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DRYING KINETICS FOR SOME FRUITS: PREDICTING OF POROSITY AND COLOR DURING DEHYDRATION.

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DRYING KINETICS FOR SOME FRUITS: PREDICTING OF POROSITY AND COLOR DURING DEHYDRATION.

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ABSTRACT

Drying kinetics of four fruits (prune, quince, fig and strawberry) were studied by using a simple mass transfer mathematical model involving a characteristic parameter (K) as a function of process variables. The model was tested with data produced in a laboratory air dryer, using non-linear regression analysis. The investigation involved three values of sample thickness (5, 10, 15mm) and three different air temperatures (50, 60, 70 °C).

The parameters of the model were found to be greatly affected by sample thickness and air temperature. The effect of moisture content on the porosity of three fruits (namely avocado, prune and strawberry) was also investigated. A simple mathematical model was used to correlate porosity with moisture content. It was found that porosity increased with decreasing moisture content.

Samples of three fruits (avocado, prune and strawberry) were investigated to estimate color changes during conventional drying at 70 °C. A first order kinetic model was fitted to experimental data with great success. It is found that the color of avocado and strawberry change while the color of prune remains the same.

Furthermore, the water sorption isotherms of three fruits (avocado, prune and strawberry) at 25^{O}C temperature were determined experimentally and the parameters at the GAB equation were evaluated by means of non-linear regression analysis. The use of the above equation produced a very good fit.

INTRODUCTION

Product quality is a major consideration during all food preservation methods. Consequently, during drying, special attention has to be paid upon the properties of the final dehydrated product, especially in terms of utility and application.

In recent years, much attention is paid on the quality of food products during drying. During water evaporation, changes on the physical structure take place and phenomena such as shrinkage determine the quality of the product. Generally speaking, the quality can be characterized by the color, the texture, the taste, the aroma, the porosity, the density and the rehydration capacity of the product (Pappas et al., 1999).

Process modeling is at a great significance in the analysis of design and optimization of dryers in order to produce high quality of food product (Vagenas et al., 1991).

The most essential part of process model development involves determination of the drying kinetics, which describe the mechanisms and the influence that certain process variables exert on moisture removal process (Mulet et al., 1989). In industrial applications the kinetic models are often empirical and involve parameters at a phenomenological nature, which have no essential physical meaning (Kiranoudis et al., 1990).

Analysis of processes affecting physical, biochemical and microbiological stability of foods, which in turn determine their quality, is largely based on sorption isotherms of the materials involved. These isotherms also reveal information about the sorption mechanism and interaction of food biopolymers with water and they are important in design and optimization of unit operations such as preservation, drying, storing, packaging and mixing (Tsami et al., 1990).

The physical state of food solids has received increasing attention because of its importance in food processing and shelf life (Simatos & Karel, 1988).

Several researchers have reported sorption isotherms: for cookies and snacks (Palou et al., 1997) for dried fruits (Tsami et al., 1990) for citrus juices and powders (Maia & Cal-Violal, 1997) etc.

Porosity, shrinkage, bulk density and particle density are very important physical properties characterizing the quality of dried foods. There is a strong relation between moisture content and shrinkage properties.

The development of porosity in foods during air drying, depends on initial moisture content, composition, size of material conditions and type of drying (Saravacos, 1967). Shrinkage properties have also been reported for fruits and vegetables (Lozano et al., 1983), for fish flesh (Rahman & Potluri, 1990).

The color of food is at great importance to the acceptability of a food product. This is due to the relation between color, flavour and aroma of dehydrated products.

The dried fruits exhibit an extensive browning reaction during air drying and storage. The kinetics of browning have been studied by Bolin and Steele, 1987.

The color changes have been studied by several researchers.

Lozano & Ibarz (1997) investigated the color changes in concentrated apple as a function of temperature, Steet and Tong (1996) studied the kinetics of degradation in green peas, (Krokida et al., 1998) the effect of temperature and air humidity on color changes during air drying.

The basic aim of this study is to represent the experimental drying kinetics of some fruits (namely, prune, quince, fig and strawberry) by means of an empirical model, in a way that all experimental information obtained should be contained in its parameters.

The equilibrium moisture content of fruits involved in the drying model was also investigated and experimentally determined.

Furthermore a simple mathematical model was used to correlate porosity with moisture content, while the three Hunter parameters redness (a) yellowness (b) and lightness (L) were used to study the color changes during air drying of avocado, prune and strawberry.

MATHEMATICAL MODEL

Drying kinetics

In this study, the suggested empirical model chosen to describe moisture removal from fruits dried, takes the form of the following equation:

$$\frac{dX}{dt} = K \cdot (X - X_e)$$

where X is the material moisture content, X_e is the equilibrium material content and K is the drying constant (Kiranoudis et al., 1997).

The latter is determined by the slope of the falling rate drying curve. The effect of other process variables can be embodied in the expression of the phenomenological parameters involved improving in this way the goodness of model fit to the experimental data.

This expression present in the form of the following equation:

$$K = k_0 \cdot T^{k_1} \cdot x^{k_2}$$

where x is the characteristic particle dimension and T is the drying air temperature. The empirical coefficients k_i=0, ... 2 can be estimated by fitting the total model employed to the experimental drying curves.

