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Influence of Boundary Conditions on Particle Density

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Abstract: The objective of this paper is an analysis of the influence of drying air temperature and the drying air velocity on the particle density. The particle density of apple, banana, potato and carrot slices during convective drying was experimentally determined. Drying experiments were conducted in a laboratory air-dryer, repeated at different air temperatures and air velocities. The drying air temperatures considered were 40, 50, 60 and 70 °C with drying air velocities of 1, 2 and 3 m/s. Two simple mathematical models for correlating the dimensionless particle density with the dimensionless material moisture content, drying air temperature and drying air velocity are proposed. The models were fitted to experimental data and the correlation coefficients and residual sum of squares were estimated.

Key words: Particle density, air temperature, air velocity, drying, apple, banana, potato, carrot.

Nomenclature

A, B, C	- parameter
MRD	- mean relative deviation
m (kg)	- mass
n	- degrees of freedom
R	- dimensionless particle density
RSS	- residual sum of squares
r	- correlation coefficient
V (m^3)	- volume
SE	- standard error of the estimate
X	- dimensionless moisture content
x (kg/kg d.b.)	- moisture content
Y_{cal}	- estimated value
Y_{exp}	- experimental value

Greek symbols

ρ (kg/m^3)	- density

Subscripts

0	- initial
a	- air
ap	- apple
ba	- banana
ca	- carrot
p	- particle
po	- potato
s	- solid
s0	- initial solid
t	- total
w	- water

1. Introduction

Drying is essential process for the preservation of agricultural and other products, including fruits and vegetables. The major objective in drying of fruits and vegetables is the reduction of moisture content to a certain level, which allows safe storage and preservation. The present demand of high-quality products in the food market requires dehydrated foods that maintain at a very high level the nutritional and sensorial properties of the initial fresh product [1].

The quality of the dried fruits and vegetables is characterized by the appearance, color, texture, shape, sizes, density, shrinkage and porosity. This quality factors are the factors that determine the worth or value of a food product to the consumer.

The most important physical properties that characterise the quality of dried and intermediate moisture foods, are porosity, bulk density and particle density [2]. Experimental values of density are necessary for designing the facility of storage,

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handling and processing of agricultural materials.

The density can be defined in different ways [3, 4]: true density, substance density, apparent density, bulk density and particle density. Bulk and particle densities are vital parameters in the design, modeling and optimization of food processing operations because they have a direct affect on the thermophysical properties of food materials [3].

The effect of material moisture content and temperature on true density of foods was studied by Boukouvalas [5]. While variation of bulk and particle density of potato starch gel with dimensionless moisture content at various air temperature was studied by Muhtaseb [6].

The aim of this paper is to investigate the influence of boundary conditions on particle density of some fruits and vegetables during convective drying. Some simple mathematical models for correlating the dimensionless particle density with the dimensionless moisture content drying air temperature and drying air velocity are proposed.

2. Materials and Methods

Fresh apples, bananas, potatoes and carrots were used in this study. To prepare samples, apples, bananas, potatoes and carrots were sliced using electric slicing machine to give a uniform sample thickness of 3 mm before being reduced to a cylinder form with diameter of 40 ± 0.1 mm. Several measurements were made using a calliper and only samples with a tolerance of ± 5% were used.

The study of influence on boundary conditions of particle density for apple, banana, potato and carrot slices was conducted in a laboratory air-dryer (Fig. 1). The slices were in contact with drying air from top and bottom surfaces. In each experiment, the shelf holding three apple, banana, potato or carrot slices was inserted into the rectangular experimental channel with dimensions 25 × 200 × 2,000 mm. The slices were dried until the equilibrium moisture content was reached. The samples of apples, bananas,

