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Some remarks on evaluation of drying models of red beet particles

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ABSTRACT

Drying behaviour of red beet particles was investigated in a laboratory type dryer, at constant air velocity 1 m/s and at constant temperature 60 °C. The effect of initial material load, particle shape and size on the dehydration characteristics of red beet was investigated. The drying experiments were conducted at three levels of initial material load of 5.33, 10.67 and 16 kg/m^2. The following particle shapes were investigated: slices, cubes, and prisms. Red beet roots were cut into 3, 6 and 9 mm slice thickness, 6, 9 and 12 mm cube thickness, and 3, 6 and 9 mm prisms thickness. Length of square based prisms equalled 50 mm. The results have shown that, the initial material load, particle shape and size influence on the drying behaviour of red beet particles. The experimental dehydration data of red beet particles obtained were fitted to the semi-theoretical, empirical and theoretical models. The accuracies of the models were measured using the correlation coefficient (R), mean bias error (MBE), root mean square error (RMSE), reduced chi-square (χ^2), and t-statistic method. All models except that used by Wang and Singh described the drying characteristics of red beet particles satisfactorily. The effect of the characteristic dimension of the particle and initial material load on the drying models parameters were also determined.

1. Introduction

Drying is one of the most common and the oldest ways of food preservation. The main objective in drying food products is the removal of water in the solids up to a certain level, at which microbial spoilage and deterioration chemical reactions are greatly minimized. Other important objectives of food dehydration are weight and volume reduction, intended to decrease transportation and storage costs. The wide variety of dehydrated foods, which today are available to the consumer and the interesting concern for meeting quality specifications and energy conservation, emphasize the need for detailed understanding of the drying process [1,2].

Recently, drying of vegetable is of a particular interest because it is added to various ready-to-eat meals in order to improve their nutritional quality due to health benefit compounds present in vegetables (vitamins, phytochemicals, dietary fibers) [3]. Usually, vegetables are dried convectively by using hot air as a medium for heating and removing evaporated water in this complex phenomenon of coupled heat and mass transfer [4].

The most important aspect of drying technology is the mathematical modelling of the drying processes and equipment. Its purpose is to allow design engineers to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to meet desired operating conditions. Full-scale experimentation for different products and systems configurations is namely sometimes costly and not possible [5]. The principle of modelling is based on having a set of mathematical equations that can adequately describe the system. The solution of these equations must allow prediction of the process parameters as a function of time at any point in the dryer based only on the initial conditions [6,7]. Therefore the use of a simulation model is a valuable tool for prediction of performance of drying systems [8].

Convection drying of biological products is a complex process that involves heat and mass transfer properties between the airflow and the product. Therefore mathematical modelling of the convection drying of these products is difficult. Mathematical modelling of the process of convection drying of vegetables, fruits and grass is especially difficult because of high initial moisture content (80–95% w.b.) and occurrence of shrinkage during drying.

Three methods of theoretical mathematical modelling of vegetables drying can be found in the literature. Authors describe the whole process using model of the second drying period (e.g. [9,10]), model the initial stage of vegetables drying only with model of the first drying period (e.g. [11,12]) or describe the whole process using model of the first drying period followed by the model of second drying period (e.g. [13,14]).

Recently, dynamic modelling of the drying characteristics of agricultural products, using artificial intelligence methods including genetic algorithms and neural network has been proposed by some authors [15,16]. To investigate the variability in the dehydration of

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Nomenclature

a, b, c, g, h, N_1, n	constants of models
D	moisture diffusion coefficient (m^2/min)
Fo_m	Fourier number for moisture transfer
k, k_0, k_1	drying rate constants (1/min)
L	characteristic particle dimension (m)
l	prism half length (m)
M	moisture content (dry basis)
M_c	critical moisture content (dry basis)
M_e	equilibrium moisture content (dry basis)
M_0	initial moisture content (dry basis)
M_t	moisture content at t (dry basis)
MBE	mean bias error
MR	dimensionless moisture content, moisture ratio
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
m	initial material load (kg/m^2)
m, n, p	number of terms in the series
N	number of observations
n	number of constants
R	correlation coefficient
R^2	coefficient of determination
RMSE	root mean square error
s	particle half thickness (m)
t	time (min)
t_c	time of drying while moisture content $M = M_c$ (min)
t-stat	t-statistic method
X, Y	variables (Eqs. (19)–(22))
χ^2	reduced chi-square

vegetables, Cronin and Kearney [17] constructed the numerical Monte Carlo model of a tray dryer.

