental data in terms of moisture ratio. The best model was evaluated numerically. For each model and data set, the statistical performance index (*ϕ*) and chi-squared (*χ^2*) value were calculated and models were ranked afterwards. The performed statistical analysis showed that the model of Midilli gave the best statistical results. Since the effect of drying air temperature and drying air velocity on the empirical parameters was not included in the basic Midilli model, a generalized form of this model was developed. With this model, the drying kinetic data of pear slices can be approximated with high accuracy. The effective moisture diffusivity was determined by using Fick’s second law. The obtained values of the effective moisture diffusivity (*D_{eff}*) during drying ranged between* 6.49×10^{-9} *and* 3.29×10^{-8} m^2 s^{-1}*, while the values of activation energy (*E_0*) varied between 28.15 and 30.51 kJ* mol^{-1}*.*

Keywords: mathematical modelling, thin-layer drying, pear, moisture diffusivity, activation energy.

Fruits play an important role in human diet and nutrition as sources of vitamins and minerals. Pears are a good source of dietary fiber, vitamins C and B6, minerals like magnesium and potassium. The worldwide pear production in 2012 was estimated at 23580845 Mt (http://faostat3.fao.org/download/Q/QC//E). With 16266000 Mt, China was the largest producer, followed by the USA (778582 Mt), Argentina (700000 Mt) and Italy (645540 Mt). Because fresh pears have very short shelf life, preservation after harvesting is necessary by using of different processes such as drying, storing in cold at controlled microclimatic conditions and canning. The common processing techniques of pears are conserves in syrup, purees for use in nectars, yogurts, and drying. Dried pears can be used in bakery products, gravies, compotes, and for consumption of the dry fruit [1]. Several drying methods are commercially used to remove moisture from food products, but convective hot air drying is the most widely used method. From a mathematical point of view, the convective drying is a complex process of simultaneous heat and mass transfer within dried material and from its surface to the surroundings caused by a number of transport mechanisms. There are several different methods of describing the complex simultaneous heat and moisture transport processes within drying material, but there is no single theory for wet material drying pre-

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diction that encompasses all transfer mechanisms. In the approach initially proposed by Philip and De Vries [2] and Luikov [3], the moisture and temperature fields in the drying material are described by a system of two coupled partial differential equations. The system of equations incorporates coefficients that are functions of temperature and moisture content thus making it a non-linear system. Such a system has been used for certain applications. However, for many practical calculations, the influence of temperature and moisture content on all transport coefficients has often been neglected and the resulting system of two linear partial differential equations has been used [4]. On the other hand, thin-layer drying models are important tools in mathematical modeling of drying curves. They are often used to estimate drying time, generalize drying curves, and have wide application due to their ease of use and requirement of less data unlike in complex models. The thin-layer drying models that describe the drying rate of food materials are categorized into three groups: theoretical, semi-theoretical and empirical [5].

In scientific literature there are many researches on the experimental studies and mathematical modelling of the drying behavior of various fruits, such as: apricot [6], apple [7,8], banana [9], cherry [10], grape [11,12], kiwi [13], quince [14] and plum [15]. There have been quite a few experimental investigations of convective hot air drying characteristics and mathematical modeling of processes of drying of pear [1,16--18].

The objectives of this study were:

a) experimental investigation of the drying kinetics of pear for drying air conditions (drying air temperatures 30, 40, 50, 60 and 70 °C; drying air velocities, 1, 1.5 and 2 m s^{-1}; absolute air humidity of 0.0154 kg water kg^{-1} dry air);

b) evaluation of suitability of thin-layer drying model and comparison of their goodness of fit, and development of the model as a function of drying conditions;

c) determination of the effective moisture diffusivity and activation energy from drying data for the above mentioned drying conditions.

