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Modelling of Convective Carrot Drying

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Drying of carrots was investigated in a laboratory dryer with an electric heater and in a dryer with infrared irradiation. Before drying, samples were blanched in a 1 % aqueous solution of ascorbic acid and 0.5 % aqueous solution of sodium chloride. Based on the experimental data, the time dependency of moisture content, drying rate and diffusion coefficient were calculated and presented. These dependencies were approximated by using a two-parameter exponential model. It was established that such approximation could be used only for experimental results obtained in the infrared irradiation dryer, owing to the excellent set-up of the measuring device for monitoring changes in sample mass. Thus obtained measurement results are in high correlation with the calculations and indicate that, as expected, the applicability of the two-parameter model is conditioned by the availability of measurements of changes in the sample mass. The diffusion coefficient of moisture was determined for different experimental conditions, ranging between 1×10^{-7} and 6×10^{-6} m^2 min^{-1} for blanched carrots in the 1 % aqueous solution of ascorbic acid, and between 1×10^{-8} and 1×10^{-5} m^2 min^{-1} for carrots blanched in the 0.5 % aqueous solution of sodium chloride.

Keywords
dehydration
two-parameter model
carrot
diffusion coefficient

INTRODUCTION

Drying of foods has drawn considerable attention in Croatia as well as worldwide due to its advantages over other preserving methods for different foodstuffs and the drying processes such as drying extrudates.[1,2] During drying, heat is supplied and the volatile component, mainly water, is eliminated from the heterogeneous mixture. During convective drying, two entirely different processes take place:

– elimination of water from the surface by warm air (drying agents)
– diffusion of water from within towards the surface due to the resulting concentration difference.

Before drying, it is essential to conduct a thorough analysis of the existing results and drying conditions, determine the dryer capacity, moisture content of the raw material and product, distribution of particles in the raw material,[3,4] the chemical composition (by HPLC),[5] physi-

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cal and thermodynamic parameters of the drying agents, maximal temperature to which the raw material may be subjected, drying curve, drying time, *etc.*

Many experts throughout the world are working on optimization and improvement of drying procedures in order to maintain product quality, shorten the drying time, conserve energy and solve a number of ecological problems.

This paper presents the results of investigating carrot samples during drying in an infrared irradiation dryer and in a dryer with an electric heater. The aim of the tests was to determine the conditions for optimal water diffusion control (Fick's law) in a material, which would result in a quality product. The obtained results would enable designing a two-parameter model of carrot drying and provide reliable parameters for dryer construction.[6–8]

EXPERIMENTAL

Carrots were dried in the infrared irradiation dryer and in the dryer with an electric heater in order to determine the optimal conditions for water diffusion control with the aim of obtaining a quality product.

The obtained experimental data were approximated using the exponential two-parameter model[9,10] that describes the entire drying process.

Material

Tests were carried out on samples of Nantes carrots. The samples were blanched in two ways:

- in 1 % aqueous solution of ascorbic acid by boiling at 90 °C for 8 minutes
- in 0.5 % aqueous solution of sodium chloride by boiling at 90 °C for 8 minutes.
- The samples were cut into various shapes and sizes: 10 × 10 × 10 mm cubes, 5 × 5 × 5 mm cubes, 1 mm thick cylinders, and were finely grated.

Drying tests were done in two ways:

- in drying plates in the dryer with electric heater
- in the laboratory dryer with infrared irradiation Mettler Lj16 (Mettler, Switzerland). The device enables direct measurement of sample mass changes with an accuracy of ± 0.001 g.

In this system, moisture and temperature parameters can be determined directly.

The composition of fresh and dried carrot was analyzed. Mass fractions of ash, cellulose and β-carotene were determined.

Measurements

Measurements were carried out in the dryer with an electric heater and in the dryer with infrared irradiation.

Before drying in the dryer with an electric heater, twelve 10 g samples were prepared and placed into drying plates for each run. The drying was carried out at preset time intervals of 0.5, 1, 3, 7, 15, 30, 45, 60, 75, 90, 105 and 120 min.

At the said intervals, the samples were taken out of the dryer and placed into the exsiccator, cooled and weighed for mass determination. Drying in the dryer with electric heater was done at 105 °C until constant mass was reached.

