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# Drying models for green peas

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A fixed or moving boundary problem was considered for the drying of green peas. The first model was solved by separation of variables, assuming that sample size and geometry remain constant during the process. For the second model, a finite difference method was used. Using experimental data from experiments carried out at different air-drying temperatures (40, 60 and 80°C), two different expressions, of Arrhenius type, for the effective diffusivity dependence on the air temperature were obtained. Throughout these expressions, it was possible to simulate the drying kinetics of green peas at temperatures (50, 70 and 90°C) different from those used to obtain the models. The second model was found to be more precise (percentage of explained variance > 99.8%) than the first one (> 98.4%).

## NOMENCLATURE

$D_{eff}$ effective diffusivity coefficient, m$^2$/s

$D_o$ pre-exponential factor Arrhenius equation, m$^2$/s

$E_a$ activation energy, J/mol

NR number of shells

$P_{dm}$ dry matter, kg

$r$ radius of the shell, m

$R$ radius of the sphere, m

$R$ gas constant, J/mol K

$S_{xy}$ standard deviation (estimation), (kg water/kg dm)$^2$

$S_y$ standard deviation (sample), (kg water/kg dm)$^2$

$t$ time, s

$T$ air-drying temperature, °C

$V$ volume, m$^3$

$V_o$ initial volume, m$^3$

$W$ average moisture content, kg of water/kg of dm

$W_c$ critical moisture content, kg of water/kg of dm

$W_e$ equilibrium moisture content, kg of water/kg of dm

$W_l$ local moisture content, kg of water/kg of dm

WL rate of water losses in the sphere, kg water/s

$v$ percentage of variance

$\Psi$ average dimensionless moisture

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## INTRODUCTION

The purpose of drying food products is to allow longer periods of storage with minimized packaging requirements and reduced shipping weights (Okos *et al.*, 1992). Drying is a combined heat and mass transfer process which has been reviewed by many researchers (Fusco *et al.*, 1991; Jayaraman & Das Gupta, 1992; Waananen *et al.*, 1993; Mulet, 1994). Most biological material drying takes place during the falling rate periods when controlling resistance to moisture movement is an internal mass transfer (Wang & Brennan, 1992). Usually, the mass transfer equation alone has been found to be adequate to describe the drying process for most agricultural products, assuming that the process is of an isothermal type.

Often a diffusion transport mechanism is assumed, and the rate of moisture movement is described by an effective diffusivity value, no matter which mechanism is actually involved in moisture movement (pressure diffusion, thermal diffusion, forced diffusion and/or ordinary diffusion).

Modelling is a useful way to validate mechanisms of drying, and to establish physical or engineering properties. It may be used to determine the reliability of calculated values of the effective diffusivity. Diffusive models were often considered for the description of convective-drying of vegetable particles (Mulet, 1994).

Several mathematical models have been proposed in food items to predict moisture transfer during the falling rate period using Fickian's diffusion as a basis to describe the moisture diffusion process (Hong *et al.*, 1986). The complexity needed in a model, or in other words, the level of detail, depends on the target to be reached. Thus, the final use of the model will establish the degree of complexity. Two useful methods to simulate the drying process in regular shaped bodies are the variables separation method (Lomauro *et al.*, 1985; Suarez & Viollaz, 1991; Rosselló *et al.*, 1992), and the finite difference method (Balaban & Pigott, 1988; Mulet *et al.*, 1989).

To apply Fick's law it is usually assumed that the product has an uniform moisture content and that internal resistance is the main resistance to mass transfer. If it is assumed that shrinkage of the sample during the drying process is negligible, the microscopic mass balance can be analytically solved by the variables separation method. When shrinkage is considered as an important factor, the moving boundary problem may be solved by a finite difference method.

The drying process is often modelled by assuming that the process that takes place is of an isothermal type (Yoshida *et al.*, 1990). Nevertheless, in their conclusions, many researchers point out the necessity of taking heat transfer into account when developing a model (Vanegas & Marinos-Kouris, 1990).

