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Experimental and Numerical Investigations of Moisture Diffusion in Pistachio Nuts during Drying with High Temperature and Low Relative Humidity

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ABSTRACT

In this study, a numerical solution based on finite element (FE) is adopted to simulate the mass distribution inside a pistachio nut (cv. Ohadi). It was found that the FE solution of the diffusive moisture transfer equation could improve nut-drying simulation of axisymmetric bodies. An axisymmetric linear triangular element with two degree of freedom per node was used to discretize the pistachio nut in the model. A thin layer pistachio nut was dried at two drying air temperatures of 55 and 70°C under constant air velocity and relative humidity and moisture content was measured every minute. The simulation data were tested using values obtained from thin layer drying experiments. Comparison showed that the simulation program gave good prediction for moisture content variations during the drying process. Results showed that there was no constant-rate drying period and the whole drying process occurs during the falling rate period. The moisture distribution inside the individual pistachio nuts was predicted using the model at five selected periods of 5, 10, 20, 50 and 100 min with drying air temperatures of 55 and 70°C. The results showed that distribution of the moisture content inside kernels was non-uniform. The moisture content at the center and surface of kernels reduced slowly and very rapidly respectively.

Key Words: Drying; Finite element method; Moisture diffusion; Pistachio nut

INTRODUCTION

Artificial drying is one of the most important stages of pistachio nut processing. Many theoretical and experimental studies have been conducted to describe the drying process of agricultural products (Ertekin & Yaldiz, 2004; Sacilik *et al*., 2006). Luikov developed a mathematical model for describing the drying of porous media (Husain *et al*., 1972). Some researchers, while applied Luikov's model to grain drying (Nemenyi *et al.,* 2000) concluded that consideration of the coupling effects of temperature and moisture in the analysis of grain drying is not required for engineering practice (Husain *et al.,* 1973). Jia *et al.* (2000) combined Luikov’s model and considered the effects of thermal behavior of grain, internal temperature and moisture gradients, which increased the drying simulation accuracy. Fortes *et al.* (1981) proposed a model for grain drying, which assumed that the liquid form of moisture diffused to the outer boundary of the kernel and evaporated on the surface of the grain. This assumption was supported by wheat drying experiments in other studies (Sokhansanj & Bruce, 1987). However, some assumptions, such as constant diffusion coefficient and material properties for simplifying calculations could affect the simulation accuracy.

The drying behavior, as described by moisture, temperature and stress distributions inside a kernel during drying and the quality traits of individual grain kernels affect the overall quality of the grain dried in a dryer (Yang *et al.*, 2003). Therefore, it is important to examine the internal behavior of a single nut in order to improve the drying process and product quality. Because of the small size of kernels, internal changes in temperature and moisture cannot easily be measured. Computer simulation is a powerful tool for achieving this goal. The increasing development of special professional software had a great impact on the design of dryers and quality evaluation of agricultural products. Much work has been done to simulate the temperature, moisture content and stress distributions inside single grain kernels (Cnossen & Siebenmorgen, 2000; Jia *et al*., 2000; Perdon *et al*., 2000; Yang *et al*., 2000, 2003; Wu *et al*., 2004), but there is no information about simulation of moisture diffusion in pistachio nut.

Ohadi variety is one of the major pistachio nut varieties that is grown in Iran. Therefore, this cultivar was selected in this study. In this study, the simulation of Ohadi variety drying was modified by the experimental data of the thin layer drying and mass transfer within pistachio nut during drying. The moisture content distribution inside the kernel at five selected times (5, 10, 20, 50 & 100 min) under drying air temperatures of 55 and 70°C was simulated.

MATERIALS AND METHODS

For pistachio nut drying simulation, the Fick’s diffusive equation describing the mass transfer process was applied (Jia *et al*., 2000):

$$\frac{\partial X}{\partial t} = div(D\nabla X)\text{, in the domain of grain, } \Omega, t > 0 \quad (1)$$

Where

X is the moisture content (d.b.); D is the diffusion coefficient (m^2/s); and t is time (s). The following initial (IC) and boundary (BC) conditions were used:

$$\text{IC: } X = X_i\text{, in the domain of nut, } \Omega, t = 0$$

$$\text{BC: } -D\frac{\partial X}{\partial n} = h_m(X_s - X_e)\text{, at the nut surface, } \Omega, t > 0 \quad (2)$$

Where

X_i, X_s and X_e are initial, surface and equilibrium moisture content of the nuts, respectively. In equation (2), h_m is surface moisture transfer coefficient and n is outward normal at the nut surface. Using a 2D Galerkin's model in cylindrical coordinate (r, ϕ, z) (Segerlind, 1984), equation 1 was rewritten as:

$$\int_\Omega [N]^T\left[D\left(\frac{\partial^2 X}{\partial r^2} + \frac{\partial^2 X}{\partial z^2}\right) - \frac{\partial X}{\partial t}\right]d\Omega = 0\text{, at the nut surface, } \Omega, t > 0 \quad (3)$$