In practical drying there is a need for simple models verified by experimental data that will provide optimum solutions for the operating process without undertaking experimental trials on the actual system. These models mainly fall into two categories namely, semi-theoretical and empirical. They require small time compared to theoretical models and do not need assumptions of geometry of a typical food, its mass diffusivity and conductivity [18,19]. The semi-theoretical models are generally derived directly from the general solution of Fick's second law by simplification. The empirical models derive a direct relationship between average moisture content and drying time. They neglect the fundamentals of the drying process and their parameters have no physical meaning. Therefore, they cannot give a clear accurate view of the important process occurring during drying although they may describe the drying curve for the conditions of the experiment [20,21]. The semi-theoretical and empirical models widely employed to describe the convection drying kinetics of vegetables are shown in Table 1.

Red beet (*Beta vulgaris esculenta cruenta*) is one of the important root vegetable crops and is highly nutritious as it contains appreciable amount of sucrose (9.5%), protein (1.8%) and fat (0.1%). It also contains many important minerals namely calcium, magnesium, potassium and sodium [37–39]. These properties make that red beets are of market interest in preparation of dry mixtures used for soups, etc. Moreover, dehydrated and red beet juice concentrates are applicable as water-soluble, natural-source red pigments in many food systems [40]. Red beet is one of the major sources of betanines. They are the pigments responsible of its red colour, and an important feature for the use of betanines relies on its antioxidant capacity, which can be associated with health benefits. Betanines are used as natural colorants to enhance the redness of different products such as dairy products, ice creams, jams, tomato paste, beverages and desserts [41,42].

Red beet dehydration has not been investigated to great extent and a few data are available in literature. Saguy et al. [40] dried the slices of red beet roots with air at temperature of 67, 73, 88, and 93 °C with constant air velocity of 0.76 m/s. Thickness of the beet slices used for the drying experiments was 4.8 mm. The purpose of this investigation was to develop a mathematical/kinetic model for predicting the losses of the main red beet pigments (betanine and vulgaxanthin-I) during air-drying. A mathematical model describing the drying behaviour of beet slices was based on application of Fick's law. The mathematical model and the data generated from the kinetic studies of temperature- and moisture-sensitive red beet pigments were combined in a computer program to simulate and predict beet pigment retention, as a function of the process variables. Predicted and actual experimental pigment retention agreed well. It turned out also from the experiments that the higher the drying air temperature the shorter was the drying time of red beet slices. Shynkaryk et al. [43] investigated the effect of the pulsed electric field (PEF) pretreatment on convective drying of red beet root tissue. The degree of material damage under the PEF and thermal treatment was studied. The drying experiments

Table 1
Semi-theoretical and empirical models applied to drying curves.

Model no.	Model equation	Model name	References
1	$MR = \exp(-kt)$	Lewis (Newton)	[22]
2	$MR = \exp(-kt^n)$	Page	[23]
3	$MR = \exp[-(kt)^n]$	Modified Page	[24]
4	$MR = a\exp(-kt)$	Henderson and Pabis	[25]
5	$MR = a\exp(-kt) + b$	Logarithmic	[26]
6	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	Two-term	[27]
7	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Two-term expotential	[28]
8	$MR = 1 + at + bt^2$	Wang and Singh	[29]
9	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Diffusion approximation	[30]
10	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Verna et al.	[31]
11	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Modified Henderson and Pabis	[32]
12	$MR = a\exp[-b(t/L^2)]$	Simplified Fick's diffusion (SFFD) equation	[33]
13	$MR = \exp[-b(t/L^2)^n]$	Modified Page II	[34]
14	$MR = a\exp(-kt^n) + bt$	Midilli et al.	[35]
15	$MR = a\exp(-k_1t) + b\exp(-k_2t) + c$	Noomhorn and Verma	[36]