In literature, the studies on drying green peas are scarce. They are mostly related to nutritional quality in order to optimize drying pretreatments and rehydration, as well as packaging and storage (Shah *et al.*, 1975; Shah & Sufi, 1979). Other studies were directed to test the performance of different solar drier models used to dry these products (Kalra & Bhardwaj, 1981; Tandon *et al.*, 1981).

From the kinetic point of view, Escardino *et al.* (1961) published a study dealing with the influence of the operating variables (bed height, air velocity, temperature). The drying took place in such an operating way that the mass transfer could not be asserted to be controlled by internal resistance (low air velocities); nor was the shrinkage of the samples taken into account.

The purpose of this research was to propose and compare two models with different degrees of complexity aimed at simulating the drying of green peas. On the one hand, to develop the first model, material shrinkage was taken as negligible. On the other hand, in the second model, the variation of the material size during drying time was taken into account. It seems useful, considering models with different degrees of complexity, to evaluate the effort required to obtain additional precision and to manage the complexity more efficiently.

## MATHEMATICAL MODEL

For the mathematical analysis it was assumed that the internal resistance controlled the drying rate. Mass transfer can be calculated in terms of Fick's law and the microscopic mass balance. To analyze the drying process in a sphere, this combination can be written as follows (Equation 1) (Brodkey & Hershey, 1988):

$$\frac{\partial W_1}{\partial t} = -D_{\text{eff}}\left(\frac{\partial^2 W_1}{\partial r^2} + \frac{2}{r}\frac{\partial W_1}{\partial r}\right) \qquad (1)$$

The material is assumed to be isotropic and the diffusion coefficient of moisture is the same in all directions. In order to solve this differential equation (Equation 1), the following initial and boundary conditions were assumed (Karathanos *et al.*, 1990; Fusco *et al.*, 1991):

$$\begin{array}{lll} t = 0 & 0 < r < R & W = W_0 \\ t > 0 & r = 0 & \dfrac{\partial W_1}{\partial r} = 0 \\ t > 0 & r = R & W = W_e \end{array}$$

It was also assumed that the critical moisture content ($W_c$) corresponds to the moisture content of the solid at the beginning of the drying period considered (Karathanos *et al.*, 1990).

### Separation of variables method

Equation (1) can be analytically solved for a constant effective diffusive coefficient, assuming that the sample size and geometry remain constant (Jayas *et al.*, 1991). The material geometry was considered to remain unchanged during the drying process as assumed by different authors (Tolaba *et al.*, 1989; Yoshida *et al.*, 1990).

In that case the solution for a sphere in terms of infinite series is known to be (Equation 2) (Skelland, 1974):

$$\Psi(t) = \frac{W - W_e}{W_c - W_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp - \frac{n^2\pi^2 D_{\text{eff}} t}{r^2} \qquad (2)$$

By means of the Marquardt scheme (Kuester & Mize, 1973) it was possible to identify the effective diffusivity value for each air-drying temperature by using nine terms from the series.

### Finite difference method

To establish the second diffusivity model, it was assumed that although the sample shape did not change, an important sample shrinkage took place during the drying process. This was due to the fact that the relationship between the volume and the moisture content may often be linearly expressed in both fruit and vegetables which was considered to be the case (Rosselló *et al.*, 1992).

Using the method of finite differences, the original sphere was considered as '*n*' concentric and thin shells of homogeneous material surrounding a spherical core. The shells had a thickness of $\Delta r$ except the outermost shell which had a thickness of $\Delta r/2$ (Patil, 1988; Chau & Gaffney, 1990). The node in each volume element, where the mass balance is performed, is at the midpoint between the two surfaces of the shell. The node for mass balance in the outermost shell was taken on its external surface. The shell and core sizes are reduced due to water losses while adjusting their dimension to the moving boundary. Meanwhile, their dry matter stays at a constant value throughout the process.

