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THIN-LAYER MODELLING OF THE CONVECTIVE AND MICROWAVE DRYING OF SUGAR BEET PULP
MODELOVANJE KONVEKTIVNOG I MIKROTALASNOG SUŠENJA REZANACA ŠEĆERNE REPE U TANKOM SLOJU

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ABSTRACT

The aim of this study is to investigate application of Midilli-Kucuk thin layer drying model for convective and microwave drying of sugar beet pulp. Also air followed by a microwave finish drying was investigated. As the parameter of quality of dried sugar beet pulp water holding capacity was investigated. The drying took place in falling rate period although a short constant period was observed during hot air drying at 65 °C. The experimental moisture ratio data were fitted to Midilli-Kucuk model and assess according to three statistical criteria: reduced chi-square, root mean square error and residual sum of squares. This model satisfactorily described the drying characteristic of sugar beet pulp. Water holding capacity was evaluated as the quality parameter. It decreased with increase of drying temperature as well as microwave power. The highest value was obtained for microwave finish drying.

***Key words**: Sugar beet pulp, Hot air, Microwave, Microwave finish drying.*

REZIME

Cilj ovog rada je ispitivanje primene Midilli-Kucuk modela sušenja u tankom sloju za opisivanje procesa konvektivnog i mikrotalasnog sušenja rezanaca šećerne repe. Pored navedena dva tipa, ispitan je i kombinovani postupak sa primenom mikrotalasnog sušenja u završnoj fazi. Kao parameter kvaliteta dobijenog proizvoda korišćen je kapacitet zadržavanja vode. Sušenje se odvija u režimu opadajuće brzine, premda na temperaturi od 65 °C može se primetiti kratak period konstantne brzine sušenja. Eksperimentalno dobijeni podaci za sadržaj vlage fitovani su Midilli-Kucuk modelom. Model dobro opisuje sušenje rezanaca šećerne repe u tankom sloju, bilo da se radi o konvektivnom ili mikrotalasnom sušenju. Vrednost kapaciteta zadržavanja vode opada sa porastom temperature i snage mikrotalasa. Najviše vrednosti ovog parametra dobijene su tokom primene kombinovanog postupka sušenja.

***Ključn reči**: rezanci šećerne repe, zagrejani vazduh, mikrotalasi, kombinovano mikrotalasno sušenje.*

INTRODUCTION

Dietary fibres represent the basic materials of plant cell walls, and they have a number of positive physiological influences on the human organism such as ability to bind bile and cholesterol and inhibit their resorption, decrease the risk of cancer and coronary heart diseases, also they prolong the feeling of being satiated by food and thus limit the calories intake. Sugar beet pulp is the residue of sugar beet tissue after the extraction of sugar in the technology of sugar processing. Sugar beet pulp can be used as an animal feed; also it can be used as raw material for pectin and cellulose extraction. Furthermore, sugar beet pulp can be used for production of concentrated dietary fibres for the food industry. It typically contains hemicelluloses (26%), pectin (24%), cellulose (23%), proteins (9%), sucrose (6%), lignin (4.5%), soluble mineral matter (4.0%), insoluble mineral matter (3.0%) and fat (0.5%) (*Broughton et al., 1995*). Drying of dietary fiber is necessary in order to obtain longer shelf life and substantial volume reduction. Drying is one of the oldest methods of food preservation and it may cause undesirable changes in dry product quality. Hot air drying is the most frequently used drying technique. Low energy efficiency and long drying time during hot air drying of foods in the falling rate period are the main disadvantages of this type of drying. Low thermal conductivity of food materials in this period causes limited heat transfer to inner sections of the materials (*Feng and Tang, 1998*). High temperatures and long drying times in conventional hot air drying may change flavour, colour and rehydration capacity of dried products (*Drouzas, et al., 1999*). In order to avoid significant quality loss and achieve fast and effective thermal drying of foods, microwave drying is increasingly used (*Maskan, 2000*). Food processing is one of the most effective and major application of microwaves due to presence of moisture in the food which can couple with microwaves and easily facilitates heating. Microwave drying is faster, more uniform and energy efficient than hot air drying. Microwave drying can be operated in continuous and pulsed modes (*Lević et al., 2005*). During microwave heating of food, many variables such as dielectric properties, size, geometry and arrangement of food materials affect the heating performance. During microwave drying beside accelerated moisture removal heat transfer to the solids is slowed because of the absence of convection (*Maskan, 2000*). The use of microwave drying in processes such as cooking, pasteurization, baking and heating results in an increased production capacity due to reduced processing time as well as improved quality of final products. Microwave drying can be used as an alternative drying process for a variety of food products such as vegetables and fruits, snack foods and etc. It is often used in combination with hot air drying to increase efficiency of the drying process (*Sharma and Prasad, 2001; McMinn, 2006*). Another approach to hot air/microwave drying is two-stage drying process. It has been suggested that microwaves should be applied in the falling rate or at low moisture content for finish drying (*Parabhanjan et al., 1995; Maskan, 2000; 2001*).

