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Modelling of rehydration kinetics of dried carrots using the Peleg model

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Abstract: *Modelling of rehydration kinetics of dried carrots using the Peleg model.* The objective of the study is to apply the Peleg model to the description of rehydration kinetics of dried carrots and to investigate the effect of the rehydration temperature and particle shape on the model constants. The changes of: mass, dry matter of solid, moisture content on dry basis and moisture content in percent wet basis were described using the Peleg model. Samples (slices of 10-millimeter thickness and 10 × 10 × 10 mm cubes) were dried at natural convection and the air temperature was kept at 60°C. The rehydration was carried out in the distilled water at the temperature of 20, 45 and 70°C. The accuracies of the model were measured using the coefficient of correlation (R), root mean square error ($RMSE$), and reduced chi-square (χ^2). It was stated that the Peleg model may be assumed to represent the relative mass increment, relative dry matter of solid decrease, and relative moisture content in % w.b. increment during the rehydration of carrot slices and cubes. The model cannot be accepted for description of relative moisture content on d.b. increment. The rehydration temperature and particle shape significantly influenced the Peleg rate constant (A_1). Both parameters significantly influenced the Peleg capacity constant (A_2) in case of mass and moisture content in % w.b. only.

Key words: rehydration, drying, rehydration temperature, particle shape, model, carrot

INTRODUCTION

Dried and rehydrated agri-food products are very important ingredients in breakfast cereals, dairy products, and dietetic foods prepared for people suffering from physiological disorders. Such products are also key ingredients for healthy people with additional needs and traditional foods such as cakes, biscuits and desserts [Seremet (Ceclu) et al. 2016]. Therefore, dried fruits and vegetables may be a finished product or half – finished product, subject to further processing, mostly rehydration.

Rehydration is one of the most important quality properties for dried products. Water uptake during rehydration is a complex process depending on morphological structure, chemical composition, drying pretreatments, drying methods, immersion media, and rehydration temperature and time [Deng et al. 2014]. The knowledge of the rehydration kinetics of dried products is important to optimise process from a quality point of view. Therefore, the rehydration process of food products is nowadays so widely investigated [Kaleta et al. 2010, Jiao et al. 2014, Kaleta et al. 2014, Vergeldt et al. 2014].

The most important aspect of rehydration technology is the mathematical modelling of the rehydration process. The rehydration behaviour of food products is described by theoretical, semi-empirical, and empirical models. Theoretical models are based on the laws of the general heat and mass transfer theory [Górnicki 2011, van der Sman et al. 2014]. Empirical models continue to be widely used. In spite of their simplicity, these models are very useful and their interpretation supplies valuable information about the kinetics of the process. The empirical Peleg model [1988] is one of the most frequently used. This model was applied to describe, among others, the rehydration process of the following dried materials: *Aloe vera* [Vega-Gálvez et al. 2009], apples [Górnicki et al. 2014], blueberries [Zielińska and Markowski 2016], carrot [Markowski and Zielińska 2011, Ricce et al. 2016], and squid fillets [Deng et al. 2014].

Carrot (*Daucus carota* L.) is considered one of the vegetable whose consumption, both fresh and processes, has increased over the past years. Its pleasant flavour is one of the main reasons for its acceptance by consumers [Gamboa-Santos et al. 2013].

The objective of this study was to apply the Peleg model to the description of rehydration kinetics of dried carrots and to investigate the effect of the temperature and particle shape on the model constants.

MATERIAL AND METHODS

Fresh carrots used in this study were acquired in local market. Homogenous lots were selected according to such maturity indicators as vegetable size and the appearance. Carrots were properly washed in tap water to remove external impurities. Then, samples were cut into slices of 10-millimeter thickness and into 10 × 10 × 10 mm cubes. Samples were dried at natural convection and the air temperature was kept at 60°C. The drying lasted until the constant weight of the dried material was attained. The dried material obtained in the given conditions from three independent experiments was mixed and stored in a tightly sealed container until it was used in the rehydration experiments.

The rehydration process was carried out in the distilled water at the temperature of 20, 45 and 70°C. The rehydration lasted from 6 h (at 20°C) to 4 h (at 70°C). An initial amount of 10 g of dried carrots was used in each trial. The weight of the dried material to the weight of the distilled water amounted to 1 : 20. Water was not stirred during the rehydration process.

Mass of the samples and dry matter content were determined during the rehydration.