MATERIAL AND METHODS

Material

The material used in the experimental part of the research was fresh pear, cultivar "William". Until the processing time, the fruit was stored in cold chamber at temperature of 4 °C and relative air humidity of 75%. Samples with thickness of 4.0±0.1 mm and spherical form, from the central medulla region, where the cell structure is more uniform, were used in the drying experiments. The initial moisture content of fresh slices was determined gravimetrically by hot air oven method at 105 °C and atmospheric pressure for a period of 24 h. The average initial moisture content of pear slices was obtained as 4.99±0.10 kg water kg^{-1} d.m.

Drying procedure

The obtained experimental data set for thin-layer drying kinetics of pear slices was performed using an experimental apparatus setup designed to reproduce industrial convective dryer conditions [19]. The dryer unit was started 1 h before each experiment in order to achieve the desired steady state conditions of the drying air flow. The drying experiments were performed at drying air temperatures of 30, 40, 50, 60 and 70 °C, drying air velocities of 1, 1.5 and 2 m s^{-1}, while the absolute air humidity remained constant at 0.0154 kg water kg^{-1} dry air. The measuring of sample mass change was conducted continually, without interruptions to the drying process by a special action of trays carrier, which was placed on the sensor (model PW6CC3MR, HBM, Germany). The mass measuring sensor was connected to a measuring acquisition system (model NI 622225, National Instruments, USA), which recorded mass change during the drying process. In the same time interval, the acquisition system recorded the temperature of dry and wet-bulb thermometer of the surrounding air using set of micro-thermocouples K-type. For measurement of air drying temperature and temperature of drying slices, micro-thermocouples type K also were used. Air velocity was measured in the measuring pipe using a Pitot tube and a Testo 506 differential micro-manometer. Drying experiments were stopped when the moisture content of samples decreased to 0.14 kg kg^{-1} d.m. from the initial value of 4.99 kg water kg^{-1} d.m. The experiments were replicated three times at each drying air temperature and drying air velocity, and the average value of the moisture ratio was used for constructing drying curves.

Experimental uncertainty

Uncertainty analysis is a powerful tool when it is used in the planning and design of experiments. If the w_R is the uncertainty in the result and $w_1, w_2, \ldots, w_n$ are the uncertainties in the independent variables, then the R is result in a given function of the independent variables $x_1, x_2, \ldots, x_n$. If the uncertainties in the independent variables are all given with same odds, then uncertainty in the result having these odds and can be calculated by [20]:

$$w_R = \sqrt{(\frac{\partial R}{\partial x_1}w_1)^2 + (\frac{\partial R}{\partial x_2}w_2)^2 + \ldots + (\frac{\partial R}{\partial x_n}w_n)^2} \quad (1)$$

The drying air temperature, the temperature of drying slices, the relative humidity of the air drying, the air drying velocity and change of mass of drying samples are independent parameters measured in the drying experiments of pears. To carry out these experiments, the sensitivity of data acquisition system is ±0.01 °C, with the measurement error is ±0.02 °C, while the sensitivity of the micro-thermocouple is ±0.01 °C, with measurement errors of ±0.11 °C. The sensitivity of mass sensor is of 0.01 g with accuracy of ±2 g, while the used differential micro-manometer has a measuring range of 0-100 hPa, resolution 1 Pa and accuracy ±1 Pa. From these data based on manufacturer's specification, total uncertainties of the moisture ratio (*MR*), and drying rate (*DR*), were calculated:

$$w_{MR} = w_{DR} = \sqrt{w_{\mathrm{mt}}^2 + w_{\mathrm{ml}}^2 + w_{\mathrm{mq}}^2} = \pm 0.15 \quad (2)$$

where w_{mt} is the total uncertainty in the measurement of time of mass loss values, w_{ml} is the total uncertainty in the measurement of mass loss values, and w_{mq} is the total uncertainty in the measurement of the moisture quantity.

Mathematical modelling of drying curves

For approximation of experimental data of the drying kinetic of pear slices five thin-layer mathematical models from scientific literature were used (Table 1).