Moisture sorption isotherms

The equilibrium moisture content of fruits and vegetables is presented in the form of the well-known GAB equation, which is the one that best represents the equilibrium moisture isotherms of sorptions (Tsami et al., 1999):

$$X = \frac{Xm\,C\,K\,aw}{(1 - k\,aw)(1 - k\,aw + C\,k\,aw)}$$

where: X is the moisture content of the material, a_w is the water activity, X_m is the monolayer moisture content, C and K are parameters related to temperature. That is:

$$C = C_O \exp(\Delta H_C / RT)$$

$$K = K_O \exp(\Delta H_K / RT)$$

where T is the absolute temperature at the surrounding air, ΔH_C and ΔH_K are functions of heat of sorption of water (mono and multimolecular layers) and heat of condensation of water vapor (Tsami et al., 1990).

The parameters of the equation were estimated by fitting the mathematical model to the experimental data.

Porosity

Assuming the total mass of the moist material to consist of dry solid, water and air, the following definitions can be derived:

$$\rho_b = \frac{m_s + m_w}{V_s + V_w + V_a}, \quad \varepsilon = \frac{V_a}{V_s + V_w + V_a}, \quad \rho_p = \frac{m_s + m_w}{V_s + V_w}, \ (\text{kg/m}^3)$$

where ρ_b is the bulk density, ρ_p is the particle density, ε is the porosity m_s, m_w are the masses of dry solid and water, respectively (kg), V_s, V_w, V_a are the volumes of dry solid (particle), water and air pores, respectively (m^3).

A simple mathematical model has been proposed to predict bulk density, particle density and porosity versus material moisture content (Krokida and Maroulis, 1997):

$$\rho_b = (1+X) / (1/\rho_{bo} + \beta' X / \rho_w)$$

$$\rho_p = (1+X) / (1/\rho_s + X / \rho_w)$$

$$\varepsilon = 1 - \rho_b / \rho_p$$

where X is the material moisture content, ρ_{bo} is the bulk density of dry solid, β' is the volume shrinkage coefficient, ρ_s is the dry solid density and ρ_w is the enclosed water density (water included as solute in material pores). The values of the required parameters (ρ_s, ρ_w, ρ_{bo}, β') can be determined by fitting the proposed model to the experimental data. When these parameters are known, then the mathematical model can be used for the determination the bulk density (ρ_b), particle density (ρ_p) and porosity (ε) as a function of material moisture content (X).

Color

The color deterioration during air drying is a function of drying time. A first order kinetic model was used to describe color changes (Krokida et al., 1998).

In order to determine color changes during drying, kinetics of the Hunder parameters redness (a), yellowness (b) and lightness (L) were investigated.

A simple mathematical model has been proposed for each parameter, which is given by the following equation:

$$\frac{L-L_e}{L_o-L_e}=e^{-k_L t},\ \frac{a-a_e}{a_o-a_e}=e^{-k_a t},\ \frac{b-b_e}{b_o-b_e}=e^{-k_b t}$$

where: L, a, b, are the color parameters, L_o , a_o , b_o and L_e, a_e, b_e are the corresponding initial and equilibrium values (which theoretically color will reach after a long period of time), k_L, k_a, k_b are the rate constant (s^{-1}) and t is the drying time (s).

The values of the required parameters can be determined by fitting the proposed model to the experimental data.

MATERIALS AND METHODS

Four fruits were used for these experiments, namely, quince, prune, fig and strawberry. Samples were cut before drying into slices of 5, 10, 15 mm and then were distributed into identical rectangular baskets, in one of the available metal pans of a laboratory air - dryer (Kiranoudis et al., 1997).

Air conditions throughout the experiments (50, 60 and 70 ^{o}C temperature, 3,5 m/s air velocity and 15% relative humidity) were measured on line and samples mass off-line. The average moisture content of each sample was obtained according to the vacuum oven method (AOAC, 1984).

Equilibrium material moisture content was determined by means of a Rotronic - Hygroskop BT apparatus (Kiranoudis et al., 1997) attached to a water circulator (Haake N2). This apparatus involved a thermically isolated compartment, where the temperature (25^{o}C) was controlled by means of water circulating in the cell. The samples of the fruits were cut in cubes of approximately 10mm side and placed in the interior of the compartment. The temperature and water activity of surrounding air was determined by appropriate sensors in the cover of the compartment. The water content of the samples was determined using a vacuum oven method (AOAC, 1984).

In order to estimate the porosity of the fruits, samples in cubes (almost 10mm side) were removed from the air dryer (at 70 ^{o}C) periodically and their weight, total volume and particle volume were measured. Weight was measured by a Mettler-160 electronic balance with an accuracy of 10^{-4} gr. Particle volume (true volume excluding air pores) was measured by a Quantacrome, stereopycnometer (model SPV-3) with an accuracy of 0,001 ml. Total volume (apparent volume including air pores) was measured by immersing the samples in n-heptane and by determining the volume displacement with an accuracy of 0,05 ml (Zogzas et al., 1994). Two samples (cubes 15 mm) of each fruit were removed at a specific time from the air dryer (70 ^{o}C) and their color (L, a, b) was measured with a Hunder lab SAV colorimeter at eight different locations to determine the average value (Krokida et al., 1998).

Experimental data

Experiments to determine the influence of process variables on the drying kinetics were performed. The variables were the characteristic dimensions of the samples (5, 10 and 15 mm) and drying air temperature (50, 60 and 70 ^{o}C).

Experiments to evaluate the influence of air water activity (at 25 ^{o}C temperature) on the equilibrium moisture content of the materials carried out.