Nomenclature

MR	– moisture ratio
X (g/g db)	– moisture content
N	– number of experimental data points
N_p	– number of parameters in model
Subscripts	
i	– initial value
t	– at time t
e	– equilibrium
exp,i	– experimental value
pred,i	– predicted value

MATERIAL AND METHOD

The sugar beet pulp was kindly obtained from Šajkaška sugar factory, Žabalj, Serbia. The sugar beet pulp had moisture content of about 75 % (wet basis). For all experiments, sugar beet pulp from the same batch was used. The samples (25 g) were evenly spread, completely covering the base of glass petri dish (7.1 cm in diameter and 1 cm deep) used as the drying pan. Three replications of each experiment were performed and the mean value was used in further calculations. Dried samples were cooled and stored for further experiments.

The dryer was operated at an air velocity of 1 m/s, parallel to the drying surface of the samples. Therefore the drying took place only from the top surface. Three hot air temperatures were selected: 65, 85 and 105 °C. Dry bulb and wet bulb temperatures were monitored in the drying chamber. Moisture loss was recorded at 15 min intervals by a digital balance (accuracy ± 0.01 g). Sugar beet pulp was dried until no weight change could be recorded (equilibrium moisture content is reached).

In microwave drying experiments a programmable domestic microwave oven with maximum output of 700 W was used. Sample was placed on the centre of a turntable fitted inside of the microwave cavity for even absorption of microwave energy. The presence of the turntable was necessary to achieve the optimum oven performance and to reduce the levels of reflected microwaves onto the magnetron (*Khraisheh et al., 1997; Maskan, 2000*). Three microwave powers were selected: 150, 250 and 350 W. These microwave powers were selected during preliminary tests. Higher microwave energy inputs resulted in samples colour quality reduction so the maximum selected microwave energy was 350 W. The experiments were done according to predetermined microwave power/time schedule. Moisture loss was measured at 2 min intervals until equilibrium moisture content is reached.

During air followed by a microwave finish drying, experiments were carried out by a combination of hot air-microwave techniques. The sugar beet pulp was dried by hot air (105 °C) for 90 min, and then dried by microwaves (250 W). This point in time corresponds to moisture content of about 0.9 kg water/kg dry solids, the point when drying slows down.

As the quality parameter to compare drying techniques water holding capacity was selected. Dried, ground samples (2.5 g) were suspended in 30 cm^3 of distilled water at 30 °C in centrifuge glass tube (50 cm^3) for 30 min. After that the suspension was centrifuged for 5 min at 5,000g. The swollen sample particles were separated from supernatant and their mass was determined. The water holding capacity of the fibres was calculated from the difference between the hydrated (swollen) and the dried sample (*Šereš et al., 2005*).

The experimental moisture content data were nondimensionlized using the equation:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \tag{1}$$

The equilibrium moisture content of sugar beet pulp is small compared to the initial moisture content and moisture content at time t, so moisture ratio can be reduced to X_t/X_0 (*Doymaz and Pala, 2002; Velić et al., 2004*). For purpose of evaluation of the goodness of fit three criteria were adopted: the reduced chi-square (χ^2), root mean square error (RMSE) and residual sum of squares (RSS). The reduced chi-square and root mean square error have been widely used as the primary criterion to select the best model for drying curves of dried samples (*Ozdemir and Devres, 1999; Ertekin and Yaldiz, 2004; McMinn, 2006*). These parameters were calculated using:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pred,i}\right)^2}{N - N_p} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pred,i}\right)^2}{N}} \tag{3}$$

$$RSS = \sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pred,i}\right)^2 \tag{4}$$

The lower value of the reduced chi-square and root mean square error indicates the better ability of the model to represent the experimental data. The reduced chi-square accounts the number of parameters in the model and the value of this statistical criterion gives a measure of the model to describe the experimental data irrespective of the number of parameters in the models (*Panchariya et al., 2002*). The residual sum of squares value is an important parameter in non-linear regression process because the fitting procedure being designed to achieve the minimum RSS.

