Influence of temperature and drying air velocity on the kinetics of convective drying in the food industry

Ing. Michal Pěnička

Project leader: Doc. Pavel Hoffman CSc.

Abstract

The aim of this study was to test the effect of the drying air change in temperature and velocity on kinetics of convection drying. In this case, the influence on the shape of the drying curve and the total drying time, where in the matter remains less than 5% moisture. This effect was compared for the three basic methods of airflow around the dried subject, which have simulated different types of dryers used in the industry. The drying curves obtained by experimental measurement were applied to eight mathematical models that are most frequently used in the food industry for the convective drying. From these mathematical models the two-term model is most in accord with measured values.

Key words

Drying curve, convective drying, mathematical model, moisture ratio, keramzit

1. Introduction

Drying is a common physical process where undesirable water is removed from a dried material namely evaporation of water into the surrounding air. From a technical perspective is drying defined as the simultaneous heat and mass transfer, where the drying process may be divided into two basic phase. The first phase is controlled process of evaporation of water from the surface of the dried material into the drying air, and then the second phase, that is controlled by a diffusion of wet from the center of the dried material on the surface. Today, the drying process is used to increase the durability, reduce weight and volume of dried material for better storage ability and transportation. Methods of drying are different and depend on many factors. Those are for example drying properties of the substance, the ambient conditions as well as energy and economic situation etc. In southern countries has been widely is used drying of on sunlight (coffee, tea, wine, tobacco, spices, ...) because of high solar activity and the energy needs of low and also slow and gentle process of drying for this materials. In industry, the drying is used very often and an inherent part of many processes. Examples of industries may be provided chemistry, manufacture of rubber, food processing, agricultural industries, etc. The drying process is energy intensive and therefore is observed today and it is the subject of many scientific studies at our country and in foreign.

2. Materials and methods

2.1. Materials

The influence of the temperature and the drying air velocity on the dried kinetics was simulated on a model material - Keramzit, which is shown in ***Fig. 1.*** The keramzit is a synthetic material, which is produced in special rotary ovens from a special kind of clay during high temperatures.

Fig. 1 *- Keramzit - the model material*

The keramzit has a spherical shape with various sizes. This material has different mechanical properties of on surface and inside. The inside material is dark and porous but on the surface material is light and compact. The main reason why this material was chosen as model material for experiments there are constant properties (dry weight, porosity, volume ...) and this material is reusable.

2.2. Methods

The experimental apparatus shown in ***Fig. 2***, which is located in industrial laboratories at the Institute of Process Engineering, Faculty of Mechanical Engineering, CTU in Prague, was used in the drying experiments. This is a circulatory drier with variable speed of drying air in the drying chamber and in the speed range from 0.5 to 3.5 ms^{-1}. The drying air is heated in two heating systems, where the first heating system has performance of the 6x500W and is placed in front of a ventilator. The second heating system installed in front of the drying chamber and the performance is a 7x1kW. The heated drying air circulates in air ducts. In the air ducts sensors Pt100 are installed. The control of heating systems and indicators of temperature sensors are located on a central control box, which is located near the experimental device.