To obtain the solution of the diffusion equation, the following relations were obtained from the difference finite method (Equations 3, 4 and 5):

$$\frac{\partial W_1}{\partial t} = \frac{W_1(r, t + \Delta t) - W_1(r, t)}{\Delta t} \tag{3}$$

$$\frac{\partial W_1}{\partial r} = \frac{W_1(r + \Delta r, t) - W_1(r, t)}{\Delta r} \tag{4}$$

$$\frac{\partial^2 W_1}{\partial r^2} = \frac{W_1(r + \Delta r, t) + W_1(r - \Delta r, t) - 2W_1(r, t)}{\Delta r^2} \tag{5}$$

A mass balance applied to a shell, in a time interval of $\Delta t$, helped to determine the local moisture content variation. Water losses (WL) in this period, were calculated through a global balance (Equation 6). The mass balance for one subvolume at time $t + \Delta t$ was obtained as a function of the neighbour subvolume properties at time $t$ (Arpaci, 1966):

$$WL = -D_{\text{eff}} P_{\text{dm}} (NR - 1) \left( \frac{W_1(R - \Delta r, t) - W_e}{\Delta r^2} + \frac{2}{R - \Delta r} \frac{W_1(R - \Delta r, t)}{\Delta r} \right) \Delta t \tag{6}$$

The effective diffusivity coefficient was identified for each experiment using the experimental data of drying kinetics carried out at different air-drying temperatures. An optimization technique, based on the Gauss–Newton method (Kuester & Mize, 1973), was used to estimate the diffusivity value at the different air temperatures considered. A mixed criterion was used for parametric estimation: the sum of relative and absolute squared moisture differences in a ratio (1/0.2) (Richalet *et al.*, 1978).

In order to solve the set of equations, a computer program in FORTRAN was written. Using this program it was possible to calculate the local moisture distribution inside the sphere and the average moisture content both as a function of drying time and effective diffusivity coefficient for different air-drying temperatures.

The sample temperature dependence of the diffusivity may be represented by an Arrhenius type relationship (Wang & Brennan, 1992; Rosselló *et al.*, 1992). If heat transfer between the particle and drying air acts quickly, it is usually assumed that the process takes place under isothermal conditions and effective diffusivity varies as a function of air temperature. Effective diffusivity values, obtained using both proposed models for the different air-drying temperatures, were fitted separately to the Arrhenius equation (Equation 7).

$$D_{\text{eff}} = \exp\left(D_0 + \frac{E_a}{R(T + 273)}\right) \tag{7}$$

The activation energy $E_a$ can be determined from the plot of the naperian logarithm of $D_{\text{eff}}$ vs $1/T$.

## MATERIALS AND METHODS

Green peas (*Pisum sativum*) from Majorca, of $1.01.10^{-2} \pm 0.10.10^{-2}$ m diameter, were the raw material used in all experiments. Drying experiments were performed in a laboratory scale hot air drier, operated at average air-flow rate of 4.2 kg/m$^2$/s and at temperatures between 40 and 90°C. The air-flow figure is high enough to ensure that drying is mainly controlled by the internal resistance and practically not affected by mass transfer from the solid surface to the gas phase. A monolayer loading of the drier basket was used.

The drier used for sample dehydration (Fig. 1) was equipped with four 500 W electric resistances (at 380 V) serially connected and regulated by an automatic temperature controller HONEYWELL (±0.1°C) linked to a computer PCs Vectra QS/20 Hewlett–Packard. The ventilation system consists of a 0.5 C.V. fan impelling the air perpendicular through the bed. The air velocity was measured by a WM DTA4000 digital anemometer with an accuracy of ±0.1 m/s placed in the air duct. The sample to be dried is placed at the exit of the air duct in a perforated plate of 13 mesh. The weighing was automatically performed with a METTLER PM2000 balance linked to the computer. For weighing, a pneumatic three-way valve deviates the air stream.