In the Mettler Lj16 dryer (Mettler, Switzerland) with infrared irradiation, 2 to 4 g samples were dried at 85 °C and 105 °C until constant mass was reached.

Calculations

Measurement data of the $X(t)$ relation obtained during drying may be approximated by the exponential two-parameter mathematical model with the following features:

Approximation of drying curves may be done by using empirical analytical functions $X = f(t)$ and $(-\mathrm{d}X/\mathrm{d}t) = g(t)$, which satisfy the following conditions:[11]

- $X(0) > 0$, which corresponds to the initial moisture content,
- $X(t) > 0,\ t \in [0,t_{eq})$
- $X(t)$ is the monotonously decreasing function at interval $t \in [0,t_{eq})$
- $X(t) \to X_{eq}$ for $t \to t_{eq}$
- $(-\mathrm{d}X(0)/\mathrm{d}t) = 0$
- $(-\mathrm{d}X(t)/\mathrm{d}t) > 0$ for $t \in [0,t_{eq})$
- $(-\mathrm{d}X(t)/\mathrm{d}t) \to 0$ for $t \to t_{eq}$

t_{eq} is the time necessary for the sample to reach the balanced state equilibrium, X_{eq}.

The mathematical form of the function satisfying the above conditions is as follows:

- for time-dependent change in the moisture content:

$$X(t) = X_0 e^{-bt^{-d}} \tag{1}$$

- for time-dependent drying rate:

$$(-\mathrm{d}X/\mathrm{d}t) = \mathrm{b} \cdot \mathrm{d} \cdot t^{(d-1)} \cdot X(t) \tag{2}$$

Parameters b and d in the model are determined by regression analysis by the least-squares method, *i.e.*, function minimization:

$$S(a,b,d) = \sum_{i=1}^{n} (X_0 - X_{eq}) \cdot \exp(-b \cdot t^d) - X_{eq}) - X_i)^2 \tag{3}$$

- $S(b,d)$ is the sum of squares of $X(t)$ deviation from experimental results,
- X_0 / ($kg_w/kg_{d.m.}$) is the initial moisture content (for $t = 0$, $X(0) = a$) of drying.

In practice, materials are dried until the allowable moisture content is reached, *i.e.*, until moisture is balanced/until moisture equilibrium. By infrared drying, total moisture from the material can be eliminated, in which case $X_{eq} = 0$.

– *b,d* are parameters dependent on the dryer geometry and drying conditions.

The obtained values of moisture content and drying rate enabled calculation of the diffusion coefficient by the expression:[12]

$$\frac{dX}{dt} = \frac{\pi^2 \cdot D \cdot (X - X_{eq})}{h^2} \quad (4)$$

where D is the diffusion coefficient expressed in $m^2\ min^{-1}$, and h is the characteristic dimension of samples in m.

RESULTS

Tables I-VI show the values of approximation model parameters *(b,d)* for carrot samples, where *r* and *s* denote the coefficient of correlation and standard deviation, respectively.

TABLE I. Approximation model parameters (*b*,*d*) for carrot samples dried in the dryer with an electric heater at 105 °C, blanched in 1 % solution of ascorbic acid[(a)]

	b	*d*	*r*	*s*
cubes 10 mm	0.007	1.161	0.977	0.087
cubes 5 mm	0.006	1.384	0.968	0.114
cylinders 1 × 27 mm	0.011	1.339	0.982	0.095
grated 1 mm	0.004	1.420	0.994	0.060

[(a)] *r*, coefficient of correlation; *s*, standard deviation.

TABLE II. Approximation model parameters (*b*,*d*) for carrot samples dried in the dryer with an electric heater at 105 °C, blanched in 0.5 % solution of sodium chloride[(a)]

	b	*d*	*r*	*s*
cubes 10 mm	0.008	1.076	0.984	0.075
cubes 5 mm	0.008	1.209	0.988	0.069
cylinders 1 × 27 mm	0.014	1.153	0.987	0.073
grated 1 mm	0.009	1.147	0.986	0.079

[(a)] *r*, coefficient of correlation; *s*, standard deviation.