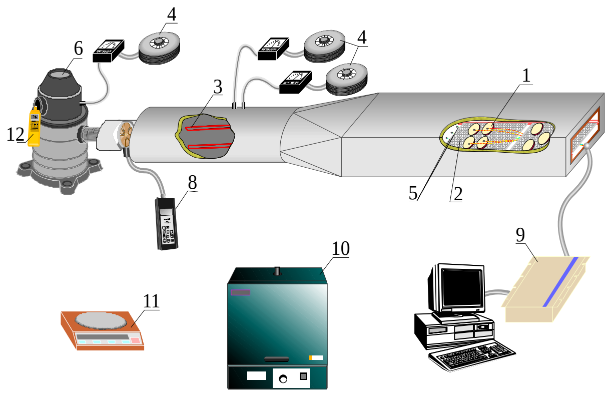

Fig. 1 Experimental apparatus; 1-material, 2-shelf, 3-electrical heaters, 4-transformers, 5-thermocouples, 6-centrifugal fan, 7-anemometer, 8-panel meter, 9-data acquisition system, 10-stove, 11-balance, 12-hygrometer.

potatoes or carrots were drawn from the dryer every 10 min and their weights and sample volumes were measured.

The initial moisture content and the initial slices' dimensions were measured as well. The experiment was repeated at different air temperatures and velocities. During the experiments, air temperature and drying air velocity were controlled. The drying air temperatures considered were 40, 50, 60 and 70 °C with drying air velocities of 1, 2 and 3 m/s.

3. Mathematical Models

In reference literature various simple mathematical models were used to relate the densities to material moisture content and drying air temperature [5, 6].

Assuming the moist material of dry solids, water and air, in literature, the following definitions are used.

True density is a density of a pure substance or a material calculated from its component's densities considering conservation of mass and volume:

$$\rho_p = \frac{m_t}{V_p} \tag{1}$$

where m_t is total mass, while $V_p = V_s + V_w$ is the true volume, which is the total volume of the sample, excluding air pores.

The enclosed water density ρ_w can be defined as:

$$\rho_w = \frac{m_w}{V_w} \tag{2}$$

where m_w is mass of water, while V_w, is volume of water.

The particle density of dry solids ρ_s is defined as:

$$\rho_s = \frac{m_s}{V_s} \quad (3)$$

where m_s is the mass of dry solids, while V_s, is volume of dry solids.

Reference literature offers four methods for determination of sample's volume (volume of dry solid):

- Direct measurement method [7, 8],
- Method of immersing the samples in n-heptanes [2, 7],
- Image analysis [8],
- Method of immersing the samples in distilled water [9].

The comparison between these methods indicates that the differences among maximum errors are less than 10% [7, 8]. Therefore, it is the method of direct measurement with caliper that was used to determine the volume of the sample.

In this paper, simple mathematical models were used to determine the dimensionless particle density:

$$R = \frac{\rho_{s0}}{\rho_s} \quad (4)$$

as a function of dimensionless material moisture content (Table 1):

$$X = \frac{x_0 - x}{x_0} \quad (5)$$

and drying air temperature and drying air velocity.

4. Results and Discussions

On the basis of experimental data for each material (apple, banana, potato and carrot) and each model from Table 1, the values of parameters A, B and C, correlation coefficient (*r*) and residual sum of squares (RSS) were determined. The following seven methods were used: Quasi-Newton, Simplex, Composition Simplex and Quasi-Newton, Hooke-Jeeves Pattern Moves, Composition Hooke-Jeeves Pattern Moves and Quasi-Newton, Rosenbrock Pattern Search and Composition Rosenbrock Pattern Search and Quasi-Newton. When the results for correlation coefficient *r* were different, the highest value was accepted as relevant. The calculations were made with software package Statistica [10]. The values of parameters A, B and C are given in Table 2.

Table 1 Mathematical models.

Model	Type	ρ_{s0}/ρ_s =
1	Logarithm	1-LOG[1+(A+B*V+C*T)*X]
2	Linear	(A+B*V+C*T)*X + 1

The adequacy of the fitted models can be evaluated by means of coefficient of correlation (*r*), residual sum of squares (RSS), standard error of estimate (SE), mean relative deviation (MRD), and the plot of residual.