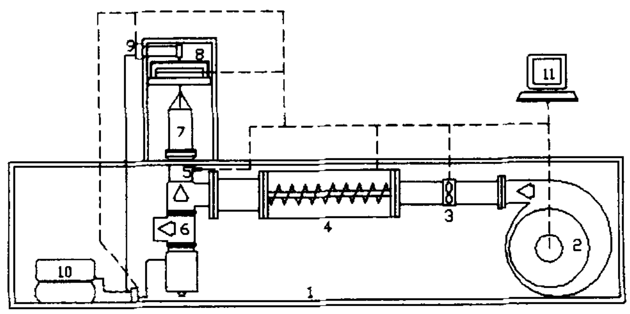


**Fig. 1.** Drier used for sample dehydration. 1 — Frame. 2 — Fan. 3 — Anemometer. 4 — Heating elements. 5 — Pneumatic valve. 6 — Temperature control measurement. 7 — Sample holder. 8 — Weighing element. 9 — Lifter. 10 — Air compressor. 11 — Computer.

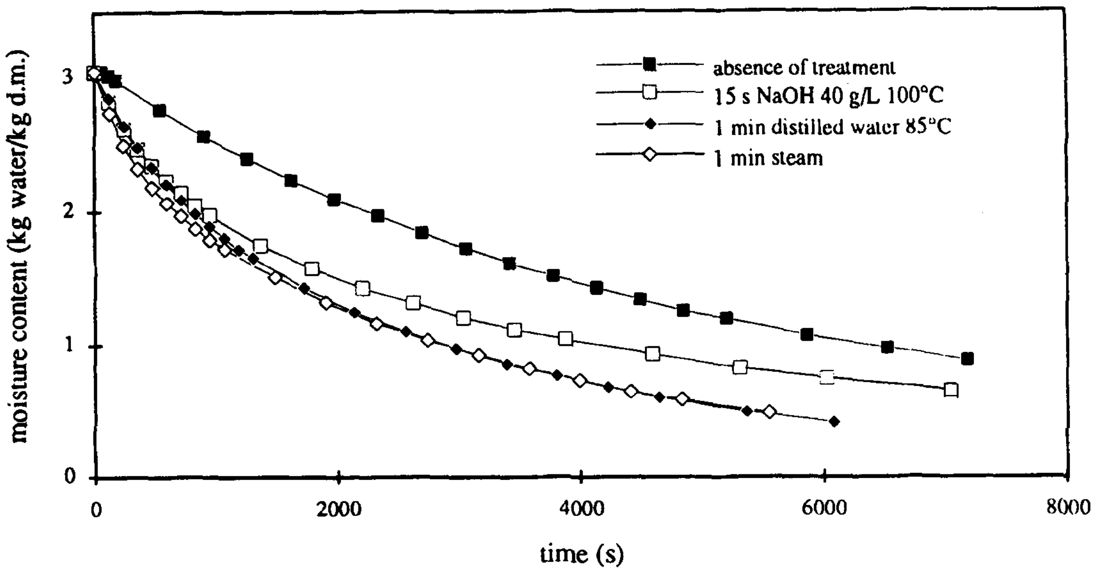


**Fig. 2.** Effect of different treatments before drying on the drying kinetics. Air temperature: 60°C. Air flow rate: 4.2 kg/m$^2$/s.

Temperature control, data acquisition and storage, as well as the general supervision of the unit, start-up and shut down, were all done by the computer program. A general layout of the unit is shown in Fig. 1.

Three different treatments of the samples before drying (a, b and c) for the drying kinetics of green peas were studied: (a) immersion in NaOH (40 g/litre) at 100°C for 15 s, (b) 60 s blanching by immersion in distilled water at 85 ± 1°C, and (c) 60 s steam-blanching at atmospheric pressure. Samples treated according to these procedures were dehydrated with air at 60°C. The choice of one of these procedures to continue with other experiments was made in order to obtain the quickest dehydration and a final product with good visual quality.

Volume changes were calculated by immersion of dried samples in distilled water to give different moisture contents, and measurement of the water displacement.

