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Drying kinetics of some vegetables

M.K. Krokida [a,*], V.T. Karathanos [b], Z.B. Maroulis [a], D. Marinos-Kouris [a]

[a] *Laboratory of Process and Analysis Design, Department of Chemical Engineering, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece*

[b] *Department of Agricultural Machinery, Technological Educational Institute of Larissa, 41110 Larissa, Greece*

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Abstract

The effect of air conditions (air temperature, air humidity and air velocity) and characteristic sample size on drying kinetics of various plant materials (potato, carrot, pepper, garlic, mushroom, onion, leek, pea, corn, celery, pumpkin, tomato) was examined during air drying. A first-order reaction kinetics model was used, in which the drying constant is function of the process variables, while the equilibrium moisture content of dried products within the range of 0.10–0.90 water activity at two temperatures (30 and 70 °C) was fitted to GAB equation. The parameters of the model considered were found to be greatly affected by the air conditions and sample size during drying. In particular the temperature increment increases the drying constant and decreases the equilibrium moisture content of the dehydrated products.

Keywords: Vegetables; Air drying; Air temperature; Air humidity; Air velocity; Sample size

1. Introduction

Dehydration operations are important steps in the chemical and food processing industries. The basic 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. The wide variety of dehydrated foods, which today are available to the consumer (snacks, dry mixes and soups, dried fruits, etc.) and the interesting concern for meeting quality specifications and energy conservation, emphasize the need for a thorough understanding of the drying process.

Conventional air-drying is the most frequently used dehydration operation in food and chemical industry. In this case, the drying kinetics is greatly affected by air temperature and material characteristic dimension, while all other process factors exert practically negligible influence (Kiranoudis, Maroulis, Tsami, & Mavinos-Kouvis, 1997). Dried products are characterized by low porosity and high apparent density (Krokida & Maroulis, 1997). Significant color changes occur during air drying (Krokida, Tsami, & Maroulis, 1998), and most frequently the dried product has low sorption capacity (Maroulis, Tsami, & Marinos-Kouris, 1988).

Literature data for drying kinetics in foods materials were selected and presented in Marinos-Kouris and Maroulis (1995). Drying constant depends strongly on air conditions and size of the material.

The drying constant depends on both material and drying air properties as it is the phenomenological property representative of several transport phenomena. The effect of air temperature, relative humidity, air velocity and material size on drying constant has been studied extensively (Karathanos & Belessiotis, 1997; Mulet, Berna, & Rossello, 1989; Lee, Voung, Schiffman, & Coggins, 1983).

The objective of this work is to investigate the drying kinetics of some vegetables. These vegetables are of particular interest in preparation of dry mixtures used for soups, etc. More specifically the aim of this work was to study the effect of some drying parameters on the progress of the drying process. The range of the studied parameters was that of usage in actual industrial air drying applications. The air temperature was 65–85 °C, the relative humidity 20–40% and the air velocity varied from about 1.5–2.5 m/s.

* Corresponding author. Fax: +30-10-7723155.
E-mail addresses: mkrok@chemeng.ntua.gr (M.K. Krokida), vkarath@tee.gr (V.T. Karathanos).

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Nomenclature

Aw	Water activity, dimensionless ($0 < \mathrm{Aw} < 1$)
b_1, b_2, b_3	dimensionless empirical constants in GAB equation (Eq. (4))
db	dry basis (kg water/kg dry solids)
d_p	particle diameter (m)
k_1, k_2, k_3, k_4	dimensionless constants (Eq. (3))
k_0	constant in Eq. (3) (h^{-1} or min^{-1})
k_r	drying rate (min^{-1})
N	number of experimental points
Rh	relative humidity of the air (%)
RR	drying ratio
S	standard deviation
T	temperature (°C)
t	time (min)
V	air velocity of drying air (m/s)
X	material moisture content in dry basis (db) (kg water/kg dry solids)
X_e	equilibrium moisture content of dehydrated material (kg/kg db)
X_i	initial moisture content of material (kg water/kg dry solids)

Subscripts

i	ith experimental observation
exp	experimental
cal	calculated

2. Mathematical modelling

A first order kinetic model describing the moisture transfer during drying is considered:

$$-\mathrm{d}X/\mathrm{d}t = k(X - X_e) \tag{1}$$

where, X is the material moisture content (dry basis) during drying (kg water/kg dry solids), X_e, is the equi-

Table 1
Mathematical model

Model: $X = X_e - (X_i - X_e)e^{-krt}$; $k = k_0 d_p^{k1} T^{k2} V^{k3} \mathrm{Rh}^{k4}$; $Xe = b_1^* \exp(b_2/T)^* (a_w/(1-a_w)^{b3})$

	Parameters					
	K_0	K_1	K_2	K_3	K_4	X_i
Panel A						
Celery	1.57	1.33	−0.20	−0.10	0.00	4.81
Leek	2.66	4.15	−0.55	0.25	−1.38	14.65
Spinach	2.54	4.77	−1.35	0.09	0.00	8.47
Onion	1.30	2.68	−0.63	0.2	−1.01	10.92
Garlic	1.55	2.80	−0.9	0.01	0.00	2.37
Mushroom	2.70	2.1	−0.52	0.38	−1.53	10.63
Tomato	0.82	3.15	−0.49	0.48	0.00	21.1
Corn	1.49	4.04	−0.99	−0.11	0.00	1.30
Carrot	1.7	4.06	−1.41	−0.07	−0.94	7.67
Green pea	1.31	5.56	−0.75	0.42	0.00	2.06
Pumpkin	1.77	4.90	−0.21	0.45	0.00	14.9
Yellow pepper	1.05	4.55	−0.25	0.18	0.00	10.12
Red pepper	1.05	2.17	−0.13	0.30	0.00	9.36
Green pepper	1.45	1.25	−0.20	0.1	0.00	16.47
	b_1	b_2	b_3			
Panel B						
Corn	0.0004	1840.000	0.5372			
Red pepper	0.0004	1839.997	1.0646			
Yellow pepper	3E-06	3647.025	0.7647			
Pumpkin	5E-07	3796.777	1.2848			
Garlic	3E-05	2596.817	0.9307			
Tomato	2E-06	3796.953	0.7665			
Green pea	2E-07	3796.777	1.2848			
Mushroom	3E-07	3796.777	1.2848			
Onion	3E-07	3796.777	1.2848			
Celery	IE-06	3796.777	1.2629			
Green pepper	IE-06	3796.777	1.2629			