Mass determination was conducted as follows: samples were weighted seven times during the rehydration. They were carefully removed, blotted with paper towel and weighted. The WPE 300 scales (RADWAG, Radom) were used for the measurement of the sample mass. Maximum relative error amounted to 0.1%. Experiments were made in three repetitions.

Dry matter of solid was determined according to AOAC (2003) standards. Seven measurements of the dry matter content were carried out during rehydration. The WPE 300 scales (RADWAG, Radom) were used for the weighting the dry matter of samples. The maximum relative error amounted to 0.1%. Measurements were made in three repetitions.

Moisture content on dry basis (decimal d.b.) of the rehydrated samples was determined according to the following formula:

$$M = \frac{m - m_{d.m.}}{m_{d.m.}} \quad (1)$$

where:
m – mass of the rehydrated sample [g];
$m_{d.m.}$ – dry matter of solid of rehydrated sample [g].

Moisture content in percent wet basis (% w.b.) of the rehydrated samples was calculated with the following equation:

$$M_w = \frac{100\left(m - m_{d.m.}\right)}{m} \quad (2)$$

The changes of the mass, dry matter of solid, moisture content on dry basis, and moisture content in percent wet basis during the rehydration of carrot samples were described using the Peleg model [1988].

The Peleg model for relative mass increment is presented with the following formula:

$$\frac{m(\tau)}{m_0} = 1 + \frac{\tau}{A_1 + A_2\tau} \quad (3)$$

where:
τ – time [s];
m_0 – mass of dried material [g],
A_1 – Peleg rate constant [s];
A_2 – Peleg capacity constant.

The Peleg model for relative dry mass of solid decrease is presented with the following equation:

$$\frac{m_{d.m.}(\tau)}{m_{d.m.0}} = 1 - \frac{\tau}{A_1 + A_2\tau} \quad (4)$$

where: $m_{d.m.0}$ – dry matter of solid of dried material [g].

The Peleg model for relative moisture content on dry basis increment is described with the following formula:

$$\frac{M(\tau)}{M_0} = 1 + \frac{\tau}{A_1 + A_2\tau} \quad (5)$$

where: M_0 – moisture content of dried material on dry basis [decimal d.b.].

The Peleg model for relative moisture content in percent wet basis increment is described with the following equation:

$$\frac{M_w(\tau)}{M_{w0}} = 1 + \frac{\tau}{A_1 + A_2\tau} \quad (6)$$

where: M_{w0} – moisture content of dried material in percent wet basis (% w.b.).

The goodness of fit of the tested Peleg model to the experimental data was evaluated with the coefficient of correlation (R), root mean square error ($RMSE$), and the reduced chi-square (χ^2). The higher the R value, and lower the $RMSE$ and χ^2 values, the better is goodness of fit. The regression analyses were done using the Statistica routine.

RESULTS AND DISCUSSION

Examples of measurements results are shown in the Figures 1 and 2. Figure 1 presents mass increase and Figure 2 presents dry matter of solid decrease of carrots dried material during rehydration in distilled water of temperatures 20° and 45°C. Three repetitions of experiments are shown in the figures.

Table 1 presents the values of Peleg model constants and comparison of results of statistical analyses on the modelling of carrot samples rehydration.

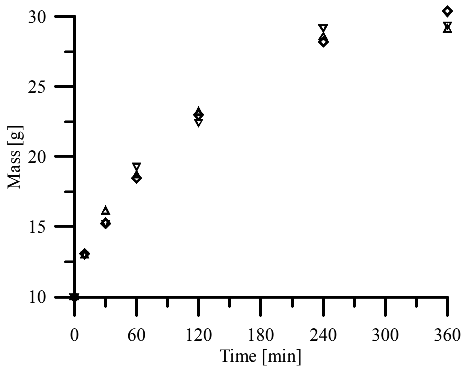

FIGURE 1. Changes of mass of dried carrot slices during rehydration in distilled water of temperature 20°C

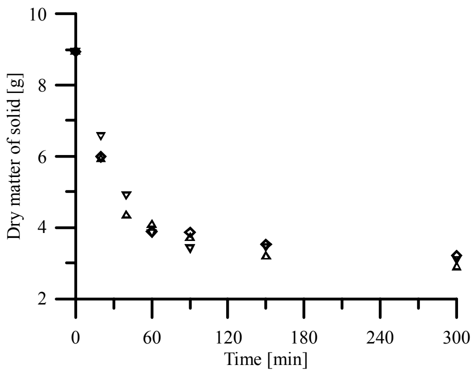

FIGURE 2. Changes of dry matter of solid of dried carrot cubes during rehydration in distilled water of temperature 45°C