Correlation coefficient (*r*) is a dimensionless index that ranges from 0 to 1 and reflects the extent of linear relationship between two data sets.

The residual sum of squares (RSS) is defined as:

$$RSS = \sum_{i=1}^{n} (Y_{exp} - Y_{cal})^2 \quad (6)$$

where Y_{exp} is the experimental-measured value, Y_{cal} is the value estimated through the fitting equation and n is the number of data points.

The standard error of estimate (SE) is the conditional standard deviation of the dependant variable and represents a measure of the predictions accuracy. The standard error of estimate for large data set is defined with Eq. (7):

Table 2 Values of parameters A, B and C.

Material	Model 1			Model 2		
	A	B	C	A	B	C
Apple	1.395036	- 0.085965	- 0.003821	- 0.935973	0.038427	0.002242
Banana	1.00891	- 0.009713	0.001301	- 0.780456	0.002820	0.000119
Potato	0.75377	- 0.112464	0.007534	- 0.575416	0.057700	- 0.004257
Carrot	1.41398	- 0.61549	- 0.000009	- 0.958091	0.030884	0.000488

$$SE = \sqrt{\frac{RSS}{n}} \quad (7)$$

The mean relative deviation (MRD) is an absolute value because it gives mean divergence of the estimated data from the measured data.

$$MRD = \frac{1}{n}\sum_{i-1}^{n}\frac{\left|Y_{exp} - Y_{cal}\right|}{Y_{exp}} \quad (8)$$

Plotting of the residuals against the independent variable is also used as a measure of errors distribution. If the model is correct, then the residual should be only random independent error with a zero mean, constant variance and arranged in a normal distribution. If the residual plots indicate a clear pattern, the model should not be accepted.

In general, low values of correlation coefficient, high values of RSS, SE and MRD, and clear patterns in the residual plots mean that the model is not able to explain the variation in the experimental data. It is also evident that a single statistical parameter cannot be used to select the best model that must always be assessed based on multiple criteria [11].

The values of correlation coefficients (*r*) for apple, banana, potato and carrot are given in Table 3.

From Table 3, it is obvious that the linear model gives better results compared to the logarithm model.

In Figs. 2-5, the influence of drying air temperature T on the dimensionless particle density for apple, banana, potato, and carrot is shown.

Table 3 Values of correlation coefficients and residual sum of squares.

Model	r_{ap}	r_{ba}	r_{po}	r_{ca}	RSS_{ap}	RSS_{ba}	RSS_{po}	RSS_{ca}
1	0.97086	0.95933	0.96888	0.96900	0.14728	0.58100	0.23785	0.42046
2	0.98472	0.97434	0.97212	0.98599	0.27895	0.91363	0.26508	0.92269

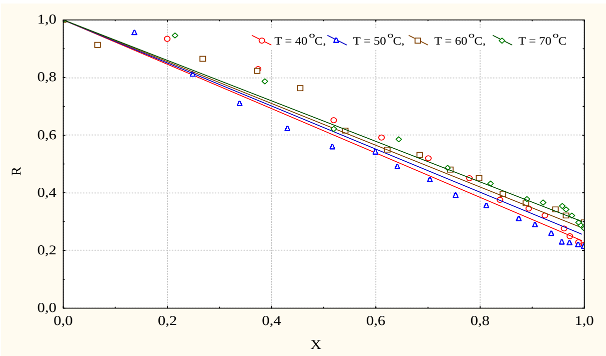

Fig. 2 Variation of dimensionless particle density of apple with dimensionless moisture content at various air temperature and v = 2 m/s.