TABLE III. Approximation model parameters (*b*,*d*) for carrot samples dried in the infrared dryer at 85 °C, blanched in 1 % solution of ascorbic acid[(a)]

	b	*d*	*r*	*s*
cubes 10 mm	0.002	1.425	0.996	0.014
cubes 5 mm	0.003	1.536	0.998	0.014
cylinders 1 × 27 mm	0.003	1.696	0.997	0.020
grated 1 mm	0.001	2.068	0.998	0.018

[(a)] *r*, coefficient of correlation; *s*, standard deviation.

TABLE IV. Approximation model parameters (*b*,*d*) for carrot samples dried in the infrared dryer at 85 °C, blanched in 0.5 % solution of sodium chloride[(a)]

	b	*d*	*r*	*s*
cubes 10 mm	0.002	1.414	0.996	0.023
cubes 5 mm	0.004	1.505	0.991	0.025
cylinders 1 × 27 mm	0.003	1.639	0.993	0.024
grated 1 mm	0.001	2.394	0.998	0.019

[(a)] *r*, coefficient of correlation; *s*, standard deviation.

TABLE V. Approximation model parameters (*b*,*d*) for carrot samples dried in the infrared dryer at 105 °C, blanched in 1 % solution of ascorbic acid[(a)]

	b	*d*	*r*	*s*
cubes 10 mm	0.002	1.544	0.996	0.015
cubes 5 mm	0.002	1.797	0.997	0.018
cylinders 1 × 27 mm	0.002	1.810	0.997	0.019
grated 1 mm	0.001	2.609	0.996	0.013

[(a)] *r*, coefficient of correlation; *s*, standard deviation.

TABLE VI. Approximation model parameters (*b*,*d*) for carrot samples dried in the infrared dryer at 105 °C, blanched in 0.5% solution of sodium chloride[(a)]

	b	*d*	*r*	*s*
cubes 10 mm	0.002	1.601	0.995	0.032
cubes 5 mm	0.003	1.708	0.986	0.056
cylinders 1 × 27 mm	0.001	1.969	0.996	0.037
grated 1 mm	0.001	2.675	0.999	0.022

[(a)] *r*, coefficient of correlation; *s*, standard deviation.

Results of the comparison of changes in diffusion coefficients with time for carrot samples drying with infrared irradiation at 85 °C and 105 °C are shown in Figures 1–4.

DISCUSSION

Blanched carrot samples were investigated during drying in order to determine the conditions for optimal control of water diffusion within the material and from its surface into air, with the aim of obtaining quality products.

While planning the experiments in the dryer with an electric heater and in the dryer with infrared irradiation, the features of these devices as well as sample areas were taken into consideration, and sample mass was adjusted accordingly.

The form of dried material, drying kinetics and diffusion-coefficient-defined moisture diffusion were analyzed. The diffusion coefficient was determined by Eq. (4).[12]

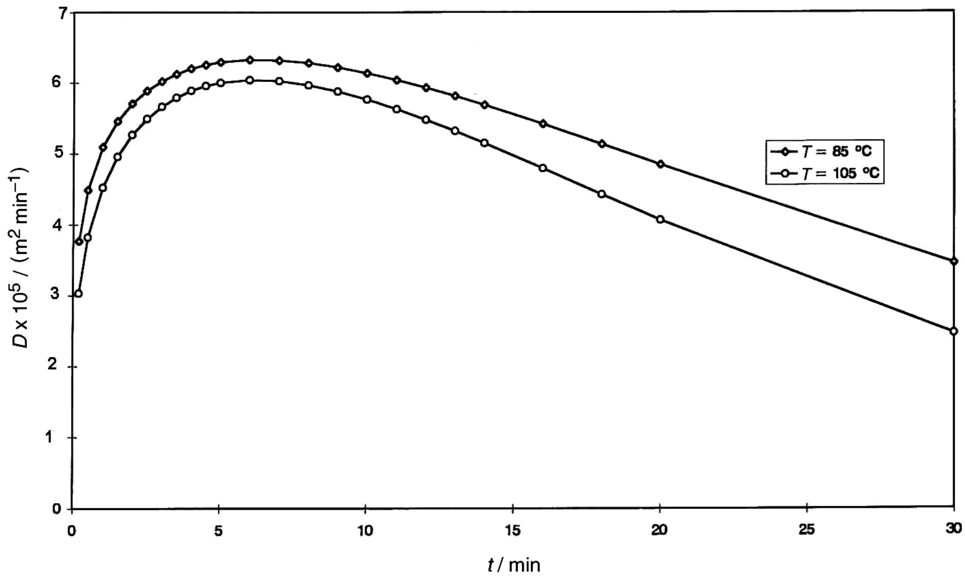

Figure 1. Dependence of the diffusion coefficient on drying time (cubes of carrot »Nantes«, 10 × 10 × 10 mm, blanched In ascorbic acid).