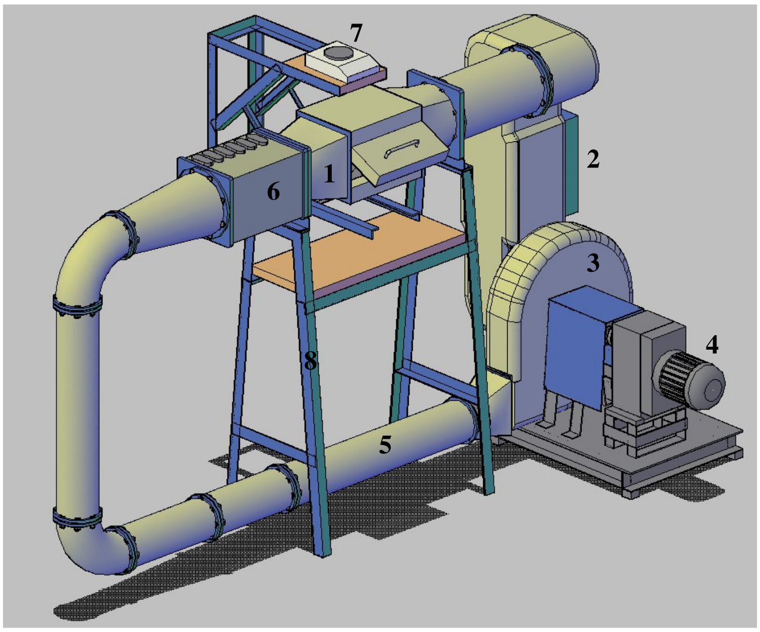
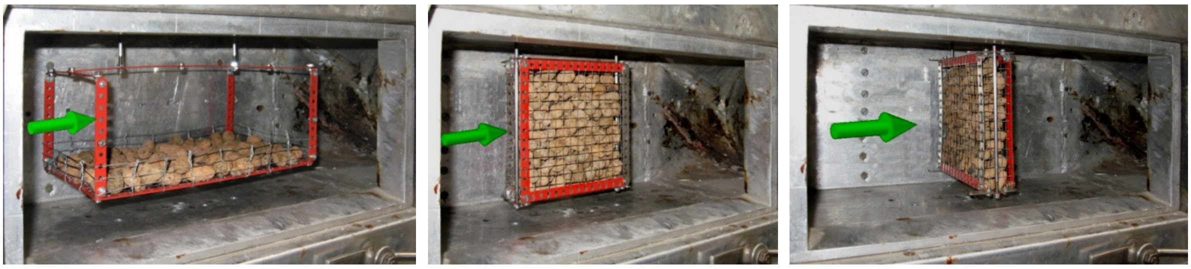


Fig. 2 *- Experimental dryer: (1)drying chamber, (2) and (6) air heating chambers, (3) ventilator, (4) motor, (5) air ducts, (7) electronic balance, (8) supporting structure*

The drying chamber with inner dimensions is 400x200x200mm. In this chamber is placed a drying basket, which is hanged on an electronic balance with range from 0 to 620 g on the accuracy of 0,001 grams. The electronic balance is connected to the computer via the R232 interface. The drying basket shown in **Fig. 3*a*** has dimensions of 250x150x35mm. This basket is used for simulate drying, where the drying air flowing over the dried material. This is mean along the one main area of the dried material. This variation is simulated drying in tray drier where the drying air flows over trays. In Fig. 3***b*** is drying basket with the dimensions of 150x150x35mm. This basket is used to simulate evenly drying, therefore, where the drying air is split evenly alongside the two main drying surface areas of sample. The same basket to the previous case, but in a different position **Fig. 3*c*** is used to simulate drying, where the drying air is blown through a layer of the dried sample with a thickness of 35mm. In this case, the thin layer drying model through blow material.



a ***b*** ***c***

Fig. 3 *- Drying basket and various of position to drying air:*
(a) blow along 1 side, (b) blow along 2 sides, (c) blow through

2.3. Experimental procedure

The experimental measurements were conducted at the drying air temperature of 40 °C and 70 °C and the air velocity was varied between 1.1 ms^{-1} to 2.5 ms^{-1}. These drying air parameters were used in all three positions of the drying basket in the drying chamber. The second heating system was not used during the measurement as experiments proceeded at low temperatures. For each measurement was repeated using 330 grams of dry keramzit (dry weight) of granules with a diameter of 8 to 16mm. The weight of dry keramzit was detected regularly after the three measurements at 110 °C for one day. The dry keramzit was moistened by immersion in water for 30 minutes. The sample is then loosely scattered in the basket and the basket with sample is placed into the drying chamber. The loss weight basket with dried material was recorded every two minutes and the temperature and the air velocity checked every 15 minutes during the measurement.

2.4. Data analysis

The data obtained from experimental measurements were converted into dimensionless moisture content ratio by the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

For long drying times, the equilibrium moisture content M_e is relatively lower compared to the humidity in the measurement of time and initial moisture $M\text{-}M_0$ and therefore the simplified expression according to equation ***(1)*** can be used:

$$MR = \frac{M}{M_0} \quad (2)$$

For a description of drying kinetics of keramzit was selected an eight commonly used mathematical models for convective drying. These models are shown in ***Table 1***

.