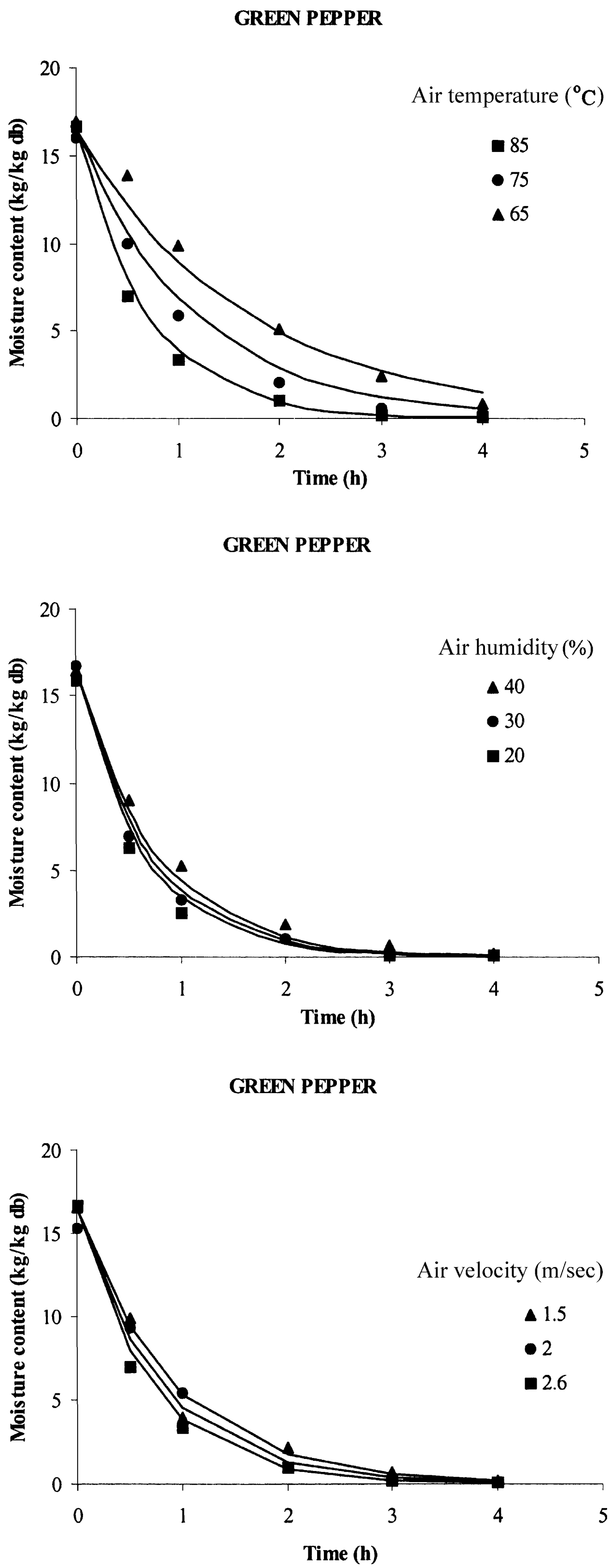

Fig. 1. Drying kinetics of green pepper.

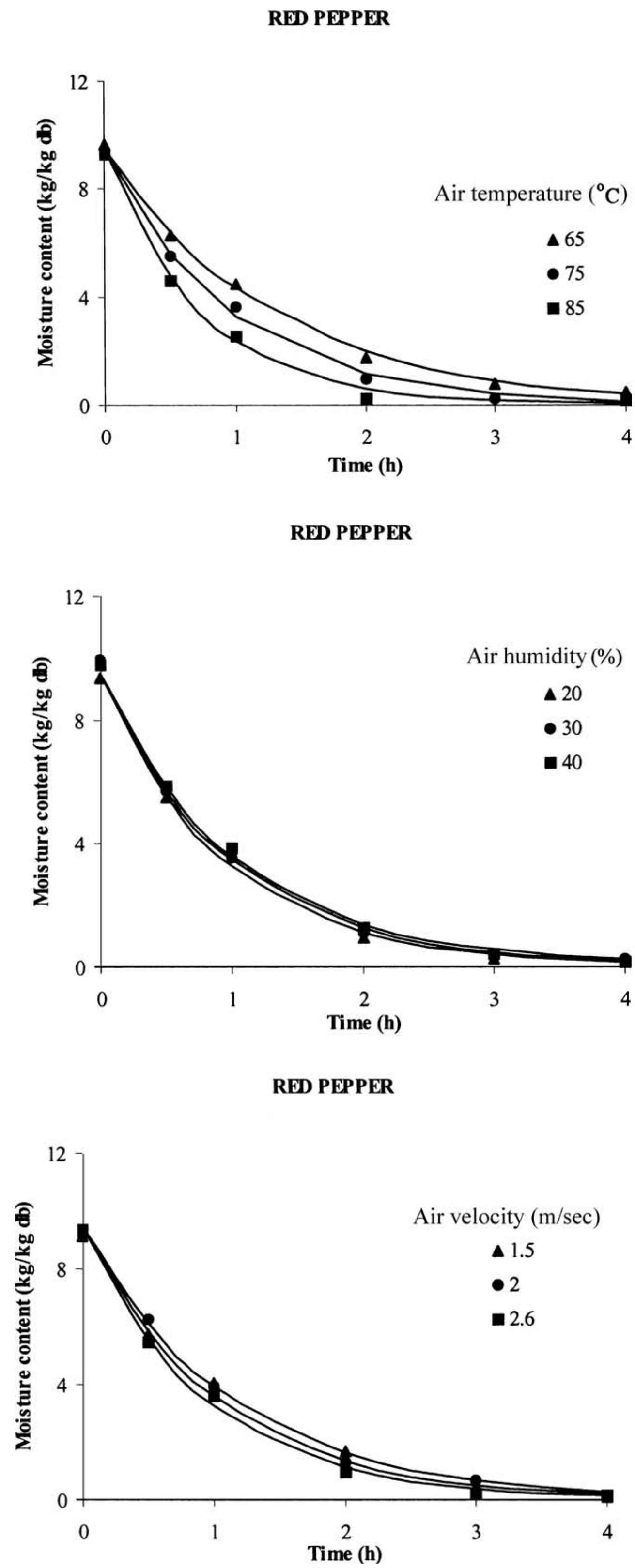

Fig. 2. Drying kinetics of red pepper.

librium moisture content of dehydrated material (kg water/kg dry solids), k is the drying rate (min^{-1}), and t is the time of drying (min). The drying rate is determined as the slope of the falling rate-drying curve.

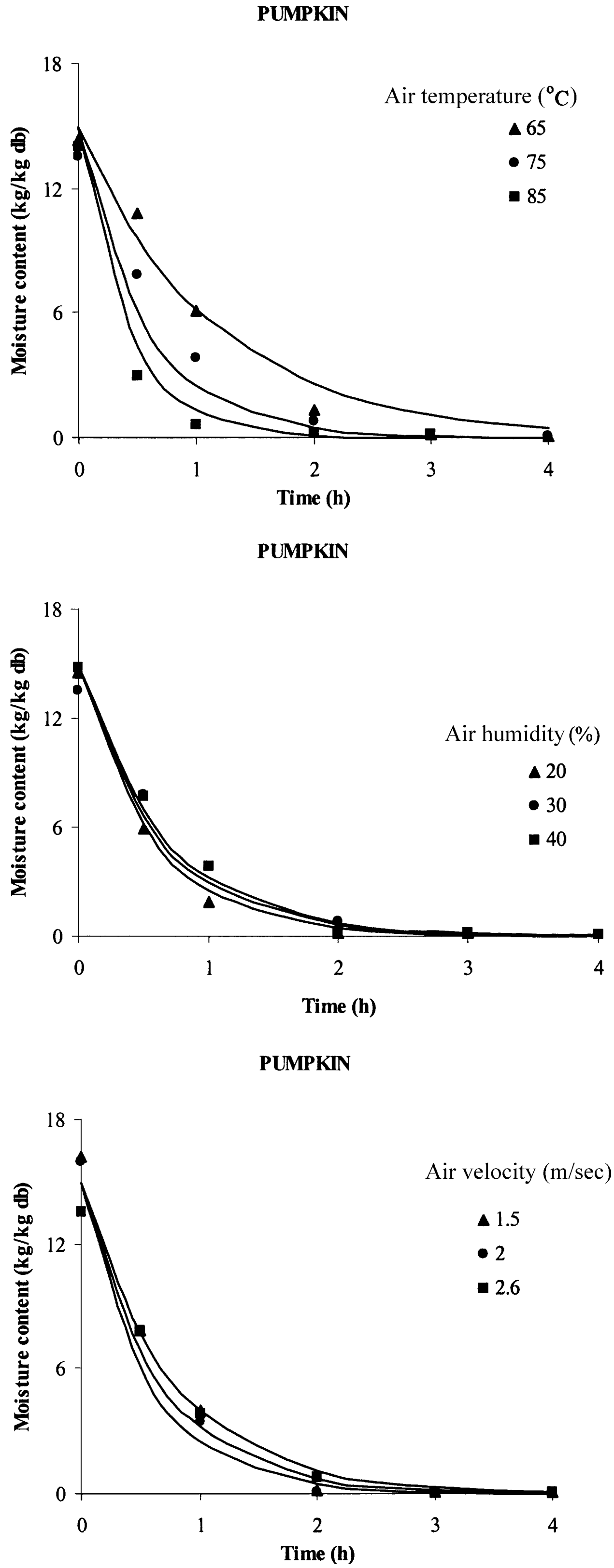

Fig. 3. Drying kinetics of pumpkin at various drying conditions.