The experimental data are presented on Table 1.

Experiments to determine the influence of moisture content on porosity of fruits were performed. The experimental data points are presented on Table 2.

Experiments to evaluate the changes of lightness (ΔL), redness ($\Delta\alpha$) and yellowness (Δb) during conventional drying at 70 ^{o}C air temperature were performed.

The experimental data are presented on Table 3.

RESULTS AND DISCUSSIONS

Drying kinetics

The investigated empirical model was applied to the experimental data, in order to ultimately determine the empirical coefficients of the equation. The

TABLE 1. Equilibrium Moisture Content of Fruits (25°C)

Avocado		Prune		Strawberry	
a_w	X_e (kg/kgdb)	a_w	X_e (kg/kgdb)	a_w	X_e (kg/kgdb)
0.467	0.071	0.890	1.545	0.705	0.686
0.437	0.062	0.851	1.038	0.686	0.629
0.381	0.052	0.706	0.697	0.656	0.340
0.365	0.049	0.689	0.629	0.644	0.474
0.347	0.049	0.611	0.364	0.579	0.390
0.338	0.048	0.513	0.242	0.560	0.335
0.329	0.045	0.472	0.185	0.550	0.389
0.312	0.043	0.440	0.172	0.418	0.144
0.294	0.040	0.369	0.161	0.336	0.279
0.238	0.030	0.333	0.145	0.331	0.260
0.179	0.023	0.263	0.103	0.292	0.269
0.169	0.026	0.247	0.109	0.290	0.092
0.134	0.023	0.237	0.094	0.263	0.102
0.128	0.022	0.217	0.089	0.236	0.103
0.115	0.019	0.210	0.082	0.232	0.092
0.107	0.021	0.207	0.082	0.223	0.084
0.084	0.014	0.204	0.076	0.219	0.089
0.061	0.005	0.197	0.063	0.215	0.058
0.048	0.002	0.194	0.063	0.202	0.065
0.035	0.001	0.182	0.002	0.201	0.082
	-	0.173	0.001	0.201	0.067
-	-	-	-	0.192	0.078
-	-	-	-	0.183	0.058
-	-	-	-	0.181	0.082

TABLE 2. Porosity and Material Moisture Content

Avocado		Prune		Strawberry	
ε	X (kg/kgdb)	ε	X (kg/kgdb)	ε	X (kg/kgdb)
0.687	0.012	0.277	0.001	0.089	11.677
0.608	0.017	0.636	0.001	0.099	10.071
0.290	0.018	0.200	0.082	0.128	2.798
0.169	0.019	0.322	0.082	0.121	1.549
0.352	0.020	0.239	0.094	0.183	0.629
0.478	0.024	0.424	0.094	0.169	0.389
0.734	0.034	0.373	0.141	0.313	0.335
0.281	0.036	0.378	0.141	0.516	0.279
0.623	0.037	0.137	0.179	0.471	0.269
0.502	0.123	0.464	0.179	0.385	0.260
0.568	0.124	0.260	0.185	0.392	0.144
0.469	0.132	0.320	0.185	0.552	0.103
0.464	0.162	0.106	0.226	0.446	0.102
0.061	0.289	0.182	0.226	0.237	0.092
0.111	1.959	0.084	0.342	0.352	0.092
0.157	3.071	0.065	0.697	0.221	0.089
-	-	-	-	0.404	0.084
-	-	-	-	0.426	0.078
-	-	-	-	0.415	0.067
-	-	-	-	0.555	0.065
-	-	-	-	0.430	0.058

TABLE 3. Color Parameters Changes during Air Drying

t(min)	L	a	b
Avocado			
0	54.20	-1.80	22.77
60	56.37	-1.24	25.59
120	43.93	-1.16	18.85
180	43.92	-1.27	18.15
240	44.45	0.21	18.05
300	37.11	0.94	16.67
360	37.76	-0.20	15.74
420	47.38	0.80	19.38
480	38.77	0.27	15.50
540	54.52	0.88	18.89
600	48.76	1.18	18.89
Prune			
0	25.43	1.31	7.80
45	29.57	0.46	7.75
45	28.26	3.99	9.01
60	35.57	4.97	12.64
60	37.99	4.61	13.81
90	41.91	5.15	16.97
90	37.44	3.81	14.70
110	48.68	7.25	16.84
110	39.29	6.30	14.51
125	41.74	7.28	18.03
125	44.30	8.91	18.08
140	44.12	4.32	17.82
140	40.35	3.87	15.31
165	48.45	4.64	20.35
165	39.98	4.40	16.50
180	49.44	7.25	20.91
180	43.30	3.16	17.87
270	42.53	6.16	19.31
270	43.19	5.61	19.36
405	43.09	8.69	19.91
405	44.12	8.73	20.77
Strawberry			
0	33.23	23.25	11.12
0	33.68	16.59	9.29
60	24.41	18.63	6.05
90	24.21	18.04	5.73
105	31.29	23.05	8.74
120	28.91	22.29	7.71
150	23.76	17.59	6.04
150	29.91	18.87	7.20
165	24.36	15.43	5.10
180	26.08	18.60	6.92
195	30.37	19.39	7.80
195	28.00	24.00	8.74
210	34.48	23.08	9.04
210	22.92	12.28	4.03
225	35.02	22.74	9.02
230	30.52	17.37	7.99
255	31.39	12.21	6.76
275	34.77	22.21	9.35
285	26.26	11.89	5.33
315	26.04	11.01	5.10
315	27.98	14.23	6.88
360	25.79	15.14	5.99
420	30.36	17.30	7.50
480	27.00	17.09	6.61
540	31.35	13.69	8.67

