Annals of Warsaw University of Life Sciences – SGGW
Agriculture No 63 (Agricultural and Forest Engineering) 2014: 73–80
(Ann. Warsaw Univ. Life Sci. – SGGW, Agricult. 63, 2014)

Application of empirical models to the description of mass changes during the rehydration of dried apples pretreated by different methods before drying*

KRZYSZTOF GÓRNICKI, ANETA CHOIŃSKA, AGNIESZKA KALETA, RADOSŁAW WINICZENKO
Department of Fundamental Engineering, Warsaw University of Life Sciences – SGGW

Abstract: *Application of empirical models to the description of mass changes during the rehydration of dried apples pretreated by different methods before drying*. Five empirical models (Peleg, Pilosof-Boquet-Batholomai, Singh and Kulshrestha, Witrowa-Rajchert, and Wesołowski) were investigated for their suitability to describe the mass changes during the rehydration of dried apples pretreated before drying. Following methods of pretreatment at temperature 20°C were applied: (i) 10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa, (ii) 30 min in 61.5% sucrose solution, (iii) 120 min in 61.5% sucrose solution. Samples (slices of 10-milimeter-thickness) were dried in a convective dryer. Air velocity was kept at 2 m/s and air temperature was kept at 60°C. The dried apples samples (the initial moisture content of approx. 6%) were rehydrated by immersion in: (i) distilled water at 20, 45, 70, and 95°C, (ii) apple juice at 20°C, (iii) 0.5% citric acid solution at 20°C, (iv) 16.5% sucrose solution at 20°C. The accuracies of the models were measured using the root mean square error (RMSE), determination coefficient (R^2), and reduced chi-square (χ^2). The Peleg model can be considered as the most appropriate (RMSE = 0.022–0.185, R^2 = 0.917–0.998, χ^2 = 0.001–0.039). The highest values of equilibrium mass were obtained for pretreating 10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa at temperature 20°C.

Key words: rehydration, drying, pretreatment, mathematical model, apple

INTRODUCTION

The knowledge of the rehydration kinetics of dried products is important to optimise process from a quality point of view because rehydration is a key quality aspect for those dried products that have to be reconstituted before their consumption. The most important aspect of rehydration technology is the mathematical modelling of the rehydration process. Many theoretical and empirical approaches have been employed and in some cases empirical models were preferred because of their relative ease of use [Kaleta and Górnicki 2006, Górnicki 2010].

The objective of this study was to apply five empirical models to the description of mass changes during rehydration of dried apples pretreated by different methods before drying. It turned out from the literature survey that although there are several works on the rehydration behaviour of apples [Prothon et al. 2001, Taiwo et al. 2002, Lis et al. 2004, Bilbao-Sáinz et al. 2005, Atarés et al. 2008, 2009, Kaleta et al. 2010, Górnicki 2011, Fijałkowska et al. 2012] there is no information on the subject undertaken in this study.

*The authors are grateful for the financial support from research project N N313 780940 from the National Science Centre, Poland.

MATERIAL AND METHODS

Ligol variety apples used in this study were acquired in local market. Homogeneous lots were selected according to such maturity indicators as fruit size and appearance. Large, yellow, and covered with bright red blush apples were chosen. They had cream-coloured, crispy, and juicy flesh and good aroma. Apples were cut into slices of 10-milimeter-thickness. Before drying slices were pretreated at 20°C by following methods: (i) 10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa, (ii) 30 min in 61.5% sucrose solution, (iii) 120 min in 61.5% sucrose solution. Samples were dried in a convective dryer. Air velocity was kept at 2 m/s and air temperature was kept at 60°C. Drying was continued until no further changes in mass samples were observed. Experiments were replicated three times. Dried material obtained in the same conditions was stored in air-tight glass container until it was used in the rehydration experiments.