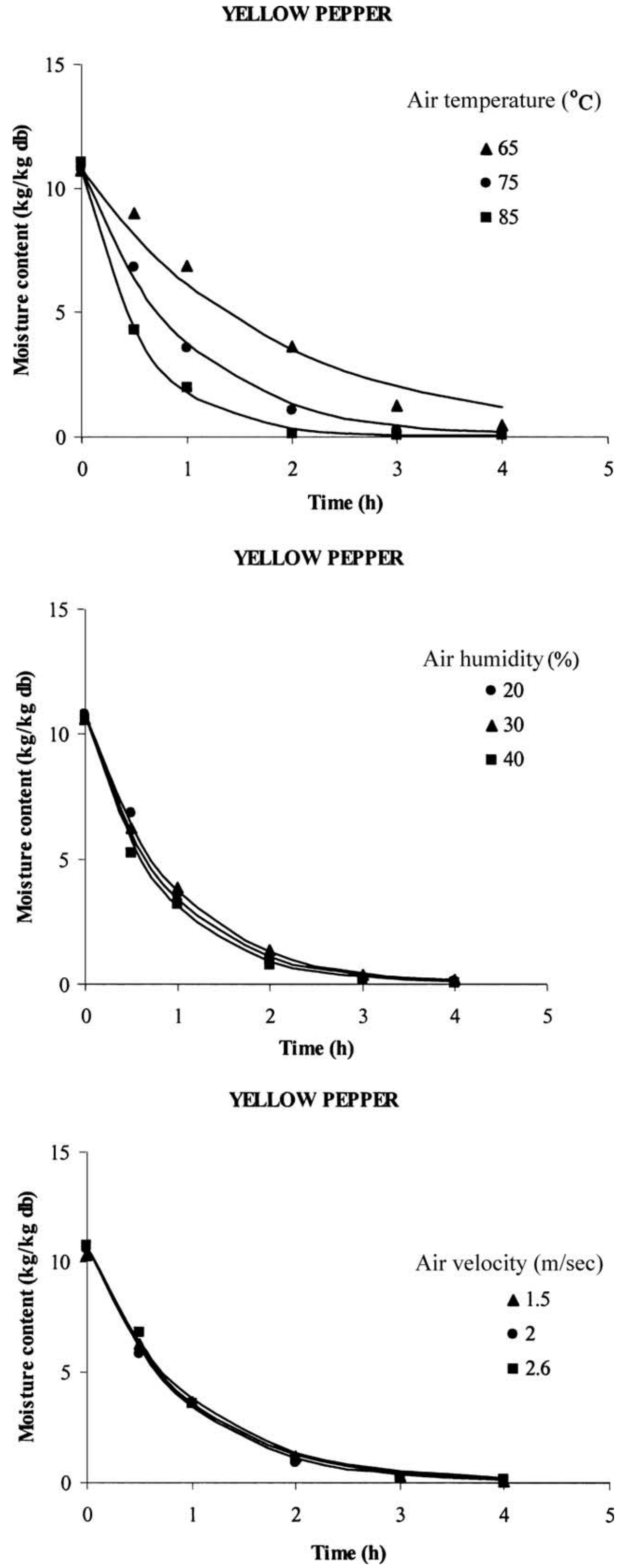

Fig. 4. Drying kinetics of yellow pepper.

At zero time, the moisture content (dry basis) of the dry material X (kg water/kg dry solids) is equal to X_i, and Eq. (1) is integrated to give the following expression:

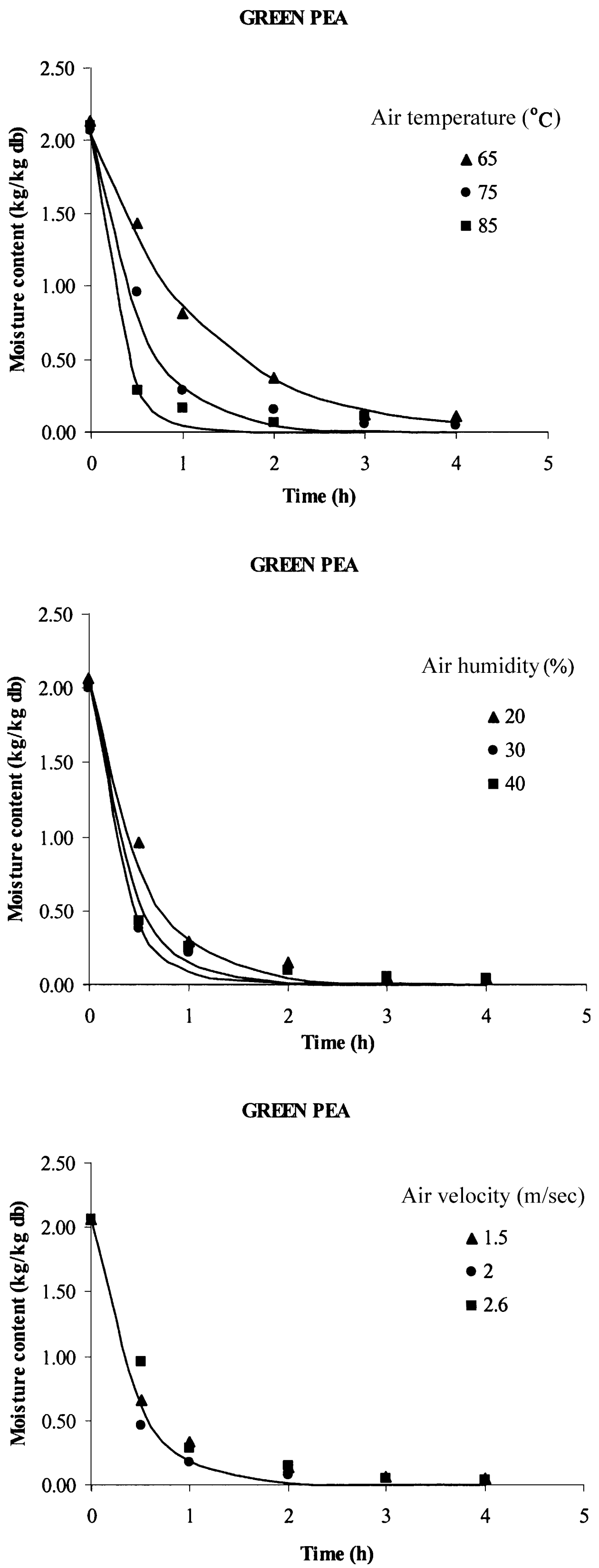

Fig. 5. Drying kinetics of green pea.

$$X = X_e - (X_e - X_i)e^{-kt} \tag{2}$$

The effect of process variables during drying can be embodied in the model parameters. Simple power-low equations can be used:

$$k = k_0 d_p^{k_1} T^{k_2} V^{k_3} \mathrm{Rh}^{k_4} \tag{3}$$

where, k_0, constant (h^{-1} or min^{-1}), k_1, k_2, k_3, k_4 are dimensionless constants (–), T is the dry bulb temperature of air (°C), V is the air velocity (m/s), Rh is the relative humidity of the air (%) and d_p particle diameter (m).

The equilibrium moisture content of foods (X_e) can be described by several mathematical models with two or more parameters (Van den Berg, 1984). However, models having more than three parameters are too complicated for straightforward interpretation or use. GAB equation (Maroulis, Tsami, & Marinos-Kouris, 1988) is the most successful three parameter model, which includes parameters with physical meaning:

$$X_e = b_1 \exp(b_2/T)(a_w/(1 - a_w))^{b_3} \tag{4}$$

where X_e is the equilibrium moisture content of the material, a_w is the water activity, b_1, b_2, b_3 are empirical constants and T is the temperature. The water activity in the dried product comes to equilibrium with the relative humidity of the air thus it may be related to the relative humidity by the formula $a_w = \mathrm{Rh}/100$.