TABLE 4. Results of the Regression Analysis of Drying Kinetics

Model

$$\frac{dX}{dt} = K \cdot (X - X_e)$$

$$K = k_0 \cdot T^{k_1} \cdot x^{k_2}$$

Parameters

Fruit	k_O (h^{-1})	k_1	k_2
Prune	2,73E-4	2,50	-1,24
Quince	5,61E-4	2,26	-1,09
Fig	5,11E-5	2,64	-0,86
Strawberry	7,83E-2	1,19	-1,07

Process variables

x: 5 - 15 mm
T: 50 - 70 °C

application of non-linear regression analysis on the experimental data, gave the results shown on Table 4.

The values of empirical coefficients expressing the influence of process parameters (size of particles and air temperature) on drying curve.

The effect of the characteristic dimension of the samples employed on the drying curves is presented for all fruits in Fig. 1.

The effect of air temperature on the drying curves is presented in Fig. 2. When all other process variables remain constant, the drying rate produced for high air temperatures is greater.

Additionally, as shown in Fig. 3 the drying constant, K, is negatively correlated with sample thickness. On the other hand there is a strong positive correlation between air temperature and drying constant. Rapid drying can be achieved when the characteristic dimension of fruit samples is small and air temperature is high.

Equilibrium moisture content

The experimental and calculated values, using the GAB equation, of

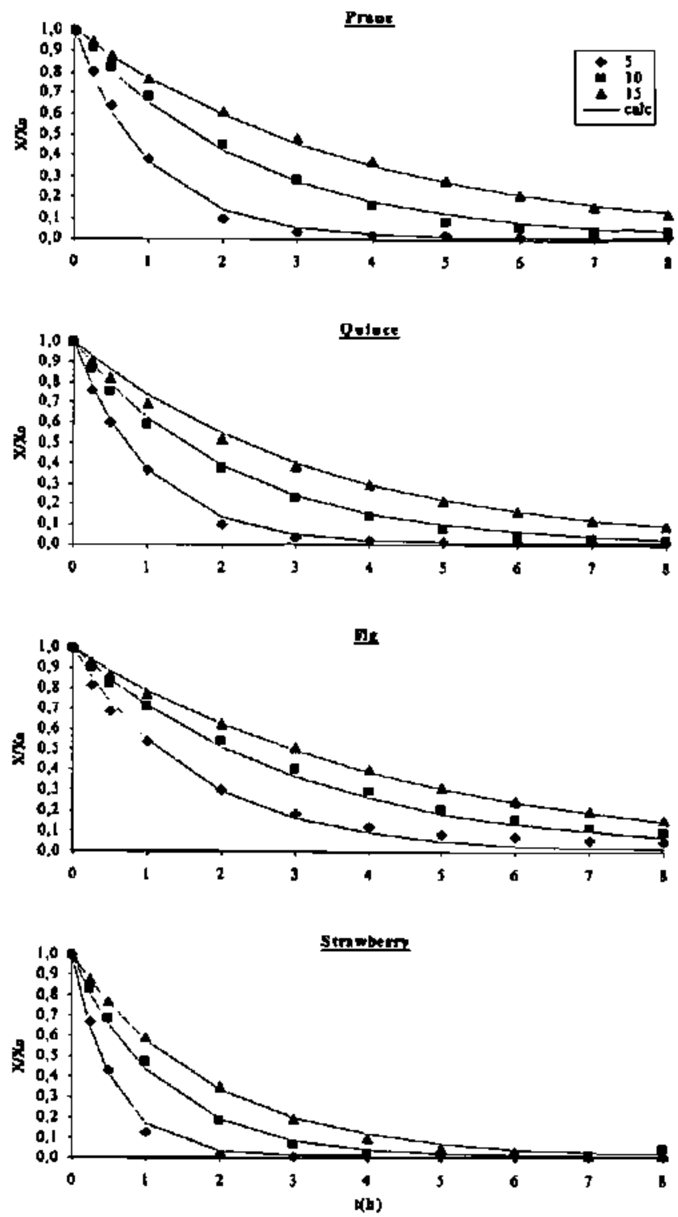

FIGURE 1. Effect of size samples on drying curves (T=60°C)