Table 1*- Drying models used for the keramzit*

	Model name	Model	Reference
1	Henderson and Pabis	MR = a exp(−kt)	(4)
2	Logarithmic	MR = a exp(−kt) + c	(5)
3	Two term	MR = a exp(−k_0t) + b exp(−k_1t)	(6)
4	Two term exponential	MR = a exp(−kt) + (1−a)exp(−kat)	(7)
5	Wang and Singh	MR = 1 + at + bt^2	(8)
6	Approximation of diffusion	MR = a exp(−kt) + (1−a)exp(−kbt)	(9)
7	Modified Henderson and Pabis	MR = a exp(−kt) + b exp(−gt) + c exp(−ht)	(10)
8	Midilli et al.	MR = a exp(−ktm) + bt	(11)

To determine the accuracy of the model the coefficient of determination (R^2), the mean relative percentage error (P), the root mean square error (RMSE) and the reduced chi-square error (χ^2) were used. The higher value of R^2 and lower values of P, RMSE and χ2, the better is the goodness of the fit. These errors were calculated using the following formulas:

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{|MR_{exp,i}-MR_{pre,i}|}{MR_{exp,i}} \quad (3)$$

$$RSME = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2\right]} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-n} \quad (5)$$

where N is the number of measurements, n is the number of coefficients in the model, MRexp,*i* and the ratio of moisture to the *i*th measurement and MRpre,*i* is calculated as the ratio of moisture content for the *i*-th measurement(2); (3)

3. Results and discussion

3.1. Influence of temperature and velocity of drying air on the kinetics of convective drying

The keramzite as a model material was dried at the drying air temperatures of 40 °C and 70 °C and at the drying air velocity of 1,1 ms^{-1} and 2,5 ms^{-1}. In spite of moistening material the same procedure was always the initial moisture content different and ranged between 13.7 to 21 kg H_2O/kg DM. ***Fig. 4*** to ***Fig***. ***6*** show the variations in the moisture content as function of drying time at various the drying air temperatures and various the velocities of drying air for 3 above mentioned ways of the drying air flow around the sample. The influence of temperature and velocity of drying air are effect for various “blow through” in the first phase, where is dominate effect evaporation from surface of sample. The total drying times to reach the final moisture content 36, 56, 60 and 88 min at the drying air temperatures of 40 and 70 °C and velocity of drying air of 1,1 and 2,5ms^{-1}. The shortest total drying time is for the temperature 70 °C and velocity of 2,5ms^{-1}. For the various “Blow along 1 side”, drying times to reach and for 40, 45, 72 and 128 “Blow along 2 sides” drying times to reach 56, 60, 155 and 164 min. With increase in the drying temperature and the velocity of drying air the drying time decreased.

3.2. Fitting of the drying curves

Table 2 *- Statistical results obtained from various drying model*

	Model no.	Model coefficients	R^2	P (%)	RMSE	χ^2
1	Henderson and Pabis	a=1,0199; k=0,083	0,9932	10,07	30,6 x10^{-3}	1,1x10^{-3}
2	Logarithmic	a=0,0941; k=0,9902; c=0,1121	0,9975	6,223	17,9 x10^{-3}	0,4x10^{-3}
3	Two term	a=0,4234; k_0=0,2901; b=0,7338; k_1=0,0625	0,9994	2,409	8,6 x10^{-3}	0,1x10^{-3}
4	Two term exponencial	a=0,424; k=0,137	0,9958	3,687	26,6 x10^{-3}	0,8x10^{-3}
5	Wang and Singh	a=0,9697; b=-0,0634	0,9867	11,75	41,1 x10^{-3}	2,1x10^{-3}
6	Approximation of diffusion	a=1,0199; k=0,083; b=223,1741	0,9932	10,07	30,6 x10^{-3}	1,2x10^{-3}
7	Modified H. and P.	a=0,3335; k=0,0446; b=0,2862 ; g=0,0429; c=0,5279; h=0,236	0,9995	20,82	43,9 x10^{-3}	3,1x10^{-3}
8	Midilli et al.	a=-0,0005; k=1,2694; m=0,231; b=0,6764	0,9992	2,559	10 x10^{-3}	0,1x10^{-3}

Experimental data obtained by measuring were transferred to the dimensionless moisture $M0$