The caption "experiment" denotes that the constant value was determined as an arithmetic mean from the values obtained separately for each of three repetitions, whereas caption "for three repetitions" denotes that the value of the Peleg constant was obtained at once from three repetitions. The Table 1 presents moreover the statistical analysis of the influence of rehydration temperature and particle shape on the Peleg model constants. In that table, homogenous groups were marked with the same letters. The significance of the discussed influence was determined with the use of the ANOVA technique applying the Levene test of homogeneity of variances. Homogenous groups were tested with the use of the Tukey test HSD ($P = 0.05$). Calculations were conducted with the use of the IBM® SPSS® Statistics 21 program.

As can be seen from the statistical analysis results, generally high correlation coefficient (R), and low values of $RMSE$ and χ^2 were found for the Peleg

TABLE 1. Peleg model constants and comparisons of results of statistical analyses on the modelling of carrot samples rehydration

Modelled variable	Particle shape	Rehydration temperature [°C]	Experiment					For three repetitions				
			A_1	A_2	R	$RMSE$	χ^2	A_1	A_2	R	$RMSE$	χ^2
Relative mass	slice	20	43.6052 e	0.3787 c	0.9960	0.0648	0.0046	43.5321	0.3789	0.9960	0.0648	0.0046
		45	28.4048 d	0.3102 ab	0.9928	0.0940	0.0098	28.4235	0.3100	0.9928	0.0940	0.0098
		70	14.2549a	0.3606 bc	0.9917	0.1014	0.0114	14.2679	0.3596	0.9917	0.1013	0.0114
	cube	20	19.3975 c	0.2678 a	0.9959	0.1052	0.0122	19.4009	0.2677	0.9959	0.1052	0.0122
		45	11.0672 a	0.2795 a	0.9991	0.0423	0.0021	11.0624	0.2795	0.9991	0.0423	0.0020
		70	6.0755 b	0.3044 a	0.9968	0.0797	0.0071	6.0840	0.3040	0.9968	0.0797	0.0070
Relative dry matter of solid	slice	20	161.4238 d	1.4474 a	0.9850	0.0329	0.0012	161.3472	1.4425	0.9850	0.0329	0.0012
		45	83.5999 c	1.4189 a	0.9799	0.0389	0.0017	83.7034	1.4156	0.9799	0.0389	0.0017
		70	45.3783 b	1.4639 a	0.9856	0.0340	0.0013	45.2747	1.4631	0.9856	0.0340	0.0013
	cube	20	33.5846 ab	1.6468 a	0.9735	0.0476	0.0025	33.5543	1.6467	0.9735	0.0476	0.0025
		45	31.5687 ab	1.3931 a	0.9805	0.0428	0.0020	31.5020	1.3921	0.9805	0.0428	0.0020
		70	16.8381 a	1.5592 a	0.9780	0.0429	0.0020	16.9503	1.5566	0.9780	0.0429	0.0020
Relative moisture content on d.b.	slice	20	2.4717 d	0.0087 a	0.9857	3.9490	17.2362	2.6148	0.0084	0.9857	3.8922	16.7442
		45	1.2962 c	0.0074 a	0.9717	6.8899	52.4681	1.3539	0.0073	0.9714	6.8408	51.7232
		70	0.7555 a	0.0079 a	0.9843	5.4760	33.1431	0.7914	0.0078	0.9842	5.4087	32.3329
	cube	20	0.7787 a	0.0106 a	0.9801	5.8378	37.6673	0.8122	0.0107	0.9800	5.7743	36.8518
		45	0.6029 ab	0.0075 a	0.9822	6.5648	47.6342	0.6183	0.0075	0.9821	6.5174	46.9475
		70	0.3598 b	0.0096 a	0.9789	6.3937	45.1831	0.3695	0.0097	0.9789	6.3422	44.4580
Relative moisture content [% w.b.]	slice	20	1.9389 c	0.094 a	0.9903	0.9906	1.0845	2.7867	0.1012	0.9939	0.3536	0.1382
		45	1.4327 bc	0.0885 a	0.9965	0.9530	1.0037	1.8492	0.0963	0.9935	0.2420	0.0647
		70	1.1734 abc	0.0883 a	0.9499	1.3876	2.1279	1.3978	0.0965	0.9507	1.1321	1.4166
	cube	20	0.7987 ab	0.1141 b	0.9974	0.9329	0.9619	1.1067	0.1281	0.9988	0.1238	0.0170
		45	0.6726 ab	0.1105 b	0.9985	0.9314	0.9589	0.8810	0.1240	0.9989	0.12337	0.0168
		70	0.3676 a	0.1129 b	0.9981	0.9364	0.9692	0.4853	0.1271	0.9986	0.1351	0.0202

a, b, c, d, e – the same letters in columns denote groups that do not differ significantly at level $P = 0.05$.