The dried apples samples (the initial moisture content of approx. 6%) were rehydrated by immersion in: (i) distilled water at 20, 45, 70, and 95°C, (ii) apple juice at 20°C, (iii) 0.5% citric acid solution at 20°C, (iv) 16.5% sucrose solution at 20°C. An initial amount of 10 g of dried apples was used in each trial. The measurements lasted from 2 h (for distilled water at 95°C) to 6 h (for each medium at 20°C). Samples were weighted seven times during the rehydration. They were carefully removed, blotted with paper towel to remove superficial medium, and weighted. The mass of samples during rehydration were weighted with electronic scales WPE-300 (RADWAG, Radom, Poland) with accuracy of ±0.001 g. Maximum relative error was 0.1%. The measurements were replicated three times.

The course of rehydration characteristics of apple slices was described with the following models:

– the Peleg [1988] model

$$\frac{m(t)}{m_0} = 1 + \frac{t}{A_1 + A_2 t} \tag{1}$$

where:
$m(t)$ – mass of rehydrated sample [g];
m_0 – mass of dried material [g];
t – time [h];
A_1 – Peleg rate constant [h];
A_2 – Peleg capacity constant.

– the Pilosof-Boquet-Batholomai [1985] model

$$\frac{m(t)}{m_0} = 1 + \frac{A_3 t}{A_4 + t} \tag{2}$$

where:
A_3, A_4 – constants;

– the Singh and Kulshrestha [1987] model

$$\frac{m(t)}{m_0} = 1 + \frac{A_5 A_6 t}{A_6 t + 1} \tag{3}$$

where: A_5, A_6 – constants;

– the Witrowa-Rajchert [1999] model

$$\frac{m(t)}{m_0} = A + B\left(1 - \frac{1}{1 + BCt}\right) \tag{4}$$

where:
A, B, C – constants;

– the Wesołowski [2000] model

$$\frac{m(t)}{m_0} = A\left(B - e^{-Ct}\right) \tag{5}$$

where:
A, *B*, *C* – constants.

The goodness of fit of the tested models to the experimental data was evaluated with the root mean square error (RMSE), the coefficient of determination (R^2), and reduced chi-square (χ^2). The higher the R^2 value, and lower the RMSE and χ^2 values, the better is the goodness of fit. In this study, the regression analyses were done using the STATISTICA routine.

The equilibrium mass (m_e) of rehydrated apple slices determined was using the discussed models. If time of rehydration is long enough ($t \to \infty$) the equilibrium mass can be calculated by: (i) $m_e/m_0 = 1 + A_2^{-1}$ for the Peleg model, (ii) $m_e/m_0 = 1 + A_3$ for the Pilosof-Boquet-Batholomai model, (iii) $m_e/m_0 = 1 + A_5$ for the Singh and Kulshrestha model, (iv) $m_e/m_0 = A + B$ for the Witrowa-Rajchert model, and (v) $m_e/m_0 = A \cdot B$ for the Wesołowski model.

RESULTS AND DISCUSSION

Example of variation in relative mass changes ($m(t)/m_0$) during the rehydration of apple slices (pretreated before drying at 20°C in 61.5% sucrose solution for 30 min, dried in convective dryer at 60°C and 2 m/s) immersed in 0.5% citric acid solution at 20°C and the results of verification of the considered empirical models are presented in Figure 1a–c. It can be seen that moisture uptake increase with increasing rehydration time, and the rate is faster in the initial period of rehydration and decreased up to the saturation level. This initial period of high water uptake can be attributed to the capillaries and cavities near the surface filling up rapidly [Garcia-Pascual et al. 2005, Cunningham et al. 2008]. As water absorption proceeds, rehydration rates decline due to increased extraction rates of soluble materials [Abu-Ghannam and Mc Kenna 1997]. Similar findings have been noted in the previous studies [Planinić et al. 2005, Jambrak et al. 2007, Deng and Zhao 2008] and for the other experiments conducted in this work.

It can be seen from Figure 1a–c that five considered empirical models describe the course of rehydration curve well. Analysis of all obtained graphs shows similar values of absolute and relative errors.