RESULTS AND DISCUSSION

Experimental values of moisture ratio can be fitted in various thin layer models, found in the literature i.e. moisture content data can be regressed against time according to the form of the selected models (*Ertekin and Yaldiz, 2004, Jokić et al., 2005a, Jokić et al., 2005b*). This models defined the drying behaviour in terms of the drying constants as appropriate to the specific correlation. The best model was Midilli-Kucuk and it was selected for representing the experimental data. This model also was found to be the most appropriate for description of moisture transfer in eggplant (*Ertekin and Yaldiz, 2004*), mushroom and pistachio (*Midilli et al., 2002*).

Model selected for the convective and microwave drying of sugar beet pulp, Midilli-Kucuk model, is represented by the following eqation:

$$MR = a\exp(-kt^n) + bt \tag{5}$$

The statistical analysis was performed using OriginPro 8 software. The aforementioned statistical criteria for hot air drying as well as for microwave drying are represented in Table 1.

Table 1. Statistical analysis for Midilli-Kucuk model

Convective drying			
Statistical criteria	65 °C	85 °C	105 °C
RSS	2.32 x10^{-3}	2.26 x10^{-3}	2.66 x10^{-3}
RMSE	1.24 x10^{-2}	1.32 x10^{-2}	1.49 x10^{-2}
χ^2	2.11 x10^{-4}	2.52 x10^{-4}	3.32 x10^{-4}
Microwave drying			
Statistical criteria	150 W	250 W	350 W
RSS	6.82 x10^{-3}	1.49 x10^{-2}	1.41 x10^{-4}
RMSE	2.13 x10^{-2}	3.53 x10^{-2}	4.48 x10^{-3}
χ^2	6.20 x10^{-4}	1.87 x10^{-3}	4.68 x10^{-5}

In the case of convective drying the chi-squared values are in the range 2.11 x 10^{-4} – 3.32 x 10^{-4}, while RSS and RMSE values vary between 2.26 x 10^{-3} and 2.66 x 10^{-3}, and 1.24 x 10^{-2} and 1.49 x 10^{-2}, respectively. The experimental data are closely correlated with computed values for selected model. The values predicted by the model, Midilli-Kucuk, are generally banded around to straight line and this makes clear that this model could be used to explain thin layer behaviour of sugar beet pulp. As for microwave drying chi-squared values for selected microwave powers are in the range 4.68 x 10^{-5} – 1.87 x 10^{-3}, while RSS and RMSE values vary between 1.41 x 10^{-4} and 1.49 x 10^{-2}, and 4.48

x 10^{-3} and 3.53 x 10^{-2}, respectively. To validate the suitability of the selected model the experimental and predicted moisture ratio values were compared (Fig. 1). As the temperature of drying air increases the time needed to achieve certain moisture content decreases. For example drying time was 285 minutes at 65 °C while it was 240 and 200 minutes at 85 °C and 105 °C, respectively. Drying rate curves for sugar beet pulp dried under convective conditions are shown in Fig. 2. Drying rates were calculated as quantity of moisture removed per unit time per unit dry solid (g/g min db). A short constant rate period was observed at 65°C, but increase in drying air temperature led to disappearance of this period i.e. it cannot be clearly determined. At 85 °C, that period is shortened and at 105 °C it disappears completely after initial heating of the samples. These results are in agreement with results for hot air drying of banana samples where constant drying rate period was not observed at 60 °C, but it is suggested that a short constant rate period can be found using lower temperatures such as 40-50 °C (*Maskan, 2000*).