For statistical evaluation of these models, the values for performance index (ϕ) and chi-squared (χ^2) value were used. The value of performance index is calculated based on the values of the coefficient of determination (R^2) the root mean squared error (*RMSE*), and the mean relative deviation (*MRD*) [24]:

$$\phi = \frac{R^2}{RMSE \times MRD} \quad (3)$$

Higher values of the performance index indicate that the thin-layer drying model better approximates the experimental drying data.

The D'Agostino-Pearson test of normality is the most effective procedure for assessing the goodness of fit for a normal distribution. This test is based on the individual statistics for testing of the residual population of skewness (z_1) and kurtosis (z_2), the values of which were calculated according to equations given in [25]. Then the chi-squared value is computed as [25]:

$$\chi^2 = z_1^2 + z_2^2 \quad (4)$$

The tabled critical 0.05 chi-square value for the degree of freedom $df = 2$ is $\chi^2 = 5.99$. 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 ($p > 0.95$), *i.e.*, the thin-layer drying model should be rejected [25]. The best model which is describing the thin-layer drying characteristics of pear slices has to be chosen on the basis of higher ϕ value and lower χ^2 value.

Determination of effective moisture diffusivity

In most studies carried out on drying, diffusion is generally accepted to be the main mechanism during the transport of moisture to the surface to be evaporated. In this study, the first term of the analytical solution of Fick's second law for infinite slab geometry was used to determine the effective moisture diffusivity of pear slices [18]:

$$MR = \frac{8}{\pi^2}\exp(-\frac{\pi^2 D_{\mathrm{eff}} t}{4L^2}) \quad (5)$$

where D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), t is the drying time (s), and L is the half-thickness of the slices (m). From Eq. (5), plotting the data in terms of ln *MR versus* drying time gives a straight line with a slope of θ, from which the effective moisture diffusivity can be calculated.

The dependence of the effective diffusivity of food materials on temperature is generally described by the Arrhenius equation [18]:

Table 1. Thin-layer drying models; MR = M_t/M_0 - moisture ratio, M_t - moisture content at any time of drying (kg water kg^{-1} d.m.), M_0 - initial moisture content (kg water kg^{-1} d.m.). A, B, C, D, E - empirical coefficients, k_1 - drying constant (min^{-1}), t - drying time (min)

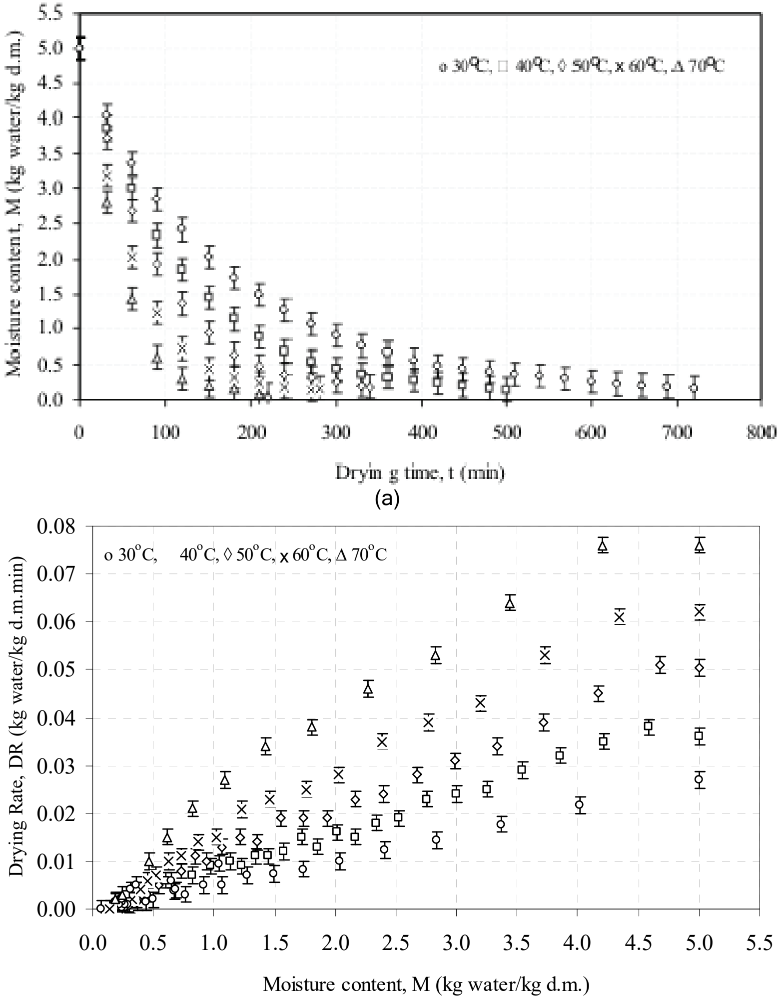
Model	Model equation	Name of model	Reference
M1	$MR = A\exp(-k_1t)+B\exp(-Ct)+D\exp(-Et)$	Modified Henderson-Pabis	[5]
M2	$MR = A\exp(-k_1t^B)+Ct$	Midilli	[21]
M3	$MR = A\exp(-k_1t)+(1-A)\exp(-k_1Bt)$	Diffusion approach	[5]
M4	$MR = A\exp(-k_1t^B)+C\exp(-Dt^B)$	Hii	[22]
M5	$MR = A\exp(-k_1t+Bt^{0.5}) + C$	Jena and Das	[23]