Temperature measurements of the green pea spheres were taken during the drying period following the methodology proposed by Simal *et al.* (1993). For a characteristic dimension smaller than 3 cm, thermal gradients can be safely neglected and the temperature, considered uniform throughout the sample although varying during the drying time (Rubiolo de Reinick & Schwartzberg, 1986). Thus, the experimental technique consisted in the insertion of a thin thermocouple in the centre of the sphere assuming the temperature to be practically uniform within the sample (Aguilera & Standley, 1990).

In order to perform the parametric identification and evaluation of the models, one set of experiments was carried out at different air-drying temperatures (40, 50, 60, 70, 80 and 90°C). Dehydration was carried out until a moisture content of ca. 0.3 kg water/kg dm (moisture content in dry matter basis) was achieved.

The average room air characteristics were: 22 ± 1°C and 68 ± 3% humidity. Water losses were measured by weighing the basket and its contents automatically. The moisture content of the dried product was obtained by the AOAC method No. 934.06 (A.O.A.C., 1990).

## RESULTS AND DISCUSSION

### Drying curves

The visual quality after rehydration of the dried green peas using the three different proposed treatments was considered adequate and equivalent by an *ad hoc* panel. To evaluate the second important aspect on the influence of pretreatments, some drying curves obtained using the different treatments before drying are shown in Fig. 2. In this figure, it may be observed that all the treatments increased the drying rate. However, treatments (b) and (c) provided higher drying rates, practically equivalent in both cases. Therefore, treatment (b) was chosen for processing before dehydration because of the lower temperature.

Experiments conducted to evaluate shrinkage helped to establish a relationship for the variation of the particle volume with the moisture content (Equation 8). The volume loss experienced by the samples was around 67%.

$$V/V_0 = 0.2677 + 0.2394W \quad r^2 = 0.999 \tag{8}$$

Drying curves proceeded from average moisture contents of ca. 3.0 down to 0.3 kg water/kg dm. A constant rate drying period was not detected in the drying experiments carried out at different air-drying temperatures, and only one diffusional-drying period was detected. Escardino *et al.* (1961) found that in a fixed bed the drying kinetics showed a constant rate drying period followed by one diffusional-drying period, although the air-flow rates were lower than those considered in this study.

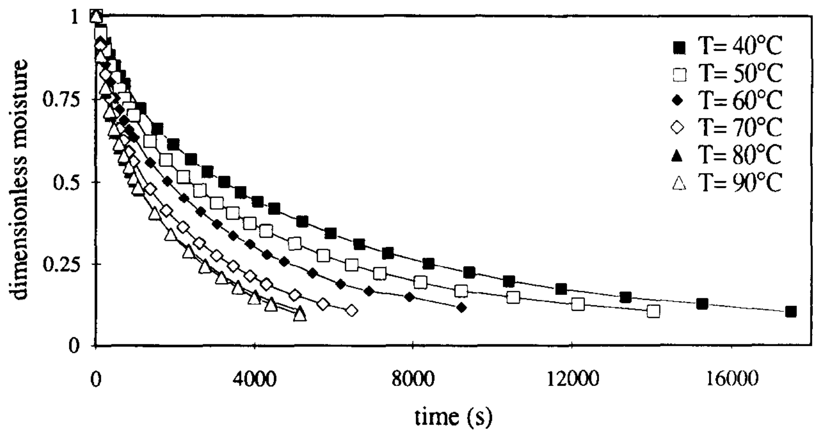


**Fig. 3.** Influence of air-drying temperature on the drying kinetics. Air flow rate: 4.2 kg/m²/s.

Figure 3 shows the drying curves of green peas at different drying air temperatures. The average moisture content was expressed as a dimensionless average moisture content (Equation 9). The equilibrium moisture content value ($W_e$) was obtained by using both the room air conditions and the moisture isotherm proposed by Iglesias & Chirife (1982) for green peas. The critical moisture content value used ($W_c$) was the initial moisture content due to the fact that no constant rate period was observed.

$$\Psi = \frac{W - W_e}{W_c - W_e} \tag{9}$$

The observation of the drying curves obtained in the experiments carried out at different air-drying temperatures showed that there was an important influence of the air-drying temperature on the drying rates except for the experiment carried out with an air temperature of 90°C (Fig. 3).