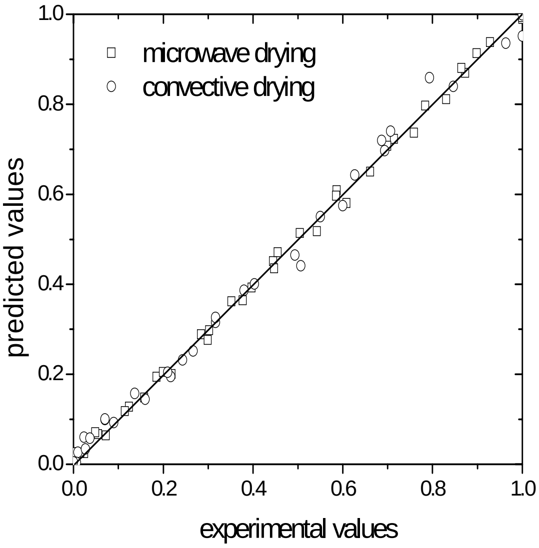

Fig. 1. Comparison of experimental and predicted values of moisture ratio for convective and microwave drying

Microwave heating causes a substantial reduction in drying time; by a factor of two for apple and a factor of four for mushroom (*Funebo and Ohlsson, 1998*). Increase in applied microwave power resulted in decrease of drying time. For example drying time was 28 minutes at microwave power level 150 W, while it was 22 and 12 minutes at 250 W and 350 W, respectively. In this way drying time of sugar beet pulp at 105 °C was reduced up to 86% when the lowest selected power level was used (150 W). Reason for this rapid decline in drying time lies in the volumetric heating (from the inside out) that provides fast and uniform heating of the entire sample and in the same time quick energy absorption by water molecules creates an outward flux of vapour (*Maskan, 2000*).

Drying rate curves for sugar beet pulp dried under different microwave power levels are shown in Fig. 3. Although sugar beet pulp has high moisture content, an expected constant rate period was not observed in the present study. Entire microwave drying process takes place in the falling rate period. In accordance with short drying times in this type of drying rates are significantly higher compared to convective drying (Fig. 2).

Parameters of the Midilli-Kucuk model are given in Table 2. Examination of the drying constant (k) in the Midilli-Kucuk model (the most suitable equation) indicates that the magnitude of the parameter accurately reflects the drying behaviour.

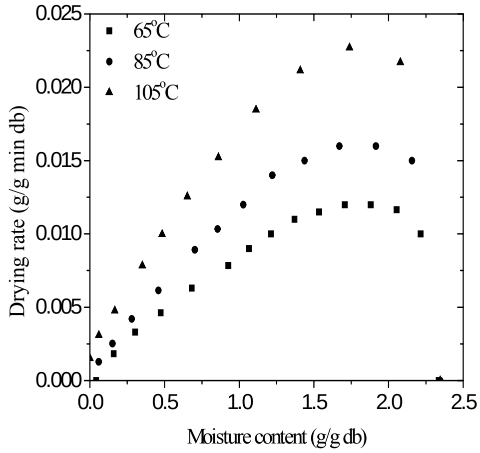

Fig. 2. Drying rate curves for convective drying of sugar beet pulp

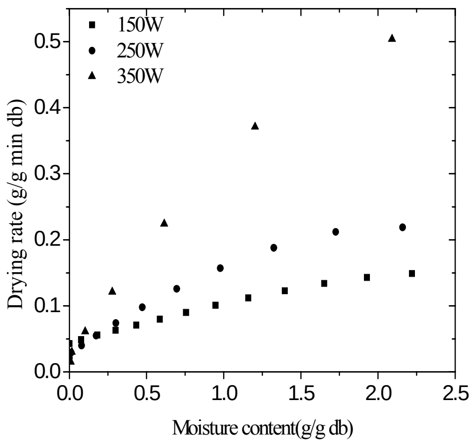

Fig. 3. Drying rate curves for microwave drying of sugar beet pulp

Table 2. Constants of Midilli-Kucuk model

Drying conditions	Constants	Value
65 °C	a	9.90 x10^{-1}
	k	1.50 x10^{-3}
	n	1.28
	b	-4.00 x10^{-4}
85 °C	a	9.94 x10^{-1}
	k	2.70 x10^{-3}
	n	1.27
	b	-1.60 x10^{-4}
105 °C	a	9.94 x10^{-1}
	k	3.42 x10^{-3}
	n	1.31
	b	-1.10 x10^{-4}
150 W	a	1.01
	k	2.84 x10^{-2}
	n	1.28
	b	-3.94 x10^{-3}
250 W	a	9.52 x10^{-1}
	k	3.61 x10^{-2}
	n	1.45
	b	-1.56 x10^{-3}
350 W	a	9.99 x10^{-1}
	k	1.41 x10^{-1}
	n	1.34
	b	-1.21 x10^{-3}

The increase in hot air gave the higher values of k, and the same conclusion can be applied to the level of microwave power. In the same time more rapid microwave drying is represented with higher k values comparing to the hot air drying. Because of high cost of microwave drying it has been suggested use of two-stage drying process involving an initial hot air drying, followed by a microwave finish drying (*Prabhanjan et al., 1995; Feng and Tang, 1998*). The drying rate versus moisture curve is shown in Fig. 4. It can be seen that microwave finish drying resulted in increase of drying rate up to 0.2 g/g min db.