$$D_{\mathrm{eff}} = D_0 \exp(-\frac{E_0}{RT_{\mathrm{k}}}) \tag{6}$$

where D_0 is the pre-exponential factor of the Arrhenius equation ($\mathrm{m^2\ s^{-1}}$), E_0 is the activation energy for moisture diffusion ($\mathrm{kJ\ mol^{-1}}$), R is the ideal gas constant (8.314 $\mathrm{J\ mol^{-1}\ K^{-1}}$), and T_{k} is the absolute temperature of drying air (K). The plot of ln D_{eff} *versus* $1/T_{\mathrm{k}}$ gives a straight line with a slope of E_0/R and the intercept equal to ln D_0. After that, by using the Arrhenius relationship, the activation energy vcan be calculated.

RESULTS AND DISCUSSION

In Figure 1a, the variations of moisture content of pear slices with drying time at drying air temperature of 30, 40, 50, 60 and 70 °C at drying air velocity of 2 $\mathrm{m\ s^{-1}}$ are shown. An increase in air drying temperature from 30 to 70 °C resulted in decreased drying time. The time needed to reach the moisture content of 0.136 kg $\mathrm{kg^{-1}}$ d.m. changed from 720 to 220 min, when temperature increased from 30 to 70 °C. The reduction in drying time resulted from the increase in vapour pressure within the dried samples with increasing temperature, enabling faster migration of moisture to the product surface. Several authors reported considerable decrease in drying time when higher temperatures were used for drying [7,10,14,18]. Figure 1b shows the influence of air drying temperature on the variation of the drying rate ($DR = (M_{t+\mathrm{d}t} - M_t)/\mathrm{d}t$) with moisture content at air drying velocity of 2 $\mathrm{m\ s^{-1}}$. It can be noticed that the drying rates were higher in the beginning of drying processes and later decreased with decrease in moisture for all samples under all drying conditions. The higher drying air temperature produced a higher drying rate and consequently faster reduction in the moisture content, and



(a)