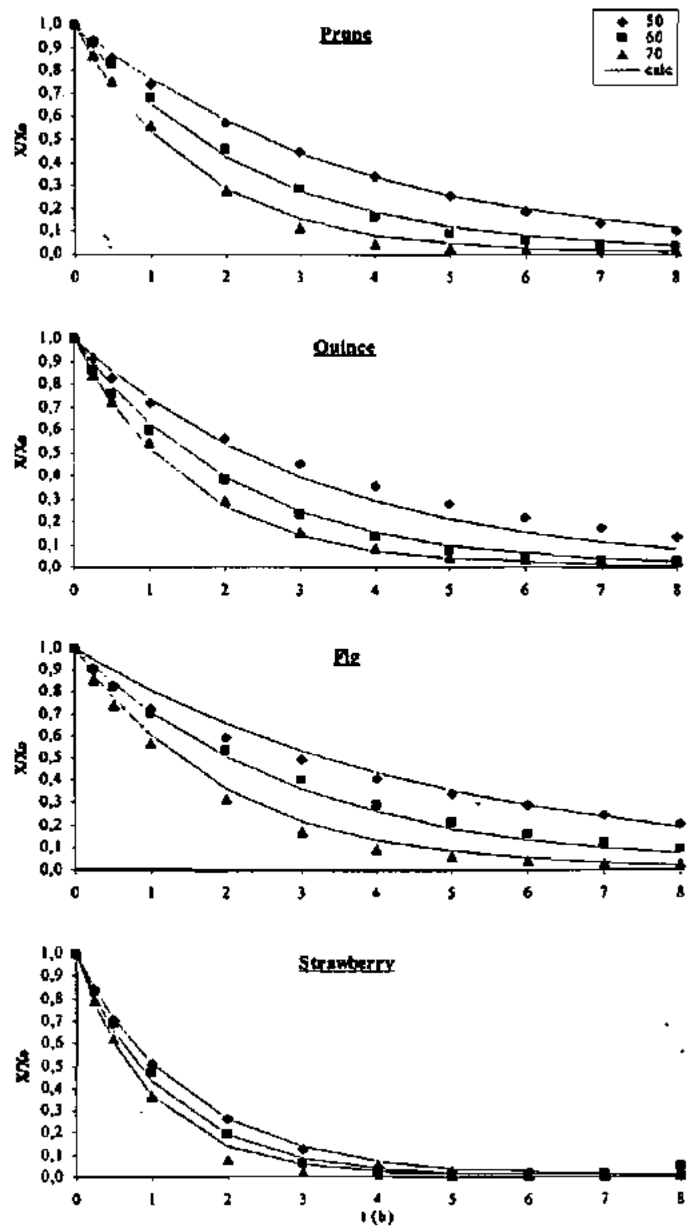

FIGURE 2. Effect of air temperature on drying curves (x=10mm)

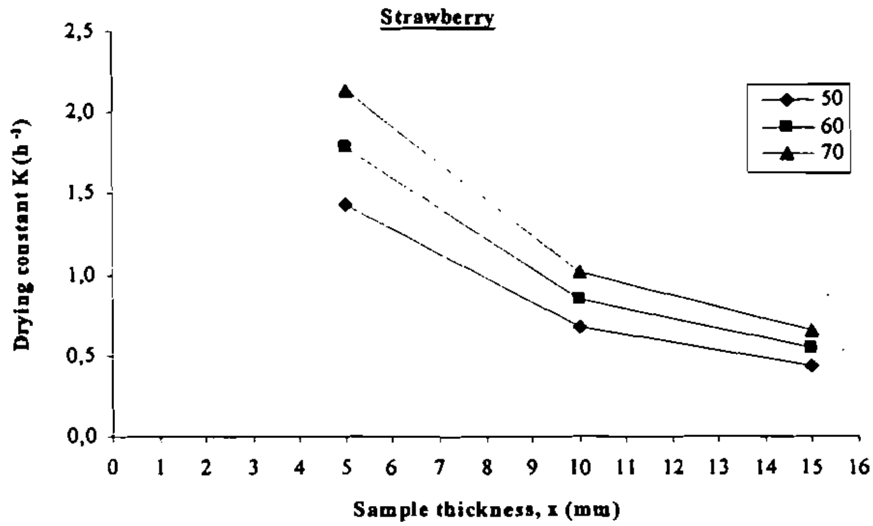

FIGURE 3. Influence of air temperature and sample thickness on drying constant

equilibrium sorption isotherms at 25 ^{o}C for three fruits dehydrated at 70 ^{o}C are presented in Fig. 4.

The results of the non-linear regression analysis of fitting the GAB equation to the experimental points are presented on table 5.

The shape of two isotherms (prune and strawberry) is sigmoid, characteristic of the high sugar food (Tsami et al., 1990 & 1999), which sorbs relatively small amounts of water at low water activities and large amounts at high relative humidities.

The shape of avocado isotherm is characteristic of the high fat food.

The equation that models successfully the equilibrium is the GAB relation. Mc Minn & Magel (1997) adopted the GAB equation to successfully characterize the experimental sorption data of starch - sugar gels Kiranoudis et al., (1993) found that the GAB equation gives the best description of the sorption behaviour of several vegetables.