The model parameters are estimated by directly minimizing the mean standard deviation between experimental and calculated values:

$$S^2 = \left[\sum_{i=1}^{N} (X_{i,calc} - X_{i,exp})/X_{i,exp}\right] \Big/ N \tag{5}$$

where, $X_{i,calc}$ is the model fitted value which corresponds to the experimental observation $X_{i,exp}$ and N is the number of residuals produced. This form of residuals is based on relative errors between experimental and calculated values, and accounts for data with different orders of magnitude.

3. Materials and methods

Fresh vegetables (such as carrot, corn, garlic, green pea, leek, mushroom, onion, pepper, potato, pumpkin, tomato) were used. The water and sugar content of these products are given by Lee, Shalenberg, and Vittum (1970).

The samples were dehydrated in an experimental air-dryer, which consists of four basic sections: air flow rate control, heating control, humidity control and drying test compartments.

Experiments to determine the influence of process variables on the drying kinetics were performed. The variables taken into consideration were the characteristic size of the sample, air temperature, air humidity and

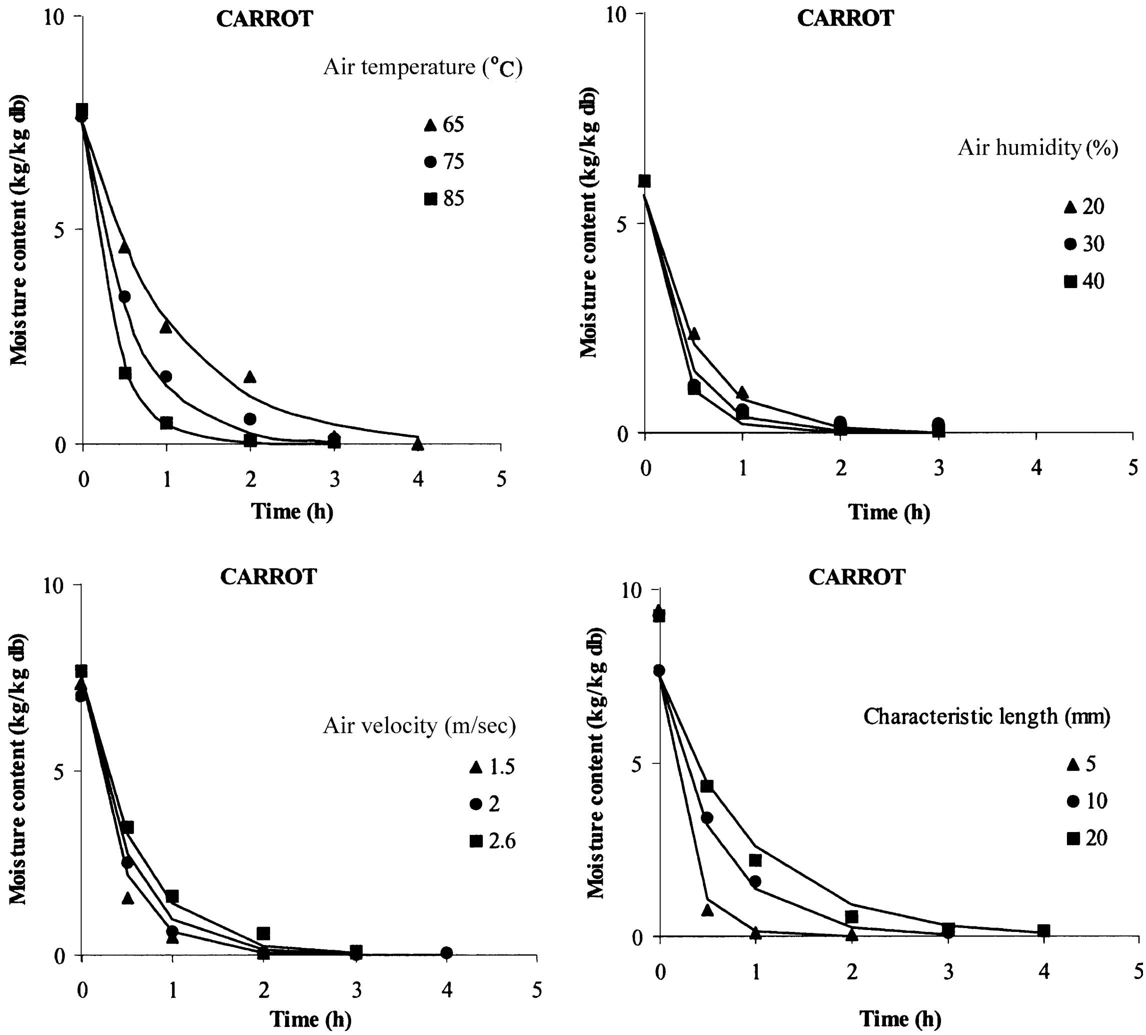

Fig. 6. Drying kinetics of carrot.

air velocity. The drying experiments were carried out at three levels of the characteristic sample size (5, 10 and 15 mm), three levels of air-temperature (65, 75 and 85 °C), three levels of air velocity (1.5, 2 and 2.6 m/s) and at three levels of relative humidity of the air (20%, 30% and 40%).

The water content of the samples during dehydration and drying procedures was determined using a vacuum oven (AOAC, 1980).

The moisture sorption isotherms were determined hygroscopically using Rotronic-Hygroskop BT apparatus attached to a water circulator (Haake N_2). This apparatus consists of a humidity and temperature sensor (DMS 100M, PT 100 respectively, model Art no. WA-40TH) that was attached to either one of the three ceramic airtight chambers, where the samples being measured were placed.

With the help of the water circulator the temperature of these chambers was kept constant at 30 and 70 °C. Readings of the RH% and T °C were taken from the digital Hygroskop BT screen (Art no. BT/O).

4. Results and discussion

The parameters of the proposed model (constants k_0, k_1, k_2, k_3 and k_4) (Eq. (3)) for prediction of the drying constant k are given in Table 1 (Panel A). These parameters resulted from an optimisation technique to minimize the mean standard deviation between experimental and calculated values of moisture content (Eq. (5)). The data of equilibrium moisture (X_e) which are used in Eq. (2) were resulted from GAB equation (Eq. (4)) using some constants (b_1, b_2, b_3) taken from experimental results of sorption isotherms. These constants (b_1, b_2, b_3) of GAB equation were resulted from an optimization technique and are given in Table 1 (Panel B).