The exemplary results of statistical analyses on the modelling of mass changes during the rehydration of dried apple slices in distilled water at 70°C and the summary results (for all experiments conducted in this work) of statistical analyses on the modelling of mass changes during the rehydration of dried apple slices are given in Tables 1 and 2. As can be seen from the statistical analyses results, generally high determination coefficient R^2 were observed for the following models: Peleg, Pilosof-Boquet--Batholomai, Singh and Kulshrestha, Witrowa-Rajchert, and Wesołowski. It can be however noticed that the Peleg model gave the lowest values of RMSE and χ^2. Therefore it turned out from the statistical analyses that the Peleg model can be considered as the most appropriate. This model has been widely used due to its simplicity, and has been reported to adequately describe the changes of moisture content during the rehydration of various dried products such as apples cv. 'Fuji' [Deng and Zhao 2008], bambara

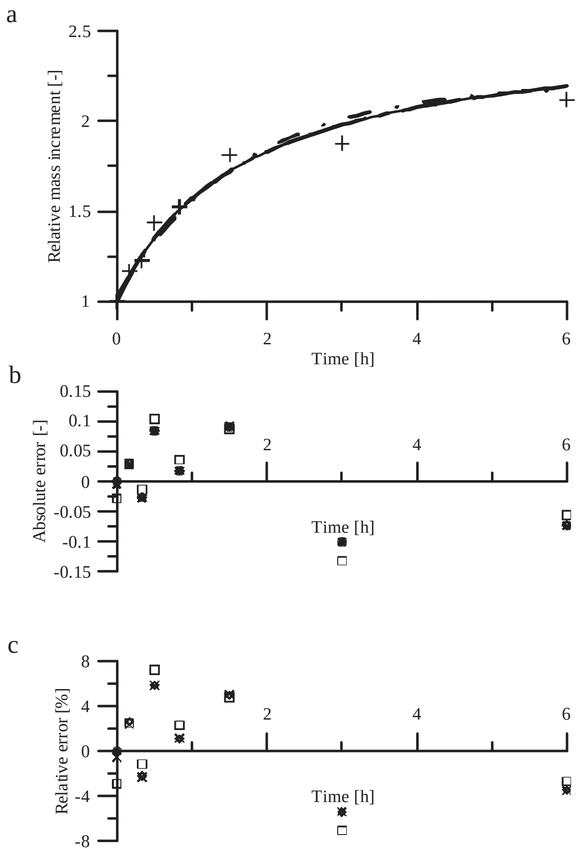

FIGURE 1. Verification of the considered empirical models for the rehydration of apple slices (pretreated before drying at 20°C in 61.5% sucrse solution for 30 min, dried in convective dryer at 60°C and 2 m/s) immersed in 0.5% citric acid solution at 20°C: (a) relative mass increment vs time; (+) experimental data, (——) Peleg model, (- - - -) Pilosof-Boquet-Batholomai model, (– – –) Singh and Kulshrestha model, (— —) Witrowa-Rajchert model, (— · —) Wesołowski model, (b) absolute error of rehydration curve approximation; (○) Peleg model, (Δ) Pilosof-Boquet-Batholomai model, (◊) Singh and Kulshrestha model, (x) Witrowa-Rajchert model, (□) Wesołowski model, (c) relative error of rehydration curve approximation; (○) Peleg model, (Δ) Pilosof-Boquet-Batholomai model, (◊) Singh and Kulshrestha model, (x) Witrowa-Rajchert model, (□) Wesołowski model

[Jideani and Mpotokwana 2009], *Boletus edulis* mushroom [Garcia-Pascual et al. 2005], chickpea [Turhan et al. 2002], and red kidney beans [Abu-Ghannam and McKenna 1997]. The Peleg model has been also verified for the increase in mass during rehydration of such dried products as apples cv. ‘Granny Smith’ [Bilbao-Sáinz et al. 2005, Atarés et al. 2008, 2009], carrots [Markowski and Zielińska 2011], and mango [Giraldo et al. 2006]. The conditions of drying and rehydration of apples at paper mentioned earlier were different from conditions applied in this work.