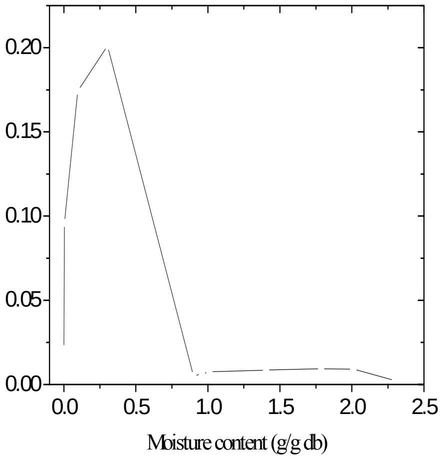

Fig. 4. Drying rate of sugar beet pulp dried by hot air (105 °C and 1 m/s) followed by microwave drying at 250W

Application of microwave power in the second stage of drying reduced drying time from 200 minutes at 105 °C to 100 minutes (50% reduction in drying time) when dried by hot air and MW-finish dried, respectively. Modelling of drying behaviour (Midilli-Kucuk model) for microwave finish drying was done separately for hot air and microwave part as it was suggested in previous reports (*Maskan, 2000*). Results for both parts of drying process indicate good approximation of experimental data (Table 3).

Table 3. Regression analysis for MW-finish drying process

Constants	Hot air part	Microwave part
a	9.93×10^{-1}	1,01
k	2.60×10^{-3}	4.06×10^{-2}
n	1.43	2.19
b	1.36×10^{-3}	8.32×10^{-3}
RSS	2.85×10^{-3}	1.23×10^{-3}
RMSE	1.26×10^{-2}	3.53×10^{-3}
χ^2	3.61×10^{-4}	1.87×10^{-3}

Water holding capacity can be used as quality index of dried products. As it was expected water holding capacity, WHC, (g water/ g dry solids) decreased with increase of drying temperature. The reason for this lies in sample shrinkage caused by sever heating and/or prolonged drying resulting in irreversible physico-chemical changes (*Maskan, 2000*). Higher WHC was expected for microwave dried samples (*Feng and Tang, 1998*) but they had lower WHC than samples dried at 65 °C, this might be due to the higher temperature rise (greater then 65 °C) during microwave drying (Fig. 5.). The highest WHC in this study was obtained for MW-finish drying. In addition to improved drying rate and thus shorter drying time it is possible that outward flux of vapour generated during microwave part of drying process helps to prevent further shrinkage of tissue structure of sugar beet pulp (*Prabhanjan et al., 1995*). Zhang et al. (2006) reported that combining microwave with other drying methods reduces drying time as well as improves product quality.

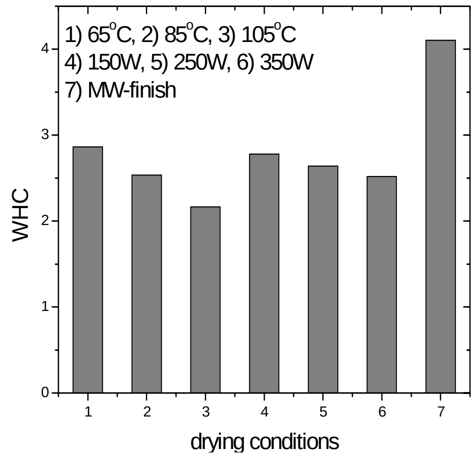

Fig. 5. Influence of drying conditions on water holding capacity of sugar beet pulp

CONCLUSION

The empirical Midilli-Kucuk model provided good representation of sugar beet pulp drying behaviour both for hot air and microwave drying. Hot air drying process takes place in the falling rate period, but it is possible to have a short constant rate period at lower temperatures i.e. 65 °C. During microwave drying there was no constant rate period. Drying time was significantly shorter when microwave power was applied in contrast to long drying times of hot air drying. Application of microwave drying in two-stage process reduced drying time by 50%. Water holding capacity of sugar beet samples decreased with increase of hot air temperature or applied level of microwave power. The highest values of water holding capacity were obtained in MW-finish drying process.

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