The explanation for this observation lies in the fact that at temperatures higher than 80°C, a case-hardening effect took place. Case hardening has been observed in hot air-drying by different authors for diverse products like root vegetables (Cho *et al.*, 1989) or carrots (Torringa *et al.*, 1993).

**First model: separation of variables**

Calculation of effective diffusivity coefficients for different air-drying temperatures ($D_{eff}$) was carried out according to the methodology previously outlined for the first model by using data from the experiments performed at 40, 60 and 80°C.

The parameters $D_o$ and $E_a$ from Equation (7) were estimated by fitting the calculated diffusivity values for each experiment. A log plot of the effective diffusivity coefficients obtained using the proposed model against the reverse of the absolute air-drying temperature is shown in Fig. 4. The results of the fitting are reported in Equation (10).

$$\ln(D_{eff}) = -2.86 - \frac{3439.7}{T + 273} \quad r^2 = 0.991 \tag{10}$$

From these results the activation energy for the

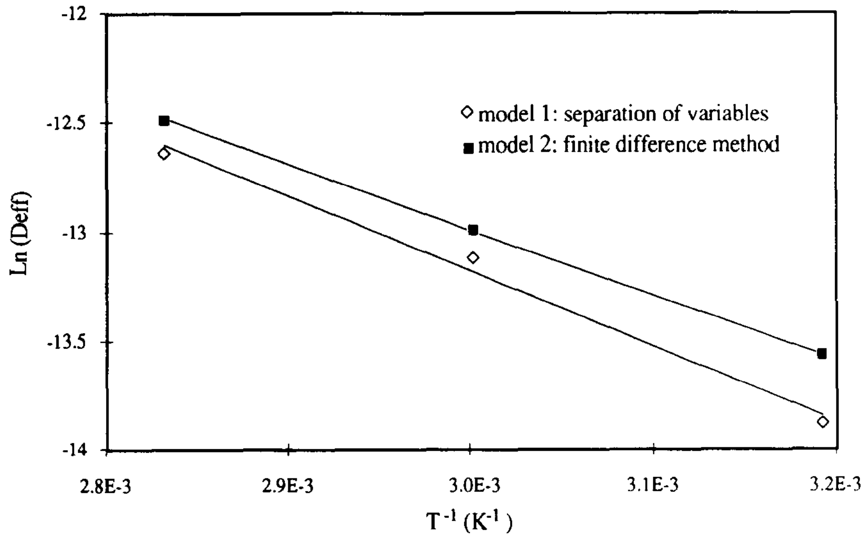


**Fig. 4.** Influence of temperature on the effective diffusivity coefficient. Air-flow rate: 4.2 kg/m²/s.

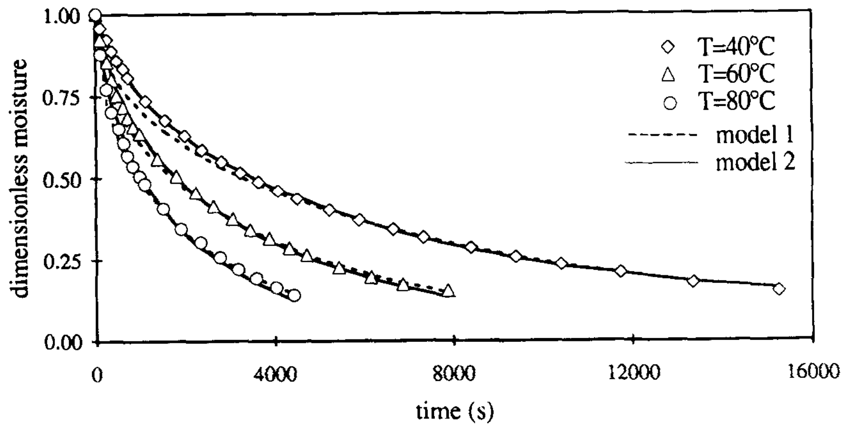


**Fig. 5.** Experimental and computed dimensionless moisture content obtained using both diffusional models. Data used for effective diffusivity identification. Air-flow rate: 4.2 kg/m$^2$/s.

diffusional period was identified as being 28.4 kJ/mol. This value is similar to those proposed by other authors for different products: 43.0 kJ/mol (Berna *et al.*, 1991) in raisins; 49.3 kJ/mol (Bimbenet *et al.*, 1985) in corn; 27.6 kJ/mol (Yousheng & Poulsen, 1988) in potato slabs.