Porosity

The mathematical model (Table 6) was fitted to experimental data and the

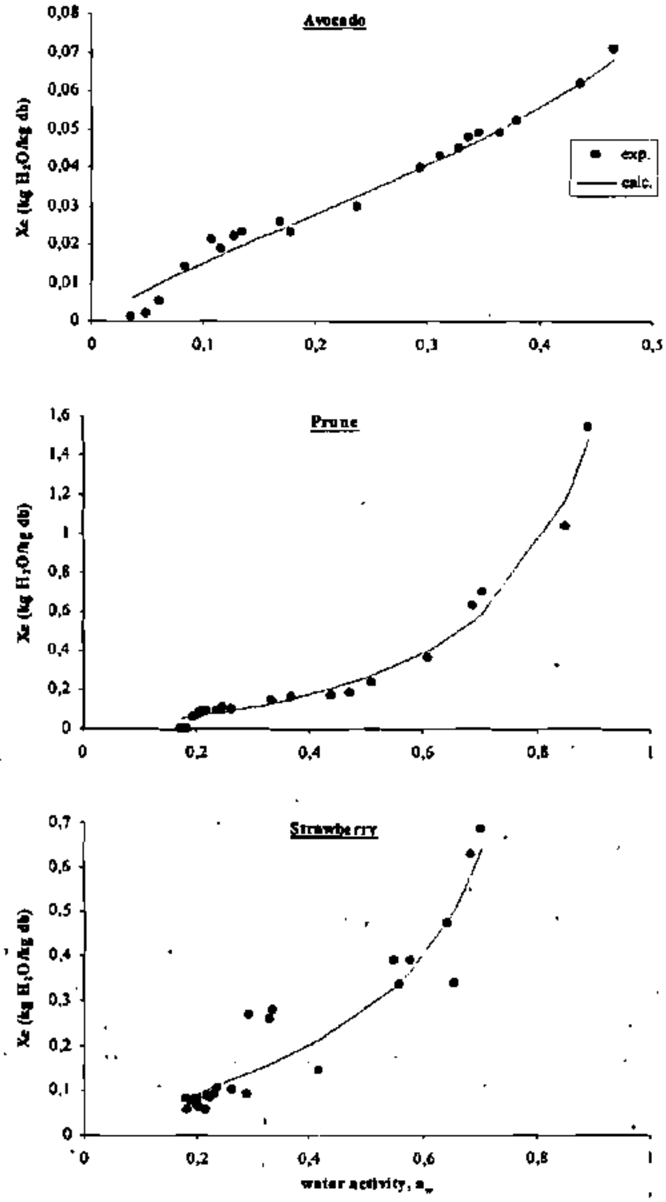

FIGURE 4. Experimental and calculated equilibrium moisture content (25°C)

TABLE 5. Results of the Regression Analysis for the GAB Equation Model

Model

$X = X_m C K a_w / (1 - k a_w)(1 - k a_w + C k a_w)$
$C = C_O \exp(\Delta H_C / RT)$
$K = K_O \exp(\Delta H_K / RT)$

Parameters

Fruit	Xm	C	K
Avocado	0,042	3,887	1,085
Prune	0,346	0,819	0,918
Strawberry	0,159	3,089	1,098

Process variables

$a_W = 0{,}03 - 0{,}9$
$T = 25\ ^{o}C$

TABLE 6: Results of Porosity Parameter Estimation

Model

$$\rho_b = (1+X) / (1 / \rho_{bo} + \beta' X / \rho_w)$$

$$\rho_p = (1+X) / (1 / \rho_s + X / \rho_w)$$

$$\varepsilon = 1 - \rho_b / \rho_p$$

Parameters

Fruit	ρ_w	ρ_s	ρ_{bo}	β'
Avocado	0,324	1,295	0,562	1,048
Prune	0,224	1,119	0,622	0,814
Strawberry	0,412	1,195	0,567	1,056

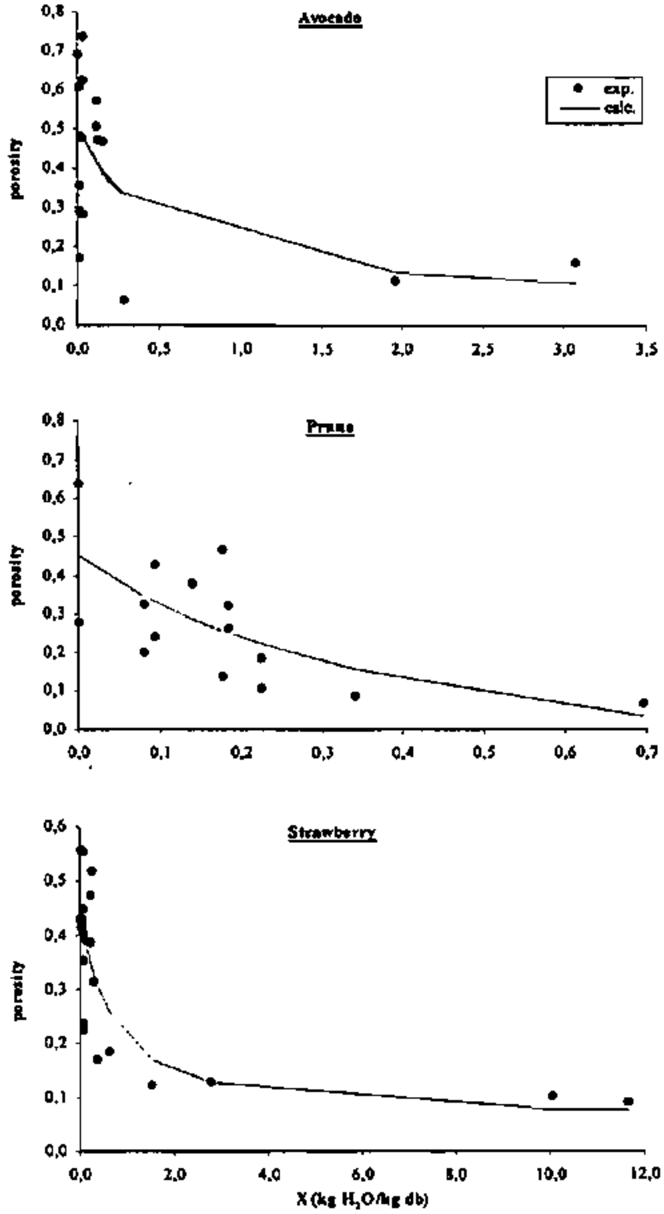

FIGURE 5. Porosity versus material moisture content

TABLE 7: Results of color parameter estimation

Fruit	L_o	L_e	K_L	a_o	a_e	k_a	b_o	b_e	k_b
Avocado	56,24	43,94	1,2E-2	-1,88	2,03	2,3E-3	24,36	17,25	7,9E-3
Prune	35,52	-707	-4E-5	3,33	-105	-1E-4	11,94	-283	-9E-5
Strawberry	29,01	-4,2E-4	1,9E-5	21,60	-815	2,3E-5	10,20	6,98	0,44

results of parameter estimation are presented the same table.