The values of equilibrium mass obtained from the Peleg, Pilosof-Boquet--Batholomai, and Singh and Kulshrestha

TABLE 1. Results of statistical analyses on the modelling of mass changes during the rehydration of dried apple slices in distilled water at 70°C

Method of pretreatment	Model name	Equation	Model parameters	Equilibrium value	RMSE	R^2	χ^2
10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa at 20°C	P	1	A_1 = 0.254 A_2 = 0.370	3.73	0.120	0.978	0.017
	PBB	2	A_3 = 2.726 A_4 = 0.691	3.73	0.120	0.978	0.017
	SK	3	A_5 = 2.726 A_6 = 1.447	3.73	0.120	0.978	0.017
	W-R	4	*A* = 1.082 *B* = 2.710 *C* = 0.466	3.80	0.113	0.979	0.016
	W	5	*A* = 2.204 *B* = 1.527 *C* = 1.042	3.37	0.153	0.962	0.029
30 min in 61.5% sucrose solution at 20°C	P	1	A_1 = 0.567 A_2 = 0.444	3.25	0.060	0.990	0.004
	PBB	2	A_3 = 2.254 A_4 = 1.279	3.25	0.060	0.990	0.004
	SK	3	A_5 = 2.254 A_6 = 0.782	3.25	0.060	0.990	0.004
	W-R	4	*A* = 1.032 *B* = 2.268 *C* = 0.317	3.30	0.058	0.990	0.004
	W	5	*A* = 1.733 *B* = 1.614 *C* = 0.742	2.80	0.074	0.983	0.007
120 min in 61.5% sucrose solution at 20°C	P	1	A_1 = 0.445 A_2 = 0.453	3.21	0.088	0.980	0.009
	PBB	2	A_3 = 2.206 A_4 = 0.983	3.21	0.088	0.980	0.009
	SK	3	A_5 = 2.206 A_6 = 1.018	3.21	0.088	0.980	0.009
	W-R	4	*A* = 1.036 *B* = 2.207 *C* = 0.425	3.24	0.089	0.980	0.009
	W	5	*A* = 1.739 *B* = 1.620 *C* = 0.885	2.82	0.106	0.970	0.014

P – Peleg; PBB – Pilosof-Boquet-Batholomai; SK – Singh and Kulshrestha; W-R – Witrowa-Rajchert; W – Wesołowski.

TABLE 2. Summary results of statistical analyses on the modelling of mass changes during the rehydration of dried apple slices

Model name	Equation	Equilibrium value	RMSE	R^2	χ^2
Peleg	1	2.041–3.849	0.022–0.185	0.917–0.998	0.001–0.039
Pilosof-Boquet--Batholomai	2	2.041–3.849	0.022–0.407	0.917–0.998	0.001–0.188
Singh and Kulshrestha	3	2.041–3.849	0.022–0.447	0.917–0.998	0.001–0.233
Witrowa-Rajchert	4	2.114–3.884	0.038–0.184	0.919–0.998	0.001–0.041
Wesołowski	5	1.871–3.366	0.032–0.638	0.893–0.996	0.001–0.509

models are the same. The Witrowa-Rajchert model gave slightly higher values of equilibrium mass and values obtained from the Wesołowski model are lower. For all considered models the highest values of equilibrium mass were obtained for pretreating 10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa at 20°C.

CONCLUSIONS

Five empirical models were investigated for their suitability to describe the mass changes during the rehydration of dried apples pretreated by different methods before drying. The root mean square error, the determination coefficient, and reduced chi-square were estimated for all models considered to compare their goodness of fit the experimental rehydration data. It turned out from the statistical analyses that the Peleg model can be considered as the most appropriate.

REFERENCES

ABU-GHANNAM N., McKENNA B. 1997: Hydration of red kidney beans (*Phaseolus vulgaris* L.). Journal of Food Science 62(3): 520–523.