model applied to the description of the changes of relative mass, relative dry matter of solid, and relative moisture content in % w.b. during the rehydration of carrot samples. In case of relative moisture content on d.b. increment the results of the statistical analysis were not satisfactory enough because of the high values of *RMSE* and χ^2. Both methods of determining of the Peleg model constants gave very similar values of *R*, *RMSE*, and χ^2 for relative mass increment, relative dry matter of solid decrease, and relative moisture content on d.b. increment, whereas in case of relative moisture content in % w.b. increment the values of *RMSE* and χ^2 were lower for the "for three repetitions" method.

It can be seen moreover from Table 1 that the influence of rehydration temperature and particle shape was significant for Peleg rate constant (A_1). As for as the Peleg capacity constant (A_2) was concerned discussed influence was significant only for the relative mass increment and relative moisture content in % w.b. increment.

Taking into account the results of statistical analysis of the influence of discussed variables, the following type of equation for determination of the Peleg model constant was considered:

$$A_1 = a_1 L + b_1 t + c_1 L t + d_1 \quad (7)$$

$$A_2 = a_2 L + b_2 t + c_2 L t + d_2 \quad (8)$$

where:
a, *b*, *c*, *d* – constants;
L – characteristic particle dimension [m];
t – temperature [°C].

According to Pabis et al. [1998]:

- for slice of thickness 2*s*

$$L = s \quad (9)$$

- for cube of thickness 2*s*

$$\frac{1}{L} = \frac{3}{s^2} \quad (10)$$

where: *s* – particle half thickness [m].

The regression analyses gave the constants presented in Table 2.

The Equations (7) and (8) with the constants given in Table 2 were then used to estimate the relative mass increment, relative dry matter of solid decrease, relative moisture content on dry basis increment, and relative moisture content in percent wet basis increment at any time during the rehydration process. Validation of the established models was made by comparing the computed relative mass, relative dry matter of solid, relative moisture content d.b., and relative moisture content in % w.b. with the measured one in any particular rehydration run under certain conditions. The accuracy of the established models is shown in Table 3. It can be admitted taking into account the results of statistical analyses that the Peleg model with Eqs. (7) and (8) represented the experimental values of relative mass increment, relative dry matter of solid decrease, and relative moisture content in % w.b. increment satisfactorily. The results of discussed analyses for relative mass

TABLE 2. Constants of Equations (7) and (8) and results of statistical analyses

Variable	Peleg constant	*a*	*b*	*c*	*d*	*R*	*RMSE*	χ^2
Relative mass	A_1	14.6921	0.1726	–0.1519	–18.2904	0.9989	0.5827	1.0187
	A_2	0.0547	0.0022	–0.0005	0.0930	0.8697	0.0199	0.0012
Relative dry matter of solid	A_1	58.7741	1.5581	–0.6811	–123.4341	0.9884	6.8236	59.8641
	A_2	–	–	–	1.5098	–	0.0916	0.0101
Relative moisture content on d.b.	A_1	0.7723	0.0169	–0.0092	–1.1741	0.9854	0.2141	0.1376
	A_2	–	–	–	0.0089	–	0.0013	0.0000
Relative moisture content [% w.b.]	A_1	0.4275	–0.0120	–	–0.0840	0.9650	0.4528	0.4100
	A_2	–0.0105	–0.0001	–	0.1460	0.9924	0.0114	0.0003

TABLE 3. Peleg model constants calculated from Equations (7) and (8) and comparison of results of statistical analyses on the modelling of carrot samples rehydration at model constants expressed with Equations (7) and (8)