Fig. 5 presents the porosity versus material moisture content during drying of the three fruits.

All fruits develop significant porosity during air drying, which increases with decreasing moisture content.

Color

The regression analysis was followed for each of the three color parameters. The results of parameter estimation for each of the three parameters (L, a, b) are summarized in Table 7.

A comparison between experimental points and calculated values (solid lines) is shown in Figures 6 through 8 for conventional drying at 70 ^oC.

They are defined as follows:

$$\Delta L = L - L_O$$

$$\Delta a = a - a_O$$

$$\Delta b = b - b_O$$

The main results are summarized as follows: color difference (ΔL) during air drying (Fig. 6) decreases strongly for avocado, increases very much for prune and practically stays the same for strawberry.

Color difference (Δa) during air drying (Fig. 7) increases strongly for avocado and prune and decreases for strawberry.

Finally color difference (Δb) during air drying (Fig. 8) decreases for avocado and strawberry and increases for prune.

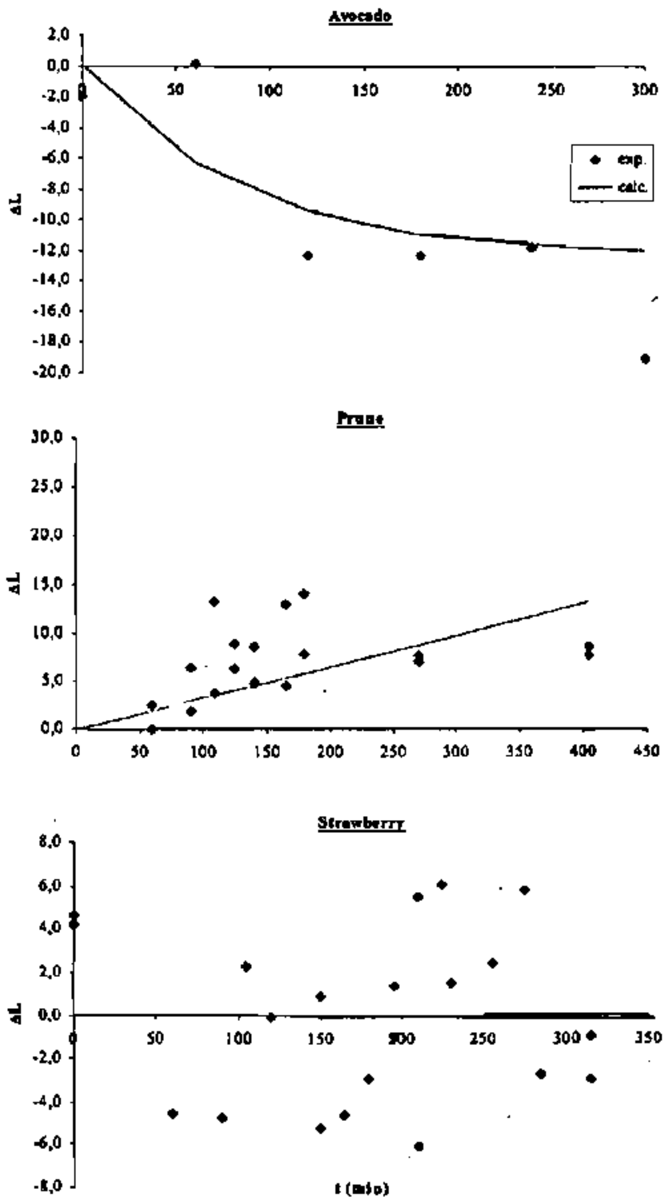

FIGURE 6. Change in Lightness ΔL versus time during air drying

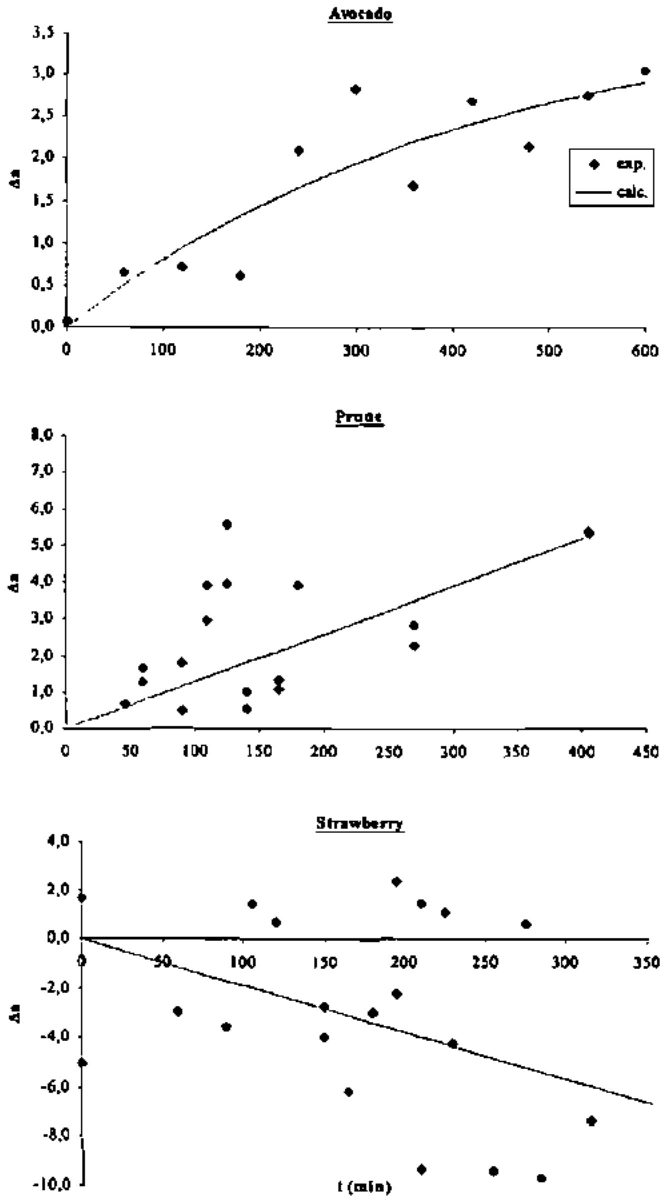

FIGURE 7. Change in Redness Δa versus time during air drying

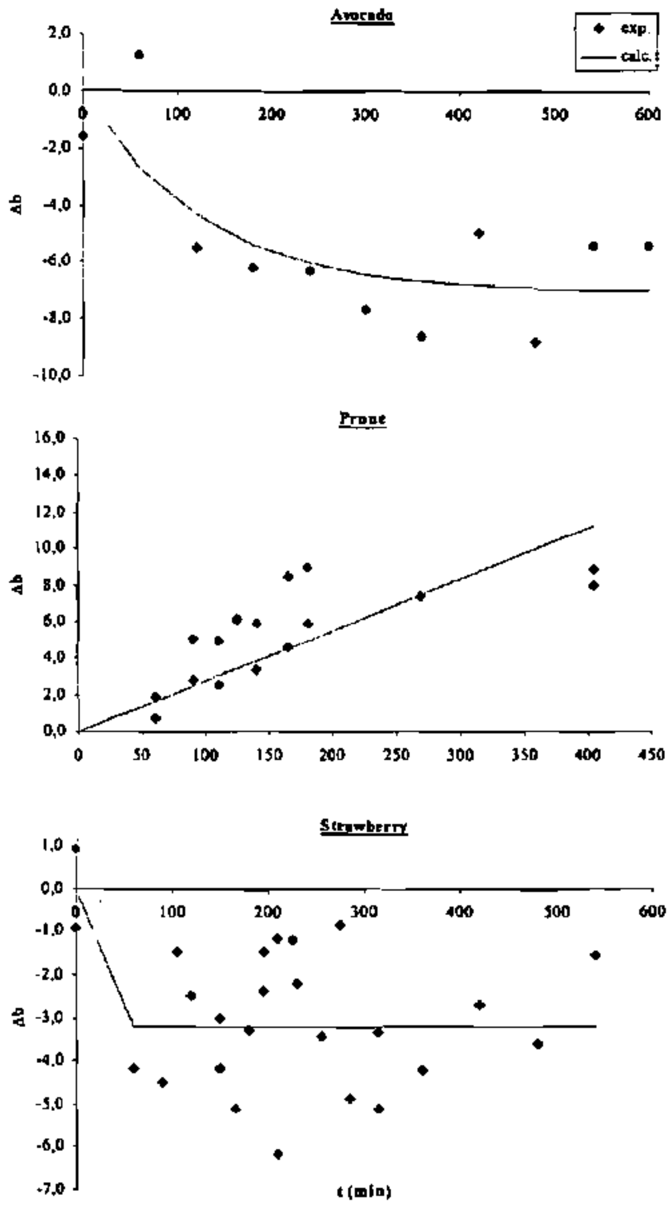

FIGURE 8. Change in Yellowness Δb versus time during air drying