ATÁRES L., CHIRALT A., GONZÁLEZ--MARTINEZ C. 2008: Effect of solute on osmotic dehydration and rehydration of vacuum impregnated apple cylinders (cv. Granny Smith). Journal of Food Engineering 89: 49–56.

ATÁRES L., CHIRALT A., GONZÁLEZ--MARTINEZ C. 2009: Effect of the impregnated solute on air drying and rehydration of apple slices (cv. Granny Smith). Journal of Food Engineering 91: 305–310.

BILBAO-SAINZ C., ANDRÉS A., FITO P. 2005: Hydration kinetics of dried apple as affected by drying conditions. Journal of Food Engineering 68: 369–376.

CUNNINGHAM S.E., McMINN W.A.M., MAGEE T.R.A., RICHARDSON P.S. 2007: Effect of processing conditions on the water absorption and texture kinetics of potato. Journal of Food Engineering 84(2): 214–223.

DENG Y., ZHAO Y. 2008: Effect of pulsed vacuum and ultrasound osmopretreatments on glass transition temperature, texture, microstructure and calcium penetration of dried apples (Fuji). LWT – Food Science and Technology 41(9): 1575–1585.

FIJAŁKOWSKA A., WITROWA-RAJCHERT D., WEROŃSKI A. 2012: Wpływ powlekania surowca na przebieg procesu suszenia i właściwości rekonstrukcyjne suszu jabłkowego. Zeszyty Problemowe Postępów Nauk Rolniczych 571: 39–47.

GARCIA-PASCUAL P., SANJUÁN N., BON J., CARRERES J.E., MULET A. 2005: Rehydration process of *Boletus edulis* mushroom: chracteristics and modelling. Journal of the Science of Food and Agriculture 85(8): 1397–1404.

GIRALDO G., VÁZQUEZ R., MARTÍN--ESPARZA M.E., CHIRALT A. 2006: Rehydration kinetics and soluble solids lixiviation of candied mango fruit as affected by sucrose concentration. Journal of Food Engineering 77: 825–834.

GÓRNICKI K. 2010: Effect of convectional drying parameters on rehydration kinetics of parsley dried slices. Annals of Warsaw University of Life Sciences – SGGW. Agriculture (Agricultural Engineering) 55: 27–33.

GÓRNICKI K. 2011: Modelowanie procesu rehydratacji wybranych warzyw i owoców. Wydawnictwo SGGW, Warszawa.

JAMBRAK A.R., MASON T.J., PANIWNYK L., LELAS V. 2007: Accelerated drying of button mushrooms, brussels sprouts and cauliflower by applying power ultrasound and its rehydration properties. Journal of Food Engineering 81(1): 88–97.

JIDEANI V.A., MPOTOKWANA S.M. 2009: Modeling of water absorption of *Botswana bambara* varieties using Peleg's equation. Journal of Food Engineering 92: 182–188.

KALETA A., GÓRNICKI K. 2006: Effect of initial processing methods used in convectional drying process on the rate of getting equilibrium state in rehydrated dried parsley root. Annals of Warsaw Agricultural University – SGGW. Agriculture (Agricultural Engineering) 49: 9–13.

KALETA A., GÓRNICKI K., KOWALIK A., BRYŚ A. 2010. Investigations on rehydration process of dried prunes, apples and strawberries obtained under industrial conditions. Annals of Warsaw University of Life Sciences – SGGW. Agriculture (Agricultural Engineering) 55: 9–13.

LIS T., LIS H., KŁOCZEK E. 2004: Zależność cech jakościowych liofilizantu, czasu suszenia i zużycia energii od jego wilgotności. Acta Agrophysica 4(3): 747–752.

MARKOWSKI M., ZIELIŃSKA M. 2011: Kinetics of water absorption and soluble-solid loss of hot-air-dried carrtos during rehydration. International Journal of Food Science and Technology 46: 1122–1128.

PELEG M. 1988: An empirical model for the description of moisture sorption curves. Journal of Food Science 53: 1216–1219.