Modelled variable	Particle shape	Rehydration temperature [°C]	A_1	A_2	*R*	*RMSE*	χ^2
Relative mass	slice	20	43.4301	0.3589	0.9962	0.0784	0.0068
		45	28.7550	0.3498	0.9923	0.1492	0.0246
		70	14.0798	0.3408	0.9918	0.1204	0.0160
	cube	20	18.8411	0.2656	0.9957	0.1092	0.0132
		45	12.1801	0.2839	0.9989	0.0956	0.0101
		70	5.5191	0.3022	0.9964	0.1020	0.0115
Relative dry matter of solid	slice	20	133.5340	1.5098	0.9833	0.0368	0.0015
		45	87.4056		0.9800	0.0445	0.0022
		70	41.2772		0.9849	0.0350	0.0014
	cube	20	38.2394		0.9707	0.0544	0.0033
		45	28.0092		0.9792	0.0493	0.0027
		70	17.7791		0.9777	0.0440	0.0021
Relative moisture content on d.b.	slice	20	2.1100	0.0089	0.9850	5.1756	29.6068
		45	1.3880		0.9718	8.4457	78.8380
		70	0.6660		0.9825	5.9792	39.5130
	cube	20	0.8666		0.9772	8.1947	74.2220
		45	0.6273		0.9820	9.4085	97.8380
		70	0.3880		0.9770	7.0278	54.5890
Relative moisture content [% w.b.]	slice	20	1.8141	0.0920	0.9893	1.2044	1.6032
		45	1.5150	0.0903	0.9963	0.7458	0.6147
		70	1.2158	0.0885	0.9428	1.3468	2.0047
	cube	20	0.9121	0.1142	0.9986	0.8233	0.7492
		45	0.6130	0.1125	0.9978	0.8720	0.8404
		70	0.3138	0.1108	0.9971	1.1643	1.4983

increment were following: *R* ranged from 0.9918 to 0.9989, *RMSE* varied between 0.0784 and 0.1492, and χ^2 changed within the range of 0.0068–0.0246. The correlation coefficient ranged from 0.9707 to 0.9849, the root mean square error changed within the range of 0.0350–0.0544, and reduced chi-square changed within the range of 0.0014–0.0033 for relative dry matter of solid decrease. The *R* values varied between 0.9428 and 0.9986, *RMSE* ranged from 0.7458 to 1.3468, and the χ^2 values changed from 0.6147 to 2.0047 for relative moisture content in % w.b. increment. The results of statistical analyses pointed out that the Peleg model with Eqs. (7) and (8) cannot be assumed to represent the changes of relative moisture content on d.b. during the rehydration of carrot particles. Although the values of the correlation coefficient were high enough (0.9718–0.9850), the values of the root mean square (5.1756–9.4085) and the reduced chi-square (29.6068–97.8380) were much to high.

CONCLUSIONS

The following conclusions can be drawn from conducted investigations:

1. The Peleg model may be assumed to represent the relative mass increment, relative dry matter of solid decrease, and relative moisture content in % w.b. increment during the rehydration of carrot slices and cubes.
2. The Peleg model cannot be accepted for description of relative moisture content on d.b. increment during the rehydration of carrot slices and cubes.
3. The rehydration temperature and particle shape significantly influenced the Peleg rate constant (A_1).
4. The rehydration temperature and particle shape significantly influenced the Peleg capacity constant (A_2) in case of relative mass increment and relative moisture content in % w.b. increment only.

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Streszczenie: *Modelowanie kinetyki rehydratacji suszonej marchwi za pomocą modelu Pelega.* Celem badań jest zastosowanie modelu Pelega do opisu kinetyki rehydratacji suszonej marchwi i zbadanie wpływu temperatury rehydratacji i kształtu cząstki na stałe modelu Pelega pod kątem jego przydatności do opisu zmian masy, masy suchej substancji, zawartości wody i wilgotności suszonej marchwi w procesie jej rehydratacji. Materiałem badawczym były 10-milimetrowe plastry i sześciany marchwi o boku 10 mm, suszone w warunkach konwekcji naturalnej w temperaturze 60°C. Proces rehydratacji przeprowadzano w wodzie destylowanej o temperaturze 20, 45 i 70°C. Miarą dokładności dopasowania danych uzyskanych z modeli do danych empirycznych były: współczynnik korelacji (R), pierwiastek błędu średniokwadratowego ($RMSE$) i zredukowany chi-kwadrat (χ^2). Model Pelega można uznać za odpowiedni do opisu krotności zmian masy, masy suchej substancji i wilgotności suszonych plastrów i sześcianów marchwi. Model Pelega nie jest odpowiedni do opisu krotności wzrostu zawartości wody. Temperatura rehydratacji i kształt cząstki wpływają znacząco na stałą szybkości modelu Pelega (A_1). Oba parametry wpływają znacząco na stałą A_2 modelu Pelega jedynie w przypadku masy i wilgotności.

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