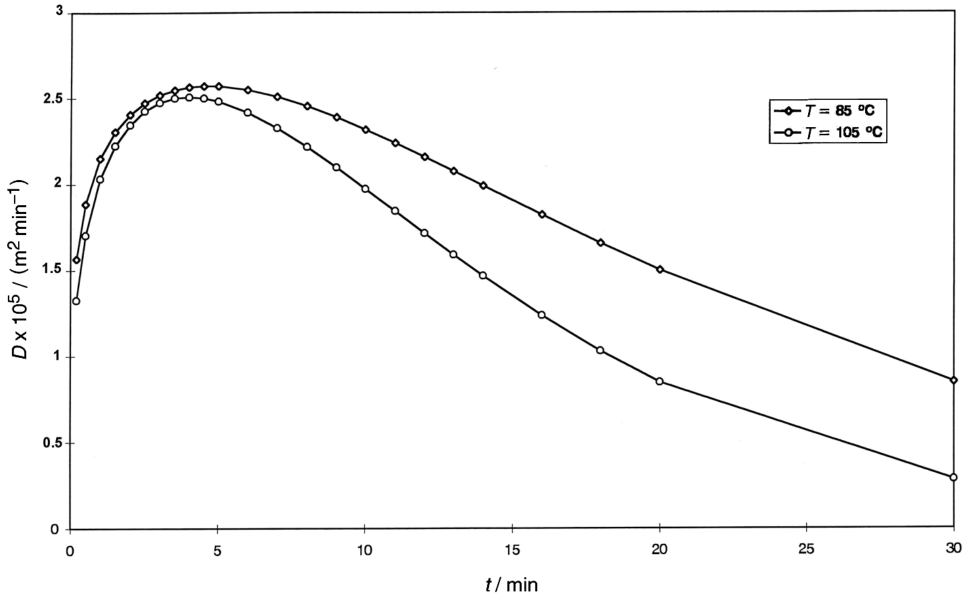

Figure 2. Dependence of the diffusion coefficient on drying time (cubes of carrot »Nantes«, 5 ×5 ×5 mm, blanched in ascorbic acid).

To find experimentally the drying rate of any material, the sample is placed into drying plates and the plates are placed into the dryer. Material surface is exposed to air flow or a drying agent. Customarily, as stated by A. S. Mujumdar,[13] moisture loss in the sample during drying may be determined at different time intervals, without interrupting the drying process. In this work, mass loss in the material being dried was measured at the mentioned intervals.

In the experiments carried out in the dryer with infrared irradiation (Mettler Lj16), the parameters of sample mass change were monitored directly.

Based on the experimental results, calculations were performed, and the sample moisture content, drying rate and diffusion coefficient were determined.

The mass fraction obtained from experimental data was correlated with the two-parameter exponential model expressed by Eq. (1).

Parameters b and d were determined on the basis of the highest values of correlation coefficients, with the requirement that the value of parameter d be greater than one. This provides very important information about the reliability of measurement results. Thus determined approximation function $X(t)$ was differentiated, yielding