(2) and applied drying models according to
Table* 1**. For example, ***Table 2 is shown the resulting set of model coefficients and statistical errors in the model. For all cases the R^2 values ranged from 0.8796 to 0.9998 for P it was from 0.6352 to 29.6575% for the RMSE of 1.5 x10^{-3} and 96.5 x10^{-3} and χ^2 from 1x10^{-4} to 11.6 x10^{-3}. The R^2 value is higher, while values of P, RMSE and χ^2 are lower, the greater the match between experimental data and mathematical model. For all models ***Table 2*** shown published "Two term" as the most suitable drying model for keramzit, it has the highest values of R^2 and lowest values of P, RMSE and χ^2 between all the drying models. ***Fig. 7*** to ***Fig. 9*** is shown a good agreement between experimental data and "Two term" drying model. In this model, the errors varied between the values for R2 from 0.9981 to 0.9998 for P from 1.3683 to 19.4037%, the RMSE from 2.8 x10^{-3} and 27.3 x10^{-3} and χ^2 from 1x10^{-4} to 4x10^{-4}.

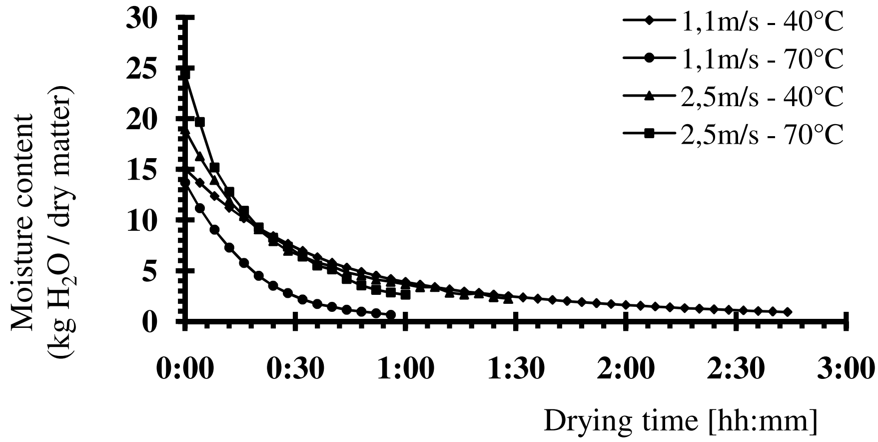


Fig. 4 - Effect of drying air temperature and drying air velocity on moisture content for various position "Blow along 2 sides"

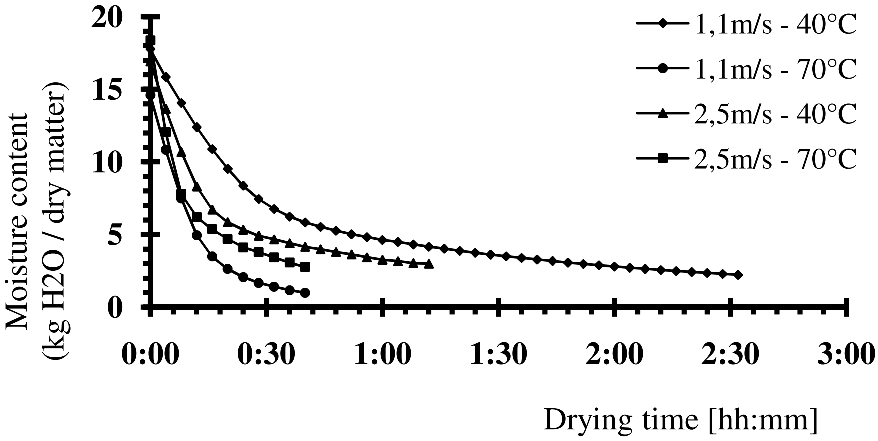


Fig. 5 - Effect of drying air temperature and drying air velocity on moisture content for various position "Blow along 1 side"