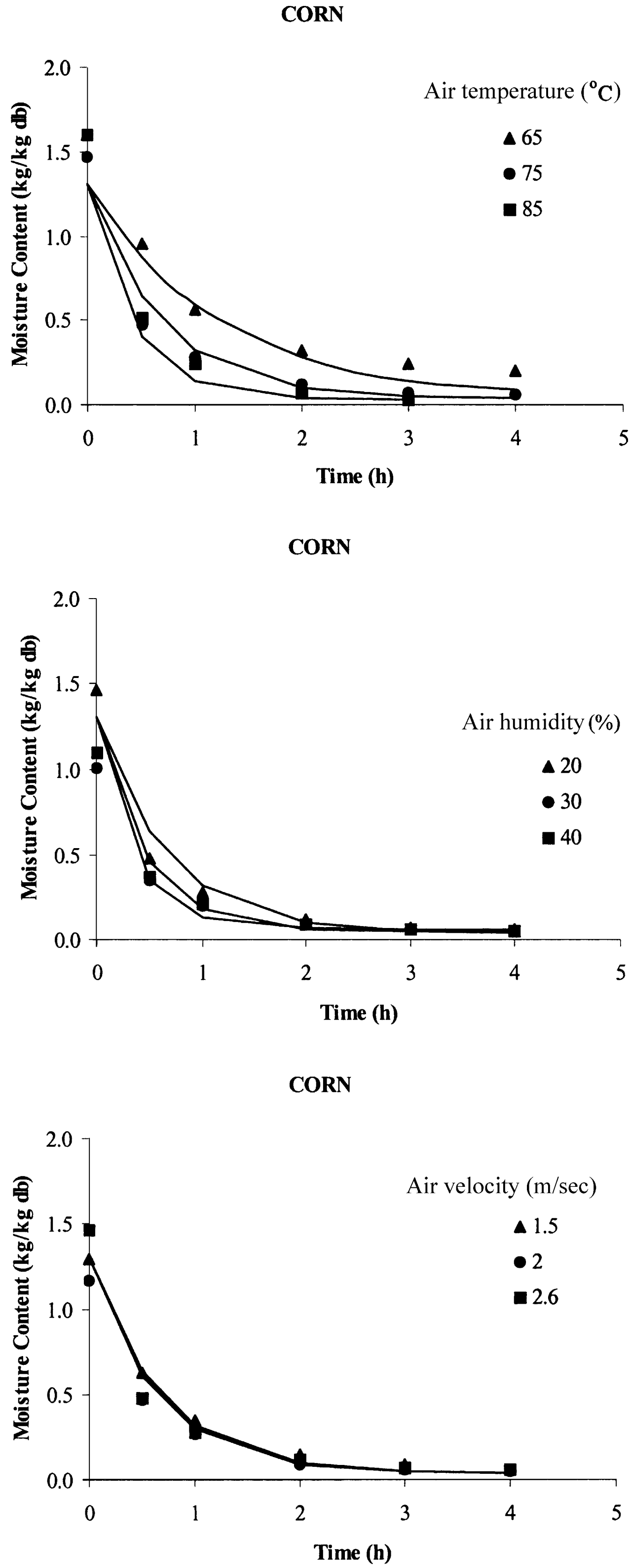

Fig. 7. Drying kinetics of corn.

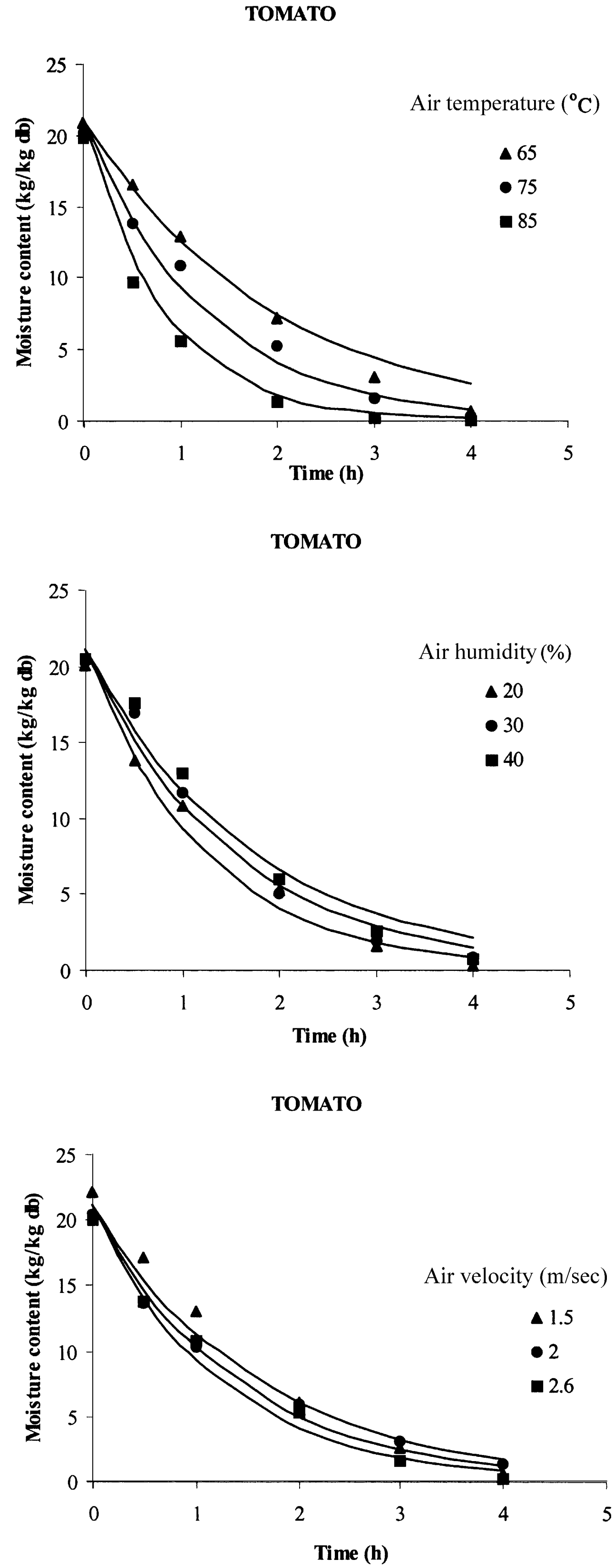

Fig. 8. Drying kinetics of tomato.

The experimental results and the results of the model for the drying of green pea are given in Fig. 1. In this figure the effect of various parameters is shown. The effect of air temperature on the drying process is shown

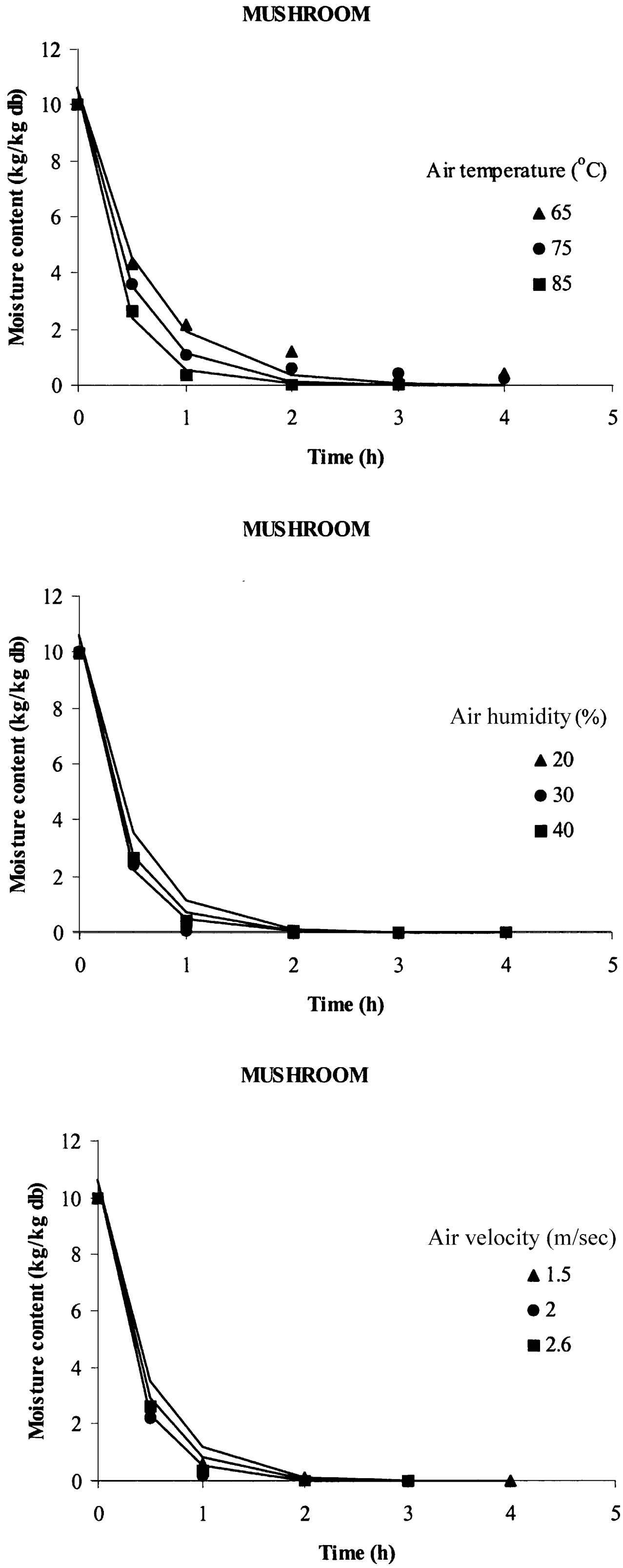

Fig. 9. Drying kinetics of mushroom.