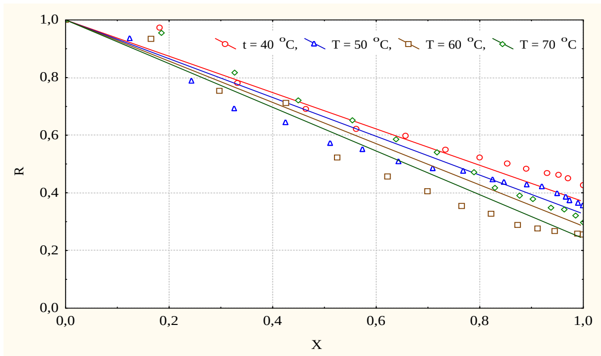

Fig. 4 Variation of dimensionless particle density of potato with dimensionless moisture content at various air temperature and v = 2 m/s.

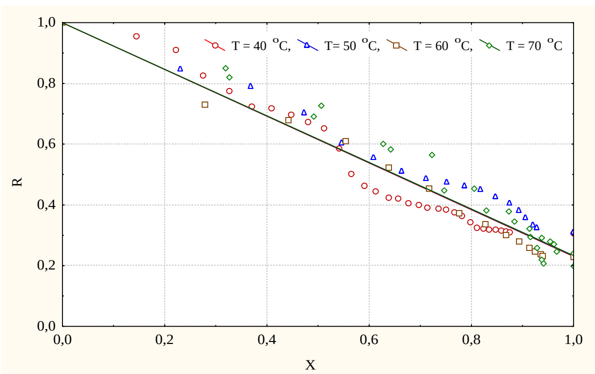

Fig. 3 Variation of dimensionless particle density of banana with dimensionless moisture content at various air temperature and v = 2 m/s.

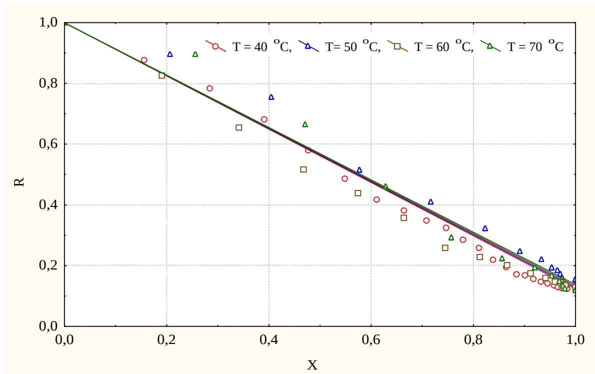

Fig. 5 Variation of dimensionless particle density of carrot with dimensionless moisture content at various air temperature and v = 2 m/s.

Air temperature has different effect on particle density. For apple, the influence of particle density at a low temperature (40 °C) is greater than at high temperature (70 °C), while for potato, air temperature has an opposite effect on particle density. From Fig. 3 to Fig. 5, it is clear that the variation of temperature has no influence on a particle density of banana and carrot.

In Figs. 6-9, the influence of drying air velocity on the dimensionless particle density for apple, banana, potato, carrot is presented.

Air velocity, on the other hand, has the biggest impact on particle density. It can be seen that high value of air velocity has small effect on dimensionless particle density, apart from banana, where variation of air velocity has a negligible effect. That can be explained with the process of caramelization. The influence of air velocity on particle density can be

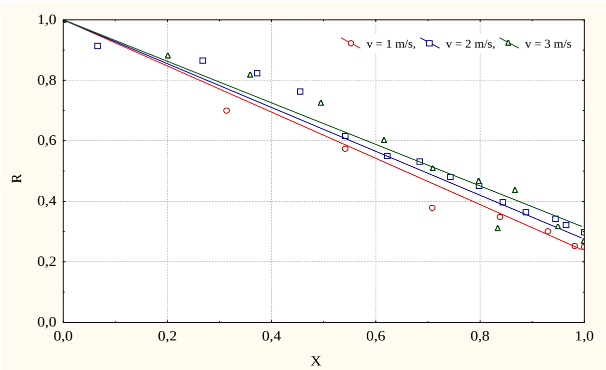

Fig. 6 Variation of dimensionless particle density of apple with dimensionless moisture content at various air velocity and T = 60 °C.