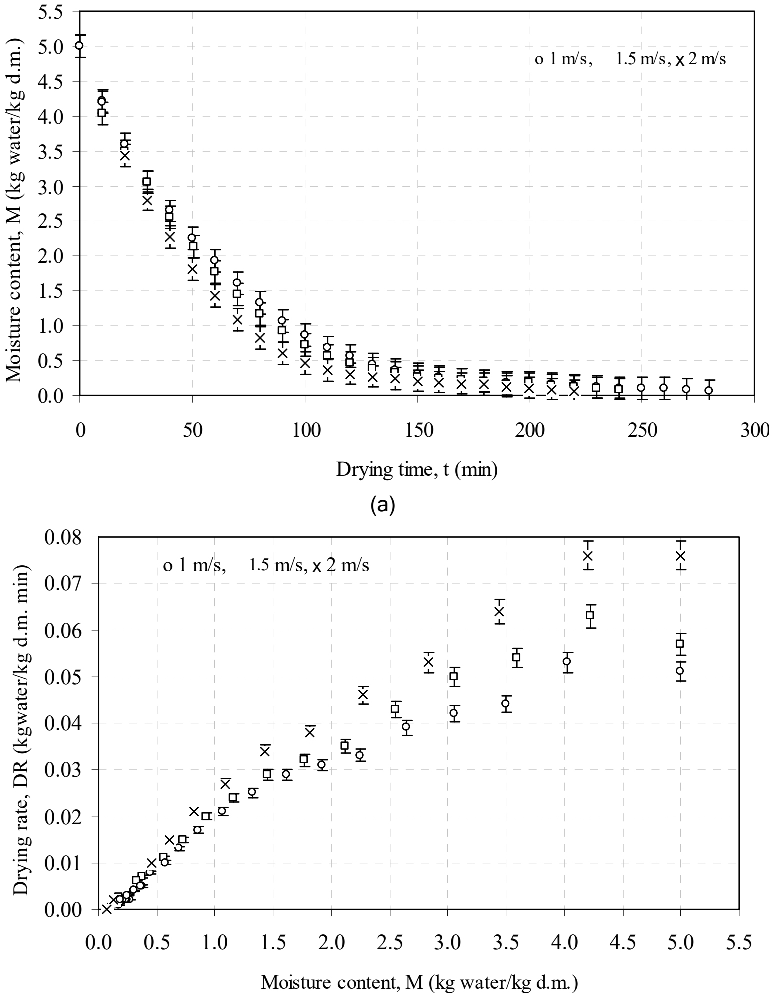
(b)

Figure 1. Drying curves of pear slices at different drying air temperatures and drying air velocity of 2 m s^{-1}: a) moisture content vs. drying time; b) drying rate vs. moisture content.

hence a decrease in drying time. Similar results were reported in literature for some various fruits [11,12,14,18]. Figure 2a shows the variation of moisture content with drying time at air drying velocities 1, 1.5 and 2 m s^{-1} at air drying temperature of 70 °C. An increase in air drying velocity from 1 to 2 m s^{-1} resulted in approximately 30% decreased drying time. The decrease in drying time results from the increase of heat and mass transfer coefficients between the drying air and drying samples. Figure 2b shows the changes in drying rate (*DR*) as a function of drying time at the different air drying velocities. The influence of the drying air velocity on drying rate is significant at the beginning of the drying process, implying that the evaporation initially takes place at the surface, being therefore more directly affected by air velocity. The predominance of drying air velocity is therefore succeeded by the moisture diffusion process [26]. These results are in agreement with some other studies in the literature on drying of various vegetables and fruits [1,26].

The experimental moisture content data obtained at different drying air temperatures and different drying air velocities were converted to the moisture ratio (*MR*) and then fitted to the five well-known thin-layer drying models given in Table 1. The method of indirect non-linear regression and quasi-Newton estimation method from StatSoft Statistica software (Statsoft Inc., USA) were used in numerical experiments. Based on the thin-layer data of pear and each model from Table 1, the average values of the coefficient of determination (R^2), root mean squared error (*RMSE*), mean relative deviation (*MRD*), performance index (ϕ) and χ^2 were calculated. After that, the thin layer models were ranked based on average values of the performance index, ϕ_a (Table 2).