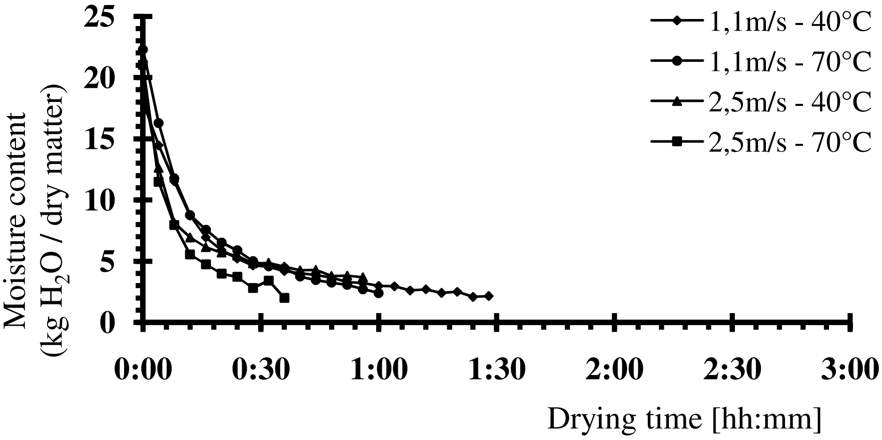


Fig. 6 - Effect of drying air temperature and drying air velocity on moisture content for various position "Blow through"

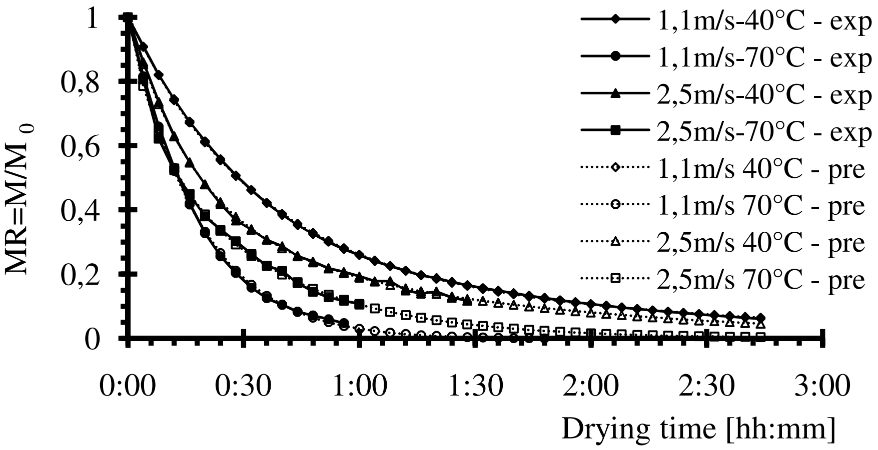


Fig. 7 - Variation of experimental and predicted moisture ratios by the two-term drying model with drying time for various position "Blow along 2 sides"

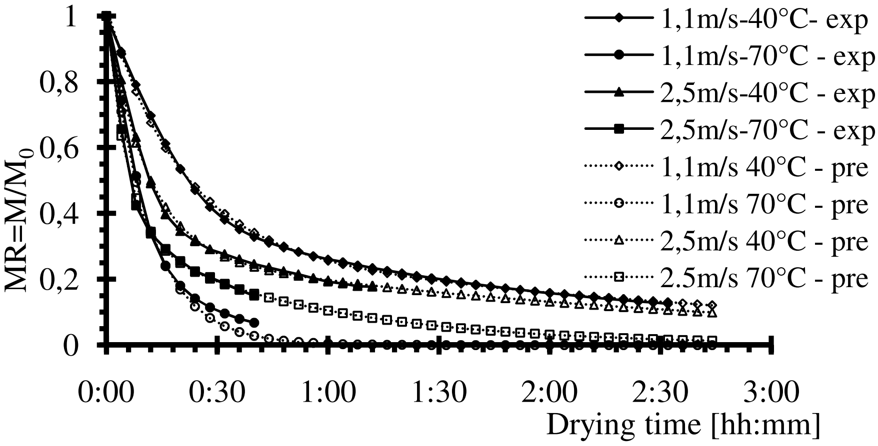


Fig. 8 - Variation of experimental and predicted moisture ratios by the two-term drying model with drying time for various position "Blow along 1 side"