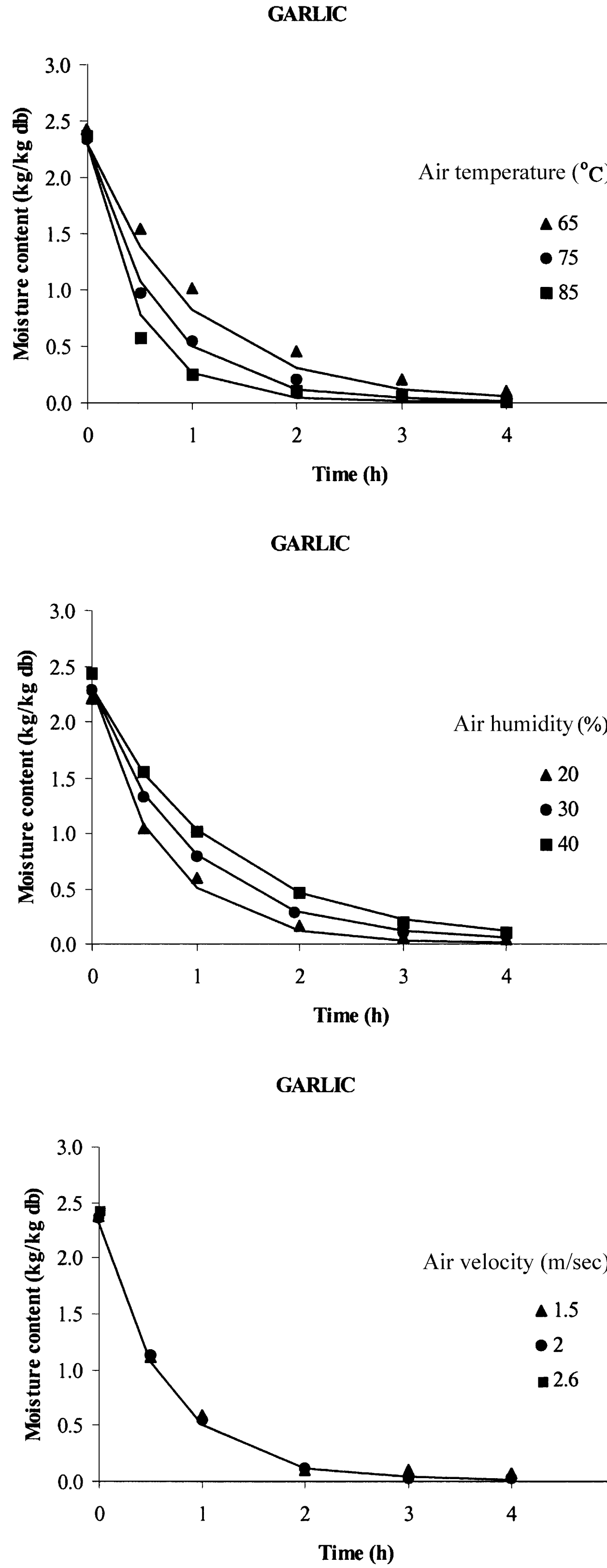

Fig. 10. Drying kinetics of garlic.

in Fig. 1a. The effect of the relative humidity of the drying air on the drying process of green pea is shown in Fig. 1b and the effect of the air velocity of the drying air on the drying process of green pea is shown in Fig. 1c.

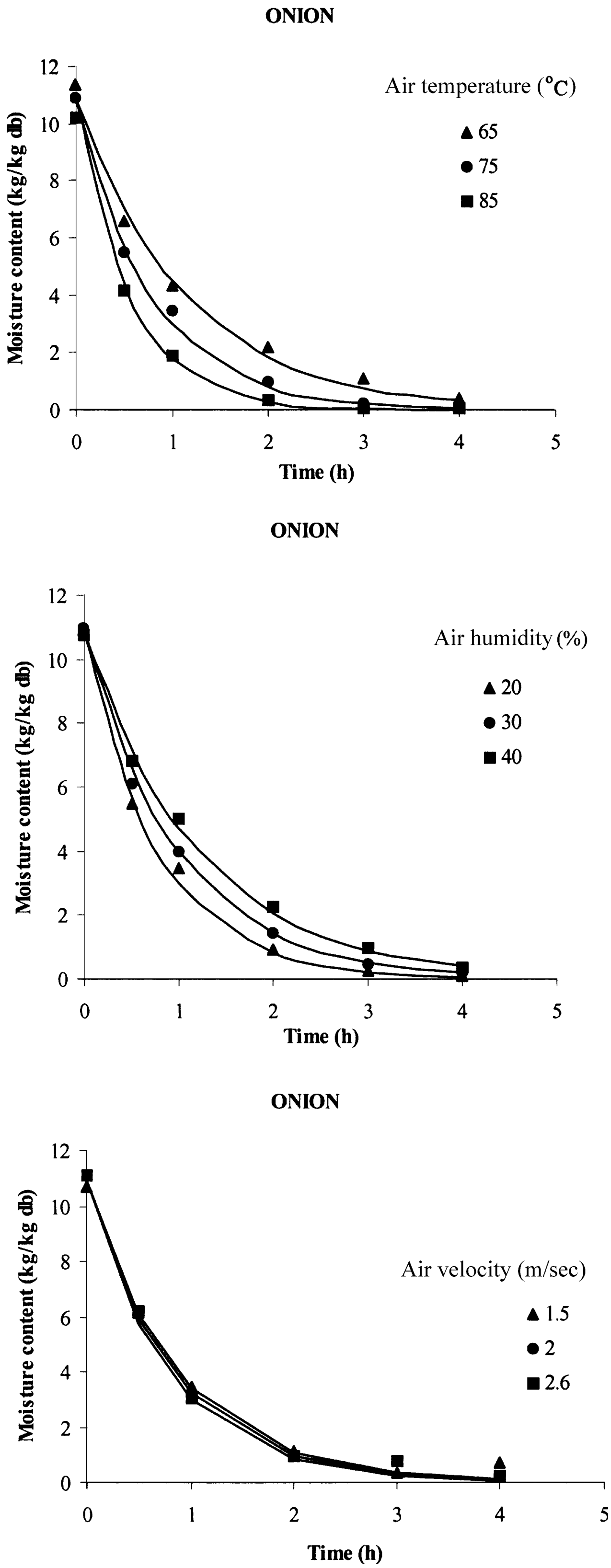

Fig. 11. Drying kinetics of onion.

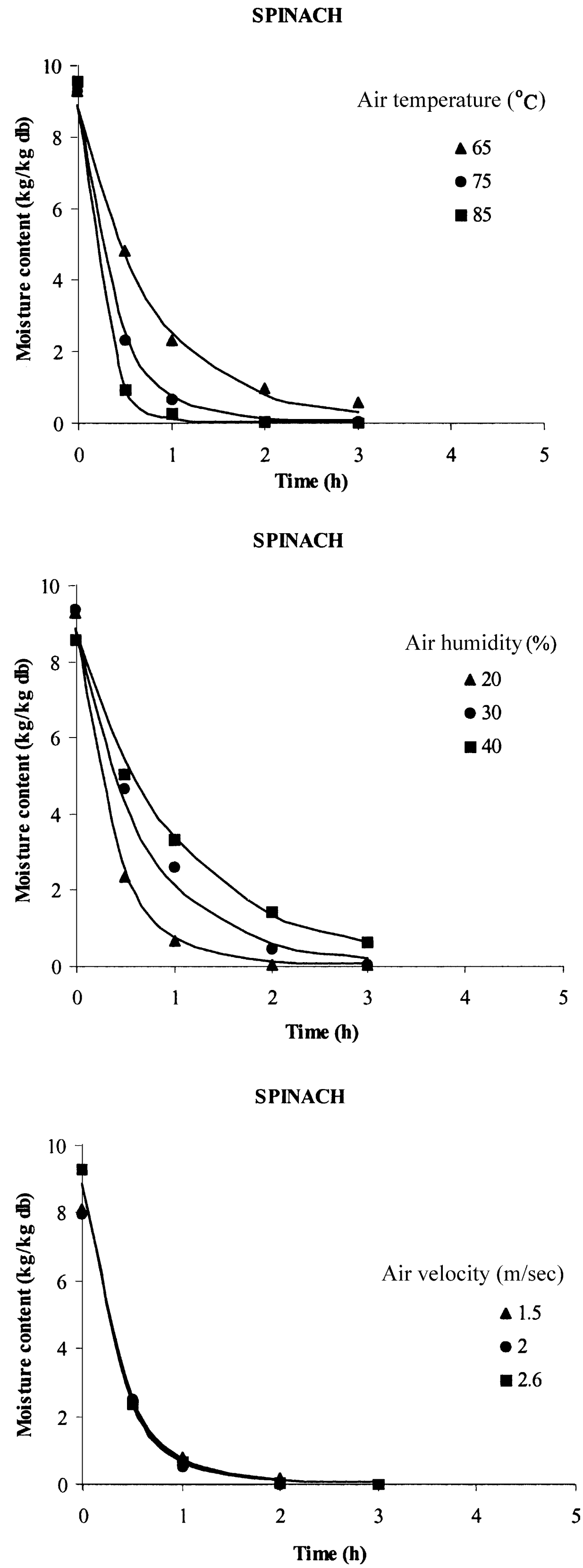

Fig. 12. Drying kinetics of spinach.