Using these parameters (Equation 10), the drying curves for green peas at different air temperatures (40, 60 and 80°C) were simulated. In Fig. 5 experimental and calculated average dimensionless moisture data were presented for these experiments. As can be observed in this figure, although the simulation at the beginning of the drying process differs from experimental results, as a whole it could be considered that curves may be adequately simulated for certain purposes using this simple model. In fact, final drying time may be accurately predicted.

### Second model: finite differences

The effective diffusivity values were identified in experiments conducted at 40, 60 and 80°C throughout the proposed method of finite differences and $D_o$ and $E_a$ values were obtained by fitting $D_{\rm eff}$ values to the Arrhenius equation (Fig. 4).

$$\ln(D_{\rm eff}) = -4.03 - \frac{2698.2}{T + 273} \quad r^2 = 0.999 \qquad (11)$$

The identified activation energy was 24.7 kJ/mol, slightly lower than the figure identified from the first model results. This difference could be due to the fact that shrinkage is considered negligible in that first model.

In Fig. 5, experimental and calculated average dimensionless moisture data obtained using the second model are represented for the experiments conducted at these temperatures. Using this model it was possible to simulate the drying kinetics accurately, even during the first drying stages.

### Temperature evolution

Figure 6 shows the results for the temperature evolution in a drying experiment at 90°C. As can be observed, although the temperature in the centre of the particle increases rapidly, its value does not reach the air temperature in the time span considered (3600 s). As a consequence, the assumption of a high energy transfer might not be adequate, at least when mass transfer is high at the beginning of the drying process. Nevertheless, by

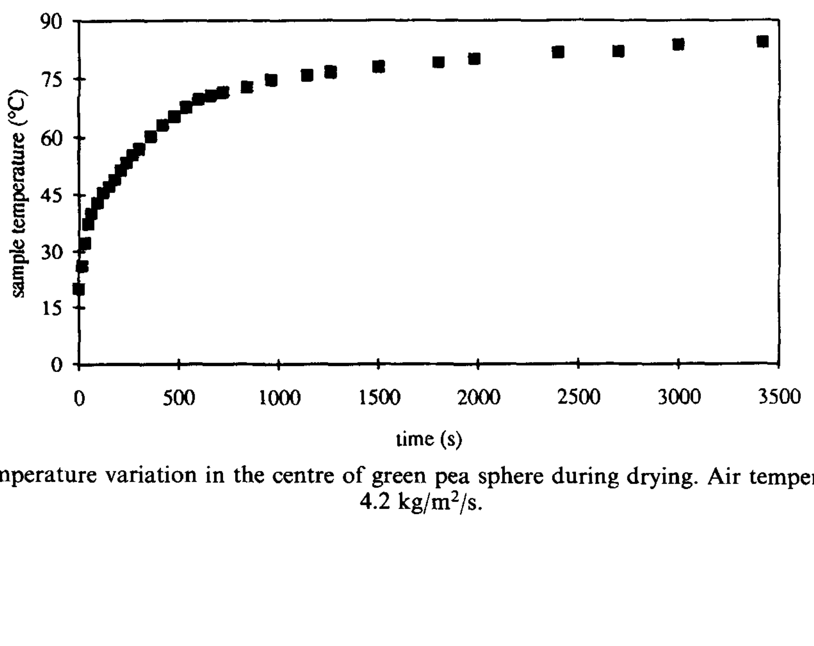


**Fig. 6.** Experimental temperature variation in the centre of green pea sphere during drying. Air temperature: 90°C. Air-flow rate: 4.2 kg/m$^2$/s.