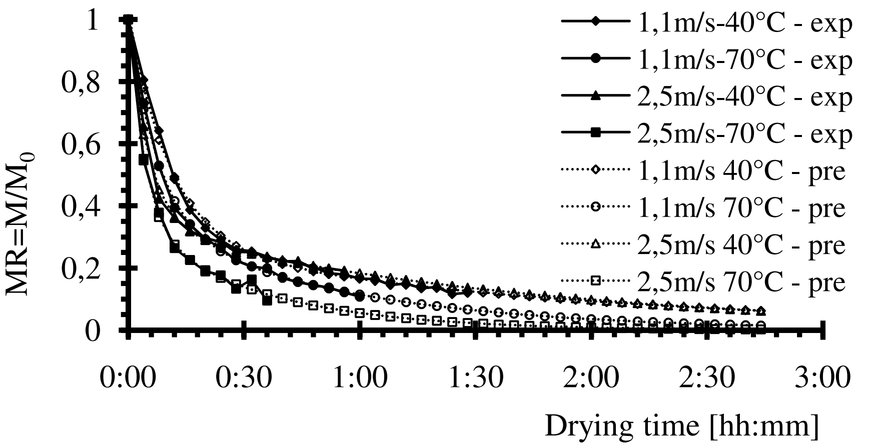


Fig. 9 - Variation of experimental and predicted moisture ratios by the two-term drying model with drying time for various position "Blow along 2 sides"

4. Conclusion

The moisture loss was measured during the convective drying at various drying air temperatures and drying air velocity for the model material-Keramzit. The values of the drying air temperature was 40 °C and 70 °C and the drying air velocity was 1.1 ms^{-1} and 2.5 ms^{-1} for three basically various position the drying sample to the drying air. These are examples, where the drying air flow through the dried material, along 1 or 2 sides of the dried material. From experimental measurements was concluded that with increasing temperature and increasing velocity of the drying air the drying time reduces especially in the first stage of drying. The two term drying model, which gave a higher value for the coefficient of determination and lower values for the root mean square error, mean relative percent error and reduced chi-square among the 8 models, was considered the best model for describing the drying behavior of keramzit.

Nomenclature

a, b, c, g, h, m	*coefficients in drying models*	*[1]*
k, k_0, k_1	*empirical constants in drying models*	*[1]*
M	*moisture content at any time of drying*	*[kg water(t)/ kg dry matter]*
M_e	*equilibrium moisture content*	*[kg water/ kg dry matter]*
M_0	*initial moisture content*	*[kg water(t_0)/ kg dry matter]*
MR	*moisture ratio*	*[1]*
MR_{exp}	*experimental moisture ratio*	*[1]*
MR_{pre}	*predicted moisture ratio*	*[1]*
n	*number of constants in the model*	*[1]*
N	*number of observations*	*[1]*
t	*drying time*	*[min]*
T	*drying temperature*	*[°C]*
R^2	*coefficient of determination*	*[-]*
P	*mean relative percent error*	*[%]*
$RMSE$	*root mean square error*	*[-]*
χ^2	*reduced chi-square*	*[1]*

Reference

1. *Drying characteristics of the solid by-product of olive oil extraction.* Doymaz, I. a Gorel, O. 2004, Biosystems Engineering, stránky 213–219.

2. *The thinlayer drying characteristics of garlic slices.* Madamba, P. S. 1996, Journal of Food Engineering, stránky 75–97.

3. *Modelling adsorption equilibrium moisture characteristics of rough rice.* Martin, M. B. 2001, Drying Technology, stránky 681–690.

4. *Relative humidity effect on the high temperature drying of shelled corn.* Westerman, P. W. 1973, Transactions of the ASAE, stránky 1136–1139.

5. *Drying characteristics of laurel leaves under different drying conditions.* Yagcioglu, A. D. Adana : autor neznámý, 1999. In Proceedings of the 7th international congress on agricultural mechanization and energy. stránky 565–569.

6. *Progress in developing the thin-layer drying equation.* . Henderson, S. M. 1974, Transactions of the ASAE, stránky 1167–1168, 1172.

7. *A model for ear corn drying.* Sharaf-Eldeen, Y. I. 1980, Transactions of the ASAE, stránky 1261–1271.

8. *A single layer drying equation for rough rice.* Wang, C. Y. 1978, Transactions of the ASAE, stránky 78-3001.

9. *Thin layer solar drying some different vegetables.* Yaldız, O. &. 2001, Drying Technology, stránky 583–596.
10. *Determination of water content of dried fruits by drying kinetics.* Karathanos, V. T. 1999, Journal of Food Engineering, stránky 337–344.
11. *A new model for singlelayer drying.* Midilli, A. K. 2002, Drying Technology, stránky 1503–1513.
12. *Effect of dipping treatment on air drying of plums.* Doymaz, I. 2004, Journal of Food Engineering, stránky 465–470.