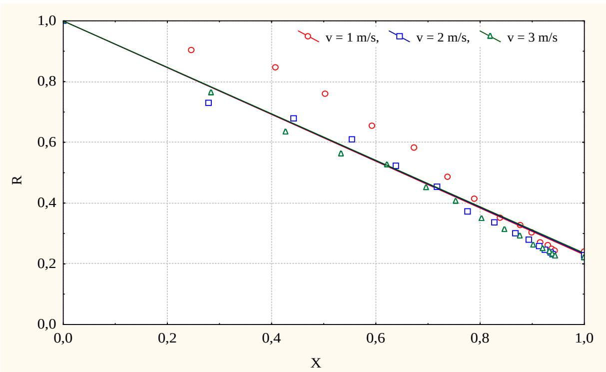

Fig. 7 Variation of dimensionless particle density of banana with dimensionless moisture content at various air velocity and T = 60 °C.

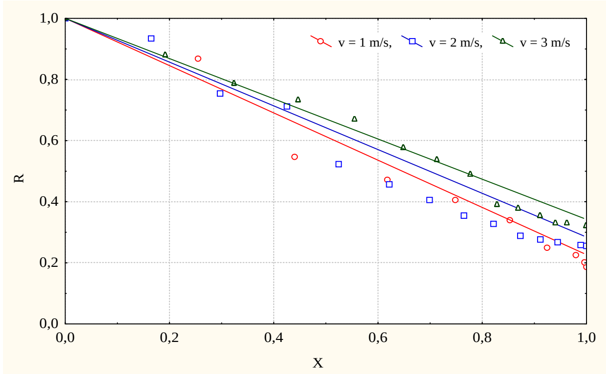

Fig. 8 Variation of dimensionless particle density of potato with dimensionless moisture content at various air velocity and T = 60 °C.

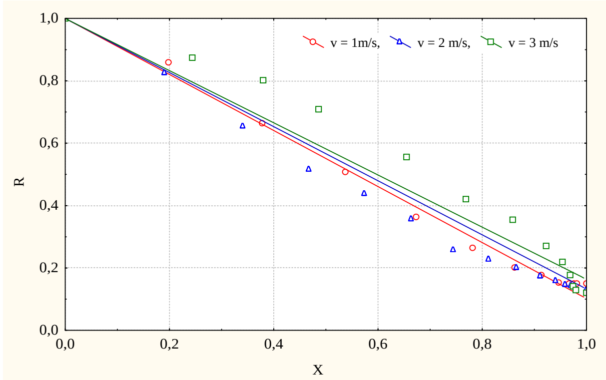

Fig. 9 Variation of dimensionless particle density of carrot with dimensionless moisture content at various air velocity and T = 60 °C.

explained on the basis of effect of variables on the mass transfer. At low air velocities, surface resistance prevails, moisture profiles in the sample are relatively flat and internal stresses are at minimum [12]. If air velocities are very high, drying makes the surface of the samples stiff, limiting the particle density even in the earliest stages. At low air velocities the surface of dry sample does not stiffen until the water content reaches very low values.

5. Conclusions

The influence of drying air temperature and drying air velocity on the particle density of apple, banana, potato and carrot slices during convective drying was studied in this particle. For this purpose, some experiments were conducted in a laboratory air-dryer. Two simple mathematical models for correlating the dimensionless particle density with the dimensionless material moisture content, drying air temperature and drying air velocity are proposed. Air temperature has different effect on particle density. For apple, the influence of particle density at low temperature is greater than at high temperature, while for potato, air temperature has an opposite effect. It was concluded that the variation of temperature has no influence on a particle density of banana and carrot. Air velocity has the biggest effect on particle density. High values of air velocity have small effect on dimensionless particle density, for apple, potato and carrot, while for banana, the variation of air velocity has a negligible effect.

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