PILOSOF A.M.R., BOQUET R., BARTHOLOMAI G.B. 1985: Kinetics of water uptake by food powders. Journal of Food Science 50: 278–279.

PLANINIĆ M., VELIĆ D., TOMAS S., BILIĆ M., BUCIĆ A. 2005: Modeling of drying rehydration of carrots using Peleg's model. European Food Research and Technology 221(3–4): 446–451.

PROTHON F., AHRNÉ L.M., FUNEBO T., KIDMAN S., LANGTON M., SJÖHOLM I. 2001: Effects of combined osmotic and microwave dehydration of apple on texture, microstructure and rehydration characteristics. Lebensmittel-Wissenschaft and Technologie 34: 95–101.

SINGH B.P.N., KULSHRESTHA S.P. 1987: Kinetics of water sorption by soybean and pigeonpea grains. Journal of Food Science 52: 1538–1541.

TAIWO K.A., ANGERSBACH A., KNORR D. 2002: Rehydration studies on pretreated and osmotically dehydrated apple slices. Journal of Food Science 67: 842–847.

TURHAN M., SAYAR S., GUNASEK--ARAN S. 2002: Application of Peleg model to study water absorption in chickpea during soaking. Journal of Food Engineering 53: 153–159.

WESOŁOWSKI A. 2000: Badanie suszenia jabłek promieniami podczerwonymi. Rozprawa doktorska. SGGW, Warszawa.

WITROWA-RAJCHERT D. 1999: Rehydracja jako wskaźnik zmian zachodzących w tkance roślinnej podczas suszenia. Fundacja "Rozwój SGGW", Warszawa.

Streszczenie: *Zastosowanie empirycznych modeli do opisu zmian masy podczas rehydratacji suszonych jabłek poddanych różnym metodom obróbki wstępnej przed suszeniem.* Badano pięć empirycznych modeli: Pelega, Pilosof-Boquet-Batholomai, Singh i Kulshrestha, Witrowej-Rajchert oraz Wesołowskiego, pod kątem ich przydatności do opisu zmian masy w procesie rehydratacji suszonych jabłek. Materiałem badawczym były 10 mm plastry jabłek suszone w warunkach konwekcji wymuszonej (w temperaturze 60°C i przy prędkości czynnika suszącego 2 m/s). Przed suszeniem krajankę jabłek poddawano następującym metodom obróbki wstępnej (w temperaturze 20°C): 10 min w soku jabłkowym, a następnie 10 min pod ciśnieniem pomniejszonym o 0,02 MPa, 30 min w 61,5-procentowym roztworze sacharozy, 120 min w 61,5-procentowym roztworze sacharozy. Proces rehydratacji prowadzono w wodzie destylowanej w 20, 45, 70 i 95°C, soku jabłkowym w 20°C, 0,5-procentowym roztworze kwasku cytrynowego 20°C. Miarą dokładności dopasowania danych otrzymanych z modeli do danych empirycznych były: pierwiastek błędu średniokwadratowego (RMSE), współczynnik determinacji (R^2) oraz zredukowany chi-kwadrat (χ^2). Model Pelega można uznać za najbardziej odpowiedni do opisu zmian masy w procesie rehydratacji suszonych jabłek (RMSE = 0,022–0,185, R^2 = 0,917–0,998, χ^2 = 0,001–0,039). Susz krajanki jabłek, który był poddany przed suszeniem obróbce wstępnej polegającej na umieszczeniu surowca na 10 min w soku jabłkowym i następnie na 10 min w warunkach obniżonego o 0,02 MPa ciśnienia w 20°C, charakteryzował się w procesie rehydratacji największą wartością równowagowej masy.

MS. received January 2014

Authors' address:
Krzysztof Górnicki
Wydział Inżynierii Produkcji SGGW
Katedra Podstaw Inżynierii
02-787 Warszawa, ul. Nowoursynowska 166
Poland
e-mail: krzysztof_gornicki@sggw.pl