From Table 2, it is evident that model M2, *i.e.*, the Midilli model, has the highest value of average



(a)

(b)

Figure 2. Drying curves of pear slices at different drying air velocity at drying air temperature of 70 °C: a) moisture content vs. drying time; b) drying rate vs. moisture content.

performance index (ϕ_a = 7898) and lowest average chi-squared value (χ_a^2 = 1.801) compared to the other models. Since the effect of drying air temperature and drying air velocity on the empirical parameters was not included in the basic Midilli model, a generalized Midilli model was developed:

$$MR = (A\log(T) + B)\exp(-Ct^D v^E) + Ft \quad (7)$$

where A, B, C, D, E and F are empirical parameters, T (°C) is drying air temperature, v (m s^{-1}), is drying air velocity, and t (min) is drying time. Furthermore, multiple indirect non-linear regression analysis was adopted including all experimental data from drying kinetics.

Table 2. Statistic summary of the regression analysis; index "a" denotes average values were calculated for five air drying temperatures and three air drying velocities

Model	R_a^2	$RMSE_a$	MRD_a	ϕ_a	χ_a^2	Rank
M1	0.998	0.010	0.098	4732	1.997	4
M2	**0.999**	**0.005**	**0.037**	**7898**	**1.801**	**1**
M3	0.997	0.009	0.118	4688	2.634	5
M4	0.999	0.005	0.042	7282	2.020	2
M5	0.999	0.008	0.070	5019	2.400	3

In order to investigate the influence of measurement error on the parameters of the generalized model and other statistical parameters, a normally distributed error with zero mean and standard deviation σ = 0.3 was added to the experimental values of moisture content. The estimated values of parameters on the generalized Midilli model, and values of statistical parameters with "exact" (without noise) moisture content data and with noise are given in Table 3.

The higher value of R^2 = 0.989 and lower values of $RMSE$ = 0.065 and $MRSE$ = 0.651 indicate that generalized the Midilli model can be used to estimate the moisture ratio of pear with a high accuracy in the measurement ranges of drying air temperatures of 30 and 70 °C and drying air velocities of 1-2 m s^{-1}.

Table 3 shows the influence of measurement error on statistical parameters. The value of root mean squared error increased from 6.5 to 9.5% when the experimental values of moisture content were adjusted with normally distributed error with zero mean and standard deviation σ = 0.3.

As shown in Figure 3, a good match was found between experimental and calculated values of drying data for pears with the generalized Midilli model.

The values of effective moisture diffusivity obtained from different drying conditions are presented in Table 4. It can be seen that the values of effective moisture diffusivity increased with the increase of drying air velocity and drying air temperature. The D_{eff} values obtained in this study varied in the range from 6.49×10^{-9} to 3.29×10^{-8} m^2 s^{-1} and are in general range from 10^{-12} to 10^{-6} m^2 s^{-1} for drying food materials [27]. The estimated values of effective moisture diffusivity reported in this study were compared with other results for pear published in scientific literature ($1.87\text{-}8.12\times10^{-10}$ m^2 s^{-1} for "d'Anjou" pear after osmotic dehydration, and 1.59×10^{-10} to $7.64\times\times10^{-10}$ m^2 s^{-1} for natural pear [28]; $5.10\text{-}11.40\times10^{-10}$ m^2 s^{-1} for pear dried in convective dryer [16]; $8.56\times\times10^{-11}$ to 2.25×10^{-10} m^2 s^{-1} for pear dried in convective dryer at 50, 57, 64 and 71 °C, within an air drying velocity of 2 m s^{-1} [18]. The differences between the results can be explained by the type, composition and tissue characteristics of the pear slices used in experimental investigations, slice thickness, proposed model for calculation and method for determination of moisture diffusivity [18].