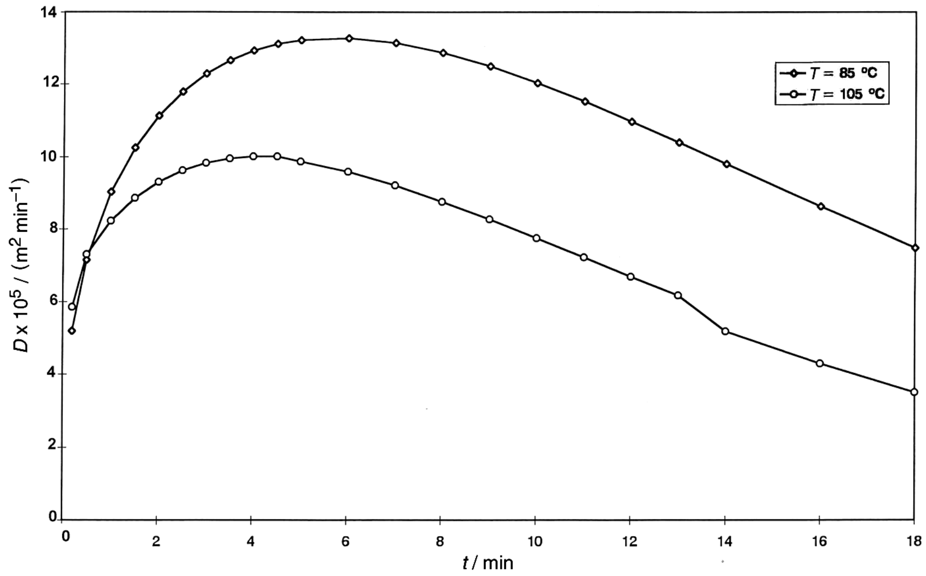

Figure 3. Dependence of the diffusion coefficient on drying time (cylinders of carrot »Nantes«, 1 mm, blanched in ascorbic acid).

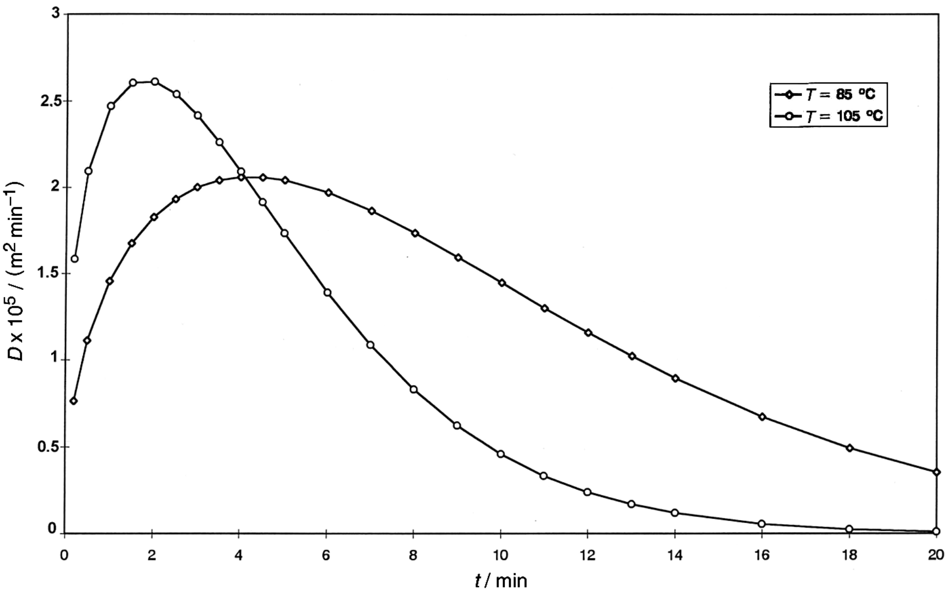

Figure 4. Dependence of the diffusion coefficient on drying time (grated carrot »Nantes«, blanched in ascorbic acid).

function d(X)/d(t), which provides an insight into the process rate changes under selected experimental conditions.

The said relations form the basis for the study of drying kinetics, related to the process conditions and geometry of the sample layer. All this provides important information about the influence of heat transfer and layer particle form on the rate of the moisture content change, on the process rate and points to the mechanism of moisture shift through the material layer. It also supplies information about relevant parameters for mass transfer and correlation model parameters.

The investigation results may be organized into two groups: those pertaining to drying in the dryer with an electric heater and those obtained from the experiments in the infrared irradiation dryer.

Each of these two groups may be further divided into two subgroups:

– The first group comprises measurement results and approximation relations of the moisture content and drying time, dependence of the drying rate on time, expressed as functional dependence of relevant parameters,

– The second group comprises parameters of the correlation model, by which experimental data have been described.

These groups of results are shown in figures and tables, with detailed descriptions enabling easy understanding.

Figures 1–4 illustrate the comparison of diffusion coefficients changes with time for equal carrot samples at 85 °C and 105 °C. The diffusion coefficient curve for all samples blanched in 1 % solution of ascorbic acid at 85 °C is above the 105 °C curve, except for grated samples, where the curves intercept at the beginning of sample heating.