CONCLUSIONS

Drying kinetics of fruits can be represented by means of an empirical model, involving a basic parameter, the drying constant. The influence of process variables, temperature and sample thickness, was examined by embodying them to the model drying constant. The sample thickness influences the drying rate in a negative way and air temperature in a positive way. The equation that models successfully the equilibrium is the GAB relation.

During air drying, avocado, prune and strawberry developed significant porosity, which increases with decreasing moisture content.

Consequently the color of the dehydrated product can be designed by controlling the drying conditions. It is found that the color of avocado and strawberry changes while the color of the prune remains the same.

NOMENCLATURE

a	redness (-)
a_w	water activity (%)
b	yellowness (-)
β'	volume-shrinkage coefficient (-)
C, K, ΔH_C, ΔH_K	parameters of the GAB equations
ε	porosity (-)
K	drying constant (h^{-1})
k_o, k_1, k_2	empirical drying constants
L	lightness (-)
m	mass (kg)
$\rho_w, \rho_p, \rho_b, \rho_{bo}$	water density, particle density, bulk density, dry solid bulk density (kg/m^3), respectively
V	volume (m^3)
t	time (h)
X	material moisture content (kg/kgdb)
X_e	equilibrium material moisture content (kg/kgdb)
X_m	monolayer moisture content (kg/kgdb)

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