Similarly, for other products, such as red pepper, yellow pepper, pumpkin, corn, tomato, mushroom, garlic, onion, spinach, leek and celery the results are given in Figs. 2–17.

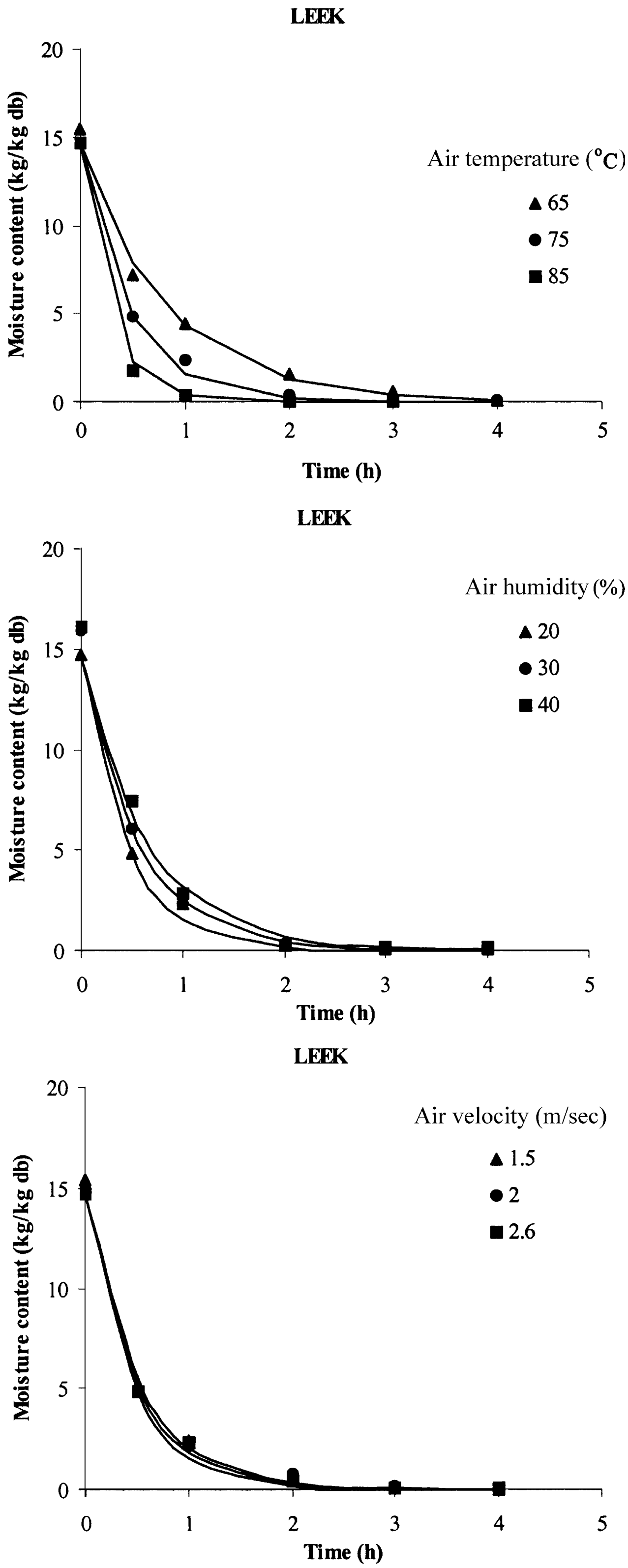

Fig. 13. Drying kinetics of leek.

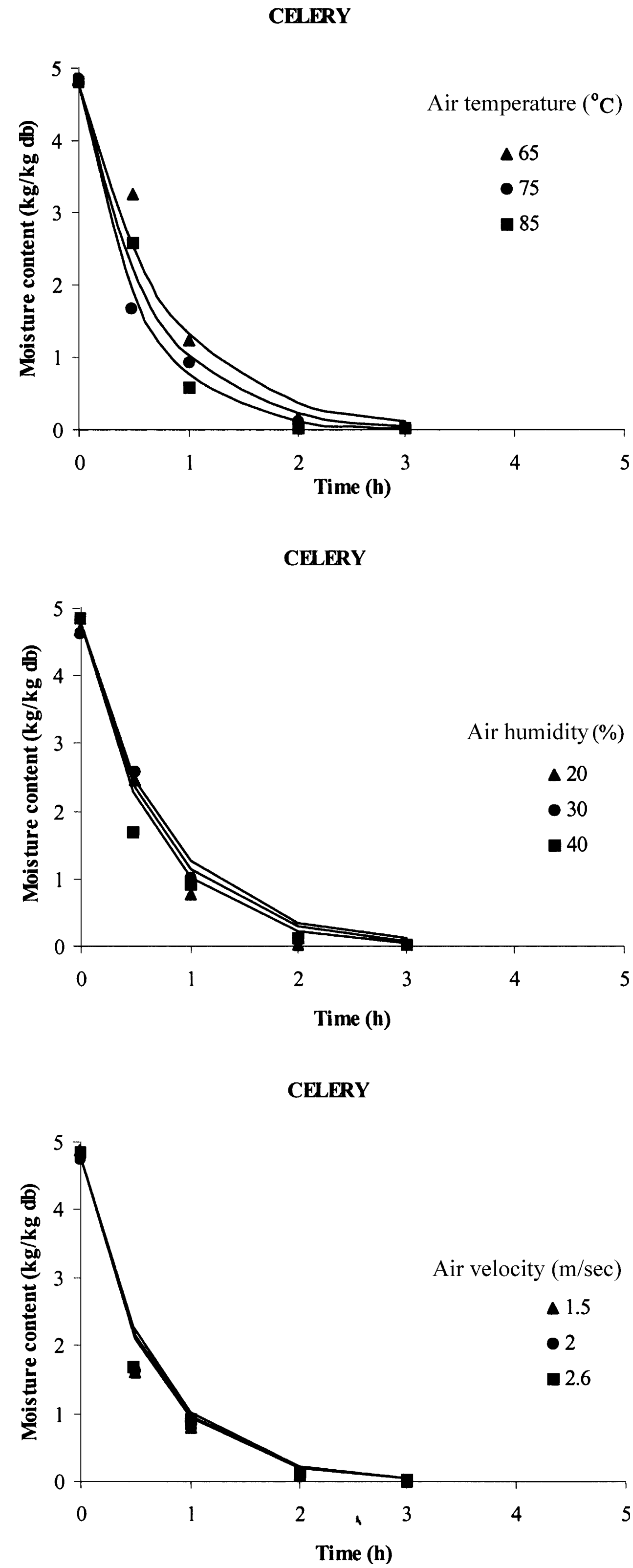

Fig. 14. Drying kinetics of celery.