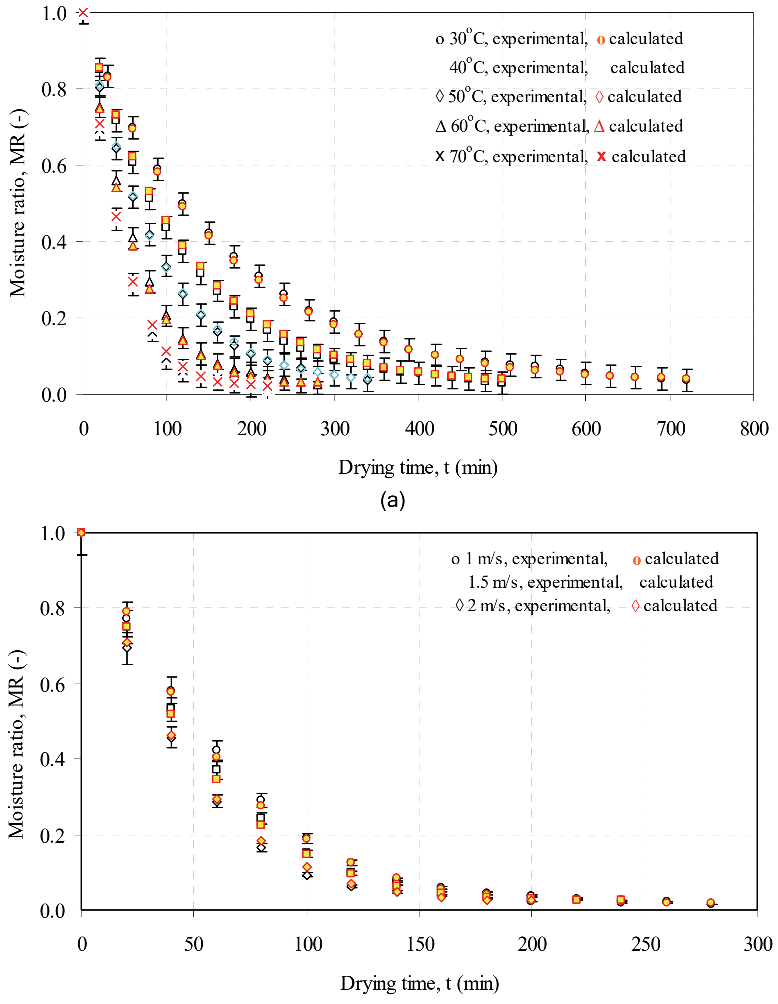
The values of pre-exponential factor for different drying air velocities varied between 4.84 x 10^{-4} to 1.44 x 10^{-3}, while the values for activation energy for different drying air velocities ranged between 28.15 kJ mol^{-1} and 30.51 kJ mol^{-1}. Those values correspond to the values given in the scientific literature for drying of different food materials which are in the range from 12.7 to 110 kJ mol^{-1} [29]. In Figure 4, a plot of the natural logarithm of D_{eff} as a function of the reciprocal of absolute temperature for drying air velocities of 1, 1.5 and 2 m s^{-1} is shown. The results show linear relation, due to Arrhenius type dependence.

CONCLUSIONS

In the present study, the drying characteristics of pear slices under convective hot-air drying were investigated. The experimental drying data in terms of moisture ratio were approximated with five well known thin layer drying models and goodness of fit was determined using performance index, ϕ, and chi-squared value, χ^2. According to the statistical results,

Table 3. Non-linear regression and statistical parameters

Values obtained	σ	A	B	C	D	E	$F\times10^5$	R^2	$RMSE$	MRD
Without noise	0	-0.661	3.575	0.014	0.904	0.308	3.500	0.989	0.065	0.651
With added noise	0.3	-0.655	3.536	0.014	0.903	0.327	4.200	0.974	0.095	0.989



(a)

(b)

Figure 3. Experimental and predicted moisture ratio: a) different air drying temperatures at drying air velocity of 2 m s^{-1}; b) different drying air velocities at temperature of 70 °C.