Chemical analyses yielded the following results for the fresh sample: 0.25 % ash, 0.77 % cellulose and 433 mg kg^{-1} β-carotene. There were no major differences in chemical composition between materials dried in the dryer with an electric heater and those dried in the infrared irradiation dryer.[13–15]

Numerical processing of $X(t)$ relations, where regression analysis was used, yields data on the values of parameters *b* and *d.*

Changes in parameters *b* and *d* are shown in Tables I–VI and are illustrated in figures.

Parameter *b* is considerably higher for carrots dried in the dryer with an electric heater than in those dried in the infrared irradiation dryer, whereas the case of parameter *d* is opposite regardless of blanching.

The results make it clear that parameter *d* exhibits considerably smaller changes with respect to material shape, and that parameter *b* responds most strongly to the drying conditions. The found values and trends of coefficients *b* and *d* dependence on processing conditions may be expressed by the corresponding functions in which dominant positions are taken by heat transfer and layer geometry. Hence, this model becomes the basis for simulating the drying process under specified conditions, and consequently for designing large-scale processes.

Experimental data obtained by the exponential two-parameter model describe the entire drying process. They could not be expressed in the dryer with an electric heater due to large deviations and the method of measurement.

CONCLUSIONS

Experimental data, calculations and the discussion point to the following conclusions:

– Measurements conducted in the dryer with an electric heater were unreliable, which was confirmed by high standard deviations and failure to interpret the results with the two-parameter model;
– Best results were achieved with grated and cylinder-shaped blanched samples during drying in the dryer with infrared irradiation;
– Experimentally found relations between sample moisture content and drying time were successfully approximated by the exponential two-parameter model for the dryer with infrared irradiation;
– Diffusion coefficients for carrots blanched in 1 % aqueous solution of ascorbic acid ranged from 1×10^{-7} and 6×10^{-6} m^2 min^{-1} whereas for carrots blanched in 0.5 % aqueous solution of sodium chloride, they ranged from 1×10^{-8} to 1×10^{-5} m^2 min^{-1};
– The highest diffusion coefficient $D_L = 1 \times 10^{-5}$ m^2 min^{-1} was obtained when drying cube-shaped blanched carrots in the dryer with infrared irradiation.

LIST OF SYMBOLS

X / ($kg_w/kg_{d.m.}$)	moisture content
t / min	time
D_L / (m^2 min^{-1})	diffusion coefficient
b	coefficient of two-parameter model
d	coefficient of two-parameter model
r	coefficient of correlation
s	standard deviation

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SAŽETAK

Modeliranje konvekcijskog sušenja mrkve

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Istraživano je sušenje mrkve u laboratorijskoj sušnici s električnim grijanjem i u sušnici s infracrvenim zračenjem. Uzorci su prije sušenja blanširani u 1%-tnoj vodenoj otopini askorbinske kiseline i 0,5 %-tnoj vodenoj otopini natrijevog klorida. Na osnovu eksperimentalnih podataka izračunata je i prikazana ovisnost o vremenu masenog udjela vode u uzorku, brzine sušenja i koeficijenta difuzije. Navedene ovisnosti su aproksimirane dvoparametarskim eksponencijalnim modelom. Utvrđeno je da se navedena aproksimacija mogla koristiti samo za eksperimentalne rezultate dobivene u sušnici s infracrvenim zračenjem zahvaljujući odličnoj izvedbi mjernog uređaja za praćenje promjene mase uzorka. Na taj način dobiveni rezultati mjerenja i proračuna pokazuju visoki stupanj korelacije i ukazuju da je primjenljivost dvoparametarskog modela, kao što se i očekivalo, uvjetovana pristupom mjerenjima promjene mase uzorka. Za različite uvjete pokusa određen je koeficijent difuzije vlage, čija se vrijednost za mrkvu blanširanu u 1 %-tnoj vodenoj otopini askorbinske kiseline nalazi u granicama od 1×10^{-7} do 6×10^{-6} m^2 min^{-1}, a za mrkvu blanširanu u 0,5 %-tnoj vodenoj otopini natrijevog klorida u granicama od 1×10^{-8} do 1×10^{-5} m^2 min^{-1}.