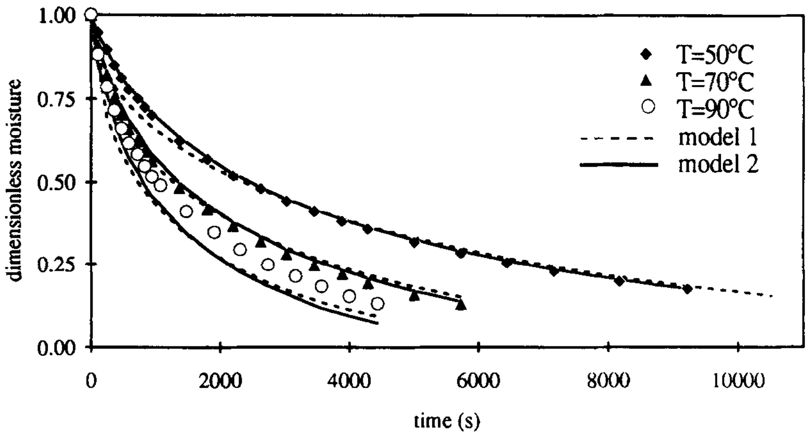


**Fig. 7.** Experimental and computed dimensionless moisture content obtained using both diffusional models. Data not used for effective diffusivity identification. Air-flow rate: 4.2 kg/m$^2$/s.

considering both drying models for describing isothermal processes, the quality of the results showed that there was no need to consider mass and energy balances simultaneously.

## Comparison of the two models

Comparison of predicted drying curves with experimental curves gives a measure of model validity. A good way to validate a model is to evaluate its accuracy for experiments not used in parameter identification. In Fig. 7 the experimental and calculated drying curves were represented using the proposed models for experiments different from those used in the identification of the effective diffusivity coefficient (50, 70 and 90°C). Using both models it is possible to simulate the drying kinetics of green peas at different air-drying temperatures (50 and 70°C). Nevertheless, model two simulates the drying of green peas more accurately, mainly during the first minutes of drying. It is observed that, at 90°C, neither model describes the drying behaviour due to case-hardening.

In order to mathematically evaluate the accuracy of both models, the percentage of explained variance ($v$) (Equation 12) was computed. The calculation was performed by using the standard deviation of the sample ($S_y$) and the corresponding estimation ($S_{yx}$):

$$v = \left[1 - \left(\frac{S_{xy}^2}{S_y^2}\right)\right]^{1/2} \times 100 \qquad (12)$$

**Table 1. Percentage of explained variance computed by comparing experimental and predicted results**

| $T$(°C) | $v$(model 1) | $v$(model 2) |
|---|---|---|
| 40 | 98.4 | 99.9 |
| 50 | 98.7 | 99.9 |
| 60 | 99.0 | 99.9 |
| 70 | 98.9 | 99.9 |
| 80 | 98.8 | 99.9 |

The results presented in Table 1 are those obtained by comparing the average experimental moisture content, and the predictions by the proposed models. Accuracy using the second model was considerably higher than that provided by the variables separation model at every one of the temperatures used in the experiments.

Moreover, another advantage is that the moisture profile in the spherical sample should be more accurately predicted using the model solved by the finite difference method. The availability of water profiles inside the particle could contribute to a better knowledge of chemical reactions taking place inside the particle during the drying process because they are often dependent on water availability. Nevertheless moisture profiles should be established from specific techniques such as NMR (McCarthy & Pérez, 1990; Shrader & Lichtfield, 1992).

The simple variable separation method could be used for preliminary estimation of the moisture diffusivity, since it was easier, saved time and reduced computer usage. The finite difference method could be used for more accurate predictions and simulation of the drying process. The results obtained through the second model, based on the percentage of explained variance, allow the conclusion that shrinkage cannot be neglected in establishing reliable values for $D_{eff}$. It does not seem advisable to increase the model complexity by considering the $D_{eff}$ dependence on local moisture and/or sample temperature, as recommended for other products in literature (Mulet, 1994).

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