Table 4. The estimated values of effective moisture diffusivity

Air velocity, m s^{-1}	Air temperature, °C	D_{eff} / 10^{-8} m^2 s^{-1}	R^2
1.0	30	0.6491	0.999
	40	0.9743	0.996
	50	1.460	0.999
	60	1.821	0.999
	70	2.583	0.991
1.5	30	6.822	0.999
	40	9.901	0.999
	50	1.624	0.995
	60	2.294	0.999
	70	2.813	0.999
2.0	30	0.8113	0.990
	40	1.142	0.992
	50	1.692	0.999
	60	2.303	0.999
	70	3.291	0.999

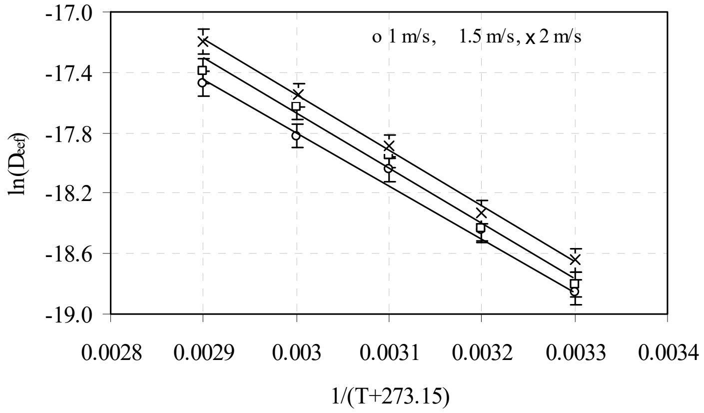


Figure 4. Effect of air drying temperature on the effective diffusivity for each air drying velocity of pear slices.

a new generalized Midilli model was developed. This model can be used to predict the moisture content of pear slices at any time of drying processes with high ability between drying air temperatures of 30 and 70 °C and drying air velocities of 1 to 2 m s^{-1}. The effective moisture diffusivity values were estimated from Fick's diffusion and ranged between 6.49×10^{-9} and 3.29×10^{-8} m^2 s^{-1}, while the values of activation energy were in the range of 28.15-30.51 kJ mol^{-1}.

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NAUČNI RAD

MATEMATIČKO MODELOVANJE SUŠENJA KRUŠKE U TANKOM SLOJU

U ovom radu je istraživano sušenje kriški kruške u tankom sloju kao u funkciji uslova sušenja. Grupe eksperimentalnih podataka istraživanja kinetike sušenja u tankom sloju pri pet različitih temperatura vazduha (30, 40, 50 , 60 i 70 °C) i tri različite brzine strujanja vazduha (1, 1,5 i 2 $m\ s^{-1}$*) u eksperimentalnoj sušari koja simulira industrijske uslove konvektivnog sušenja. Pet dobro poznatih kinetičkih modela je korišćeno za fitovanje eksperimentalnih podataka za sadržaj vlage, a najbolji model je određen numerički. Za svaki model i grupu podataka, izračunati su statistički indeks uspešnosti (*ϕ*) i* χ^2*-vrednost, a zatim su modeli rangirani. Izvršena statistička analiza pokazuje da model Midilli daje najbolje statističke ocene. Kako uticaj temperature i brzine strujanja vazduha na empirijske parametre nije bio uključen u osnovni Midilli model, razvijen je generalizovani oblik ovog modela. Sa ovim modelom, kinetički podaci sušenja kriški krušaka mogu biti aproksimirani sa visokom tačnošću. Efektivna difuzivnost vlage je određena korišćenjem drugog Fikovog zakona. Dobijene vrednosti efektivne difuzivnosti vlage (*D_{eff}*) tokom sušenja su između* $6,49\times10^{-9}$ *i* $3,29\times10^{-8}$ $m^2\ s^{-1}$*, dok vrednosti energije aktivacije (*E_0*) variraju od 28,15 do 30,51* $kJ\ mol^{-1}$.

Ključne reči: matematičko modelovanje, sušenje u tankom sloju, difuzivnost vlage, aktivaciona energija.