As expected, there is an acceleration of the drying process due to the increase of the temperature of the drying air from 65 to 85 °C. This is very obvious during the first periods of drying. The effect of air

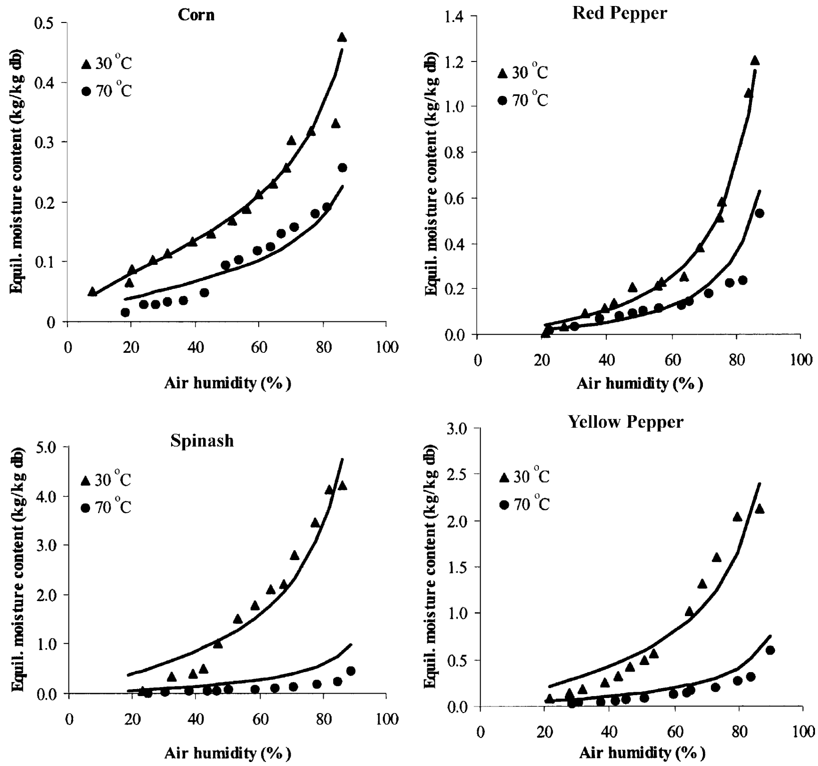

Fig. 15. Isotherms of corn, red pepper, yellow pepper and spinach.

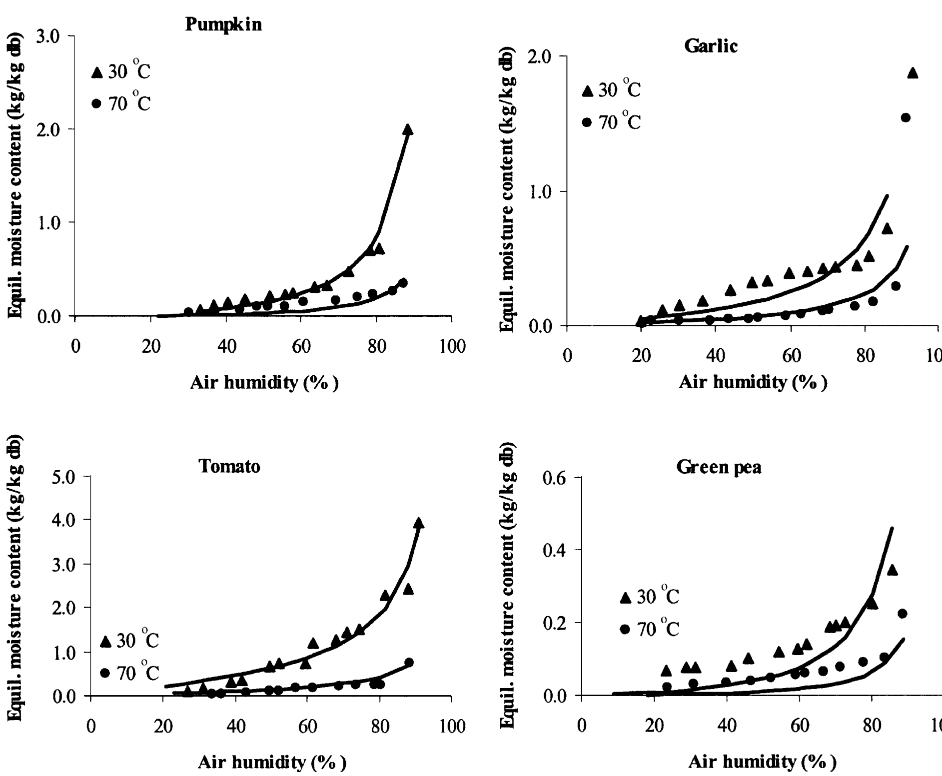

Fig. 16. Isotherms of pumpkin, garlic, tomato and green pea.

temperature is considered very important, which makes the temperature of drying as the most important factor of drying rate for all the examined materials.

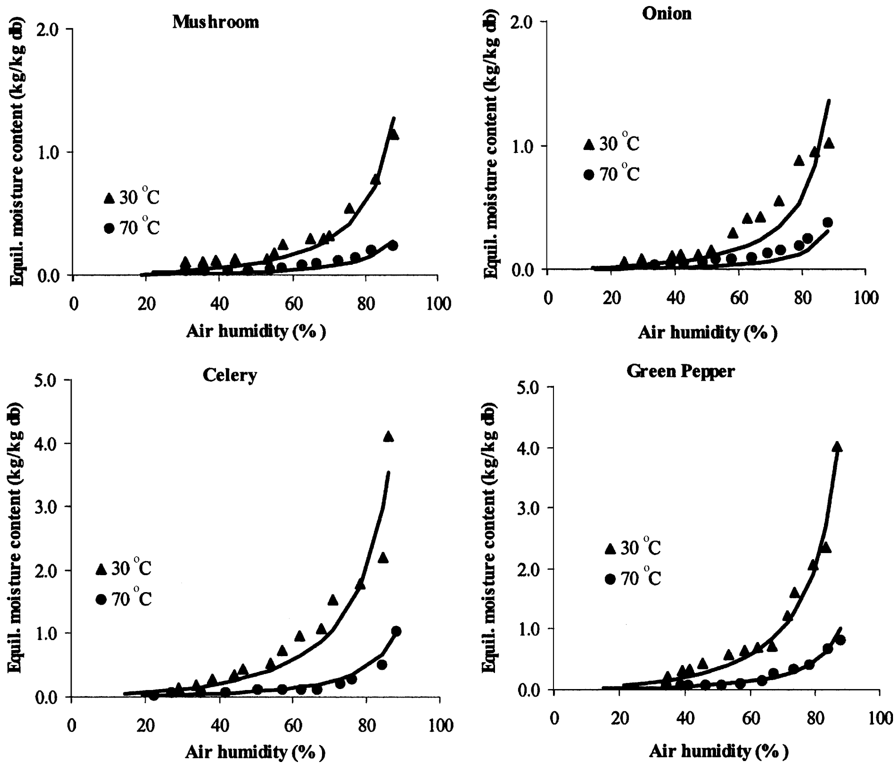

Fig. 17. Isotherms of mushroom, onion, celery and green pepper.

The effect of air velocity on the acceleration of the drying progress is considered, in general, as low. The reason may rely on the fact that the lower air velocity studied was considered already relatively high (1.5 m/s). An air velocity of that size is essential to limit the resistance to air drying to the interior of the vegetables (Mulet et al., 1989; Marinos-Kouris & Maroulis, 1995; Karathanos & Belessiotis, 1997). Thus, the diffusion of water prevails to the resistance and the resistance at the exterior of the product is not very important.

The effect of air humidity on the acceleration of the drying progress is considered, in general, as lower than that of air temperature. As expected, there is an acceleration of the drying process due to the decrease of the air humidity of the drying air from 40% to 20%.

5. Conclusions

The effect of drying parameters, such as air temperature, relative humidity of drying air, air velocity and particle size on the progress of the drying process of various vegetables were investigated. A drying model was developed, incorporating the effect of the above parameters on the drying process. The equilibrium moisture content of the vegetables was also found based on a GAB model. The drying model predicted successfully the drying of several vegetables.

Temperature of drying is the most important factor of drying rate for all the examined materials, while the effect of air velocity and air humidity is considered lower than that of air temperature.

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