Where

$[N]$ is the shape function matrix and r and z are cylindrical components. In conventional drying, the surface of the nut exchanges heat with the environment via convection, while the internal part of the nut is heated by conduction. For modeling a mathematical mass transfer in nut, it was assumed that liquid diffusion of moisture to the outer boundaries of the nut and evaporation only at the surface of nut. After some mathematical steps and replacing the notation Ω, with the two-dimensional space, A, the following system of first-order differential equations can be written:

$$K\{X\} + C\{\dot{X}\} - F = 0 \quad (4)$$

Where

K is the global moisture conductance matrix, C is the global moisture capacitance matrix and F the load vector. The forward difference method is used to approximate $\{X\}$, therefore equation (4) is rewritten as:

$$\left(K + \frac{C}{\Delta t}\right)X^{n+1} = \frac{C}{\Delta t}X^n + F \quad (5)$$

A computer program for a two-dimensional transient field problem such as the one described by equation (5) was written by Segerlind (1984). The effect of moisture content for each time step was modified for use of axially symmetric triangular elements. This new program first solves equation (5) for given initial nodal values. For every time step, Δt and a given set of nodal values, $\{X\}^i$ a set of nodal moisture values $\{X\}^{i+1}$ were obtained and stored.

The results of formulation used to model drying of a pistachio nut can be compared with experimental data. The differential equation for mass transfer (Equation 1) can predict the moisture distribution within the nut.

The pistachio nut was modeled with a two-dimensional axisymmetric finite element grid. Each grid consisted of 1600, 3-node elements, 861 nodes and time step Δt was 1s.

Thin layer drying data of pistachio nuts. The pistachio nuts were sliced for thin layer drying. The experiments were conducted at two different drying air temperatures (55 & 70ºC). Throughout the experiments the air velocitiy and relative humidity (RH) were maintained at 1.5 m/s and 5%, respectively. To reduce experimental errors, each test was performed in triplicate. The ambient, up-stream and down-stream dry bulb temperatures, air relative humidity, air velocity and sample weight were continuously monitored and the data were recorded every 60s (Fig. 1). Drying was continued until the moisture content (w.b.%) of the sample was reduced to 5%. The average moisture content of the samples during each weighing period was calculated, based on the initial mass and final moisture content of the samples. After each drying experiment, the samples were oven-dried at 103 ± 2ºC to determine the moisture content (Kashaninejad & Tabil, 2004).

RESULTS AND DISCUSSION

Equation (5) was solved numerically in order to predict moisture distributions within the pistachio nuts during drying. Nodal moisture values were calculated during drying. Because of inherent symmetry of pistachio nuts only a quarter of pistachio nut was modeled. Consequently, a finite element computer code for predicting the moisture fields inside a quarter of pistachio nut was developed using Fortran-90 language. Good agreements were observed when the output of the model was compared to the experimental data. The Mean Relative Deviation between simulation values for modified moisture diffusivity and experimental thin layer drying at drying air temperatures of 55 and 70°C, were 0.0824 and 0.1039, respectively. This confirmed that simulated results were very close to experimental data. Similar results have been reported by other researches for wheat (Jia *et al.*, 2000; Gaston *et al.*, 2002), peanut (Casada & Young, 1994), maize (Jia *et al.*, 1996) and rough rice (Yang *et al.*, 2000, 03).

Drying rates of pistachio nut at 55 and 70°C drying air temperature were also calculated (Fig. 2 & 3). A closer look at the results shown in these figures reveals that there is no constant-rate drying period and all the drying processes occur during the falling rate period. During the first 20 min the simulated values for drying air temperature of 55°C was

Fig. 1. Diagram of thin layer dryer

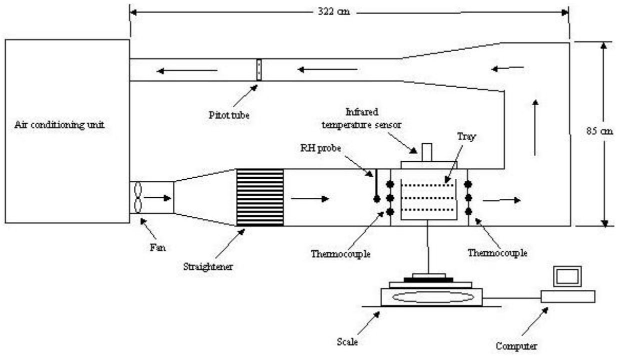


Fig. 2. Variation of drying rate with drying time and initial moisture content of 59.13% (d.b.), T = 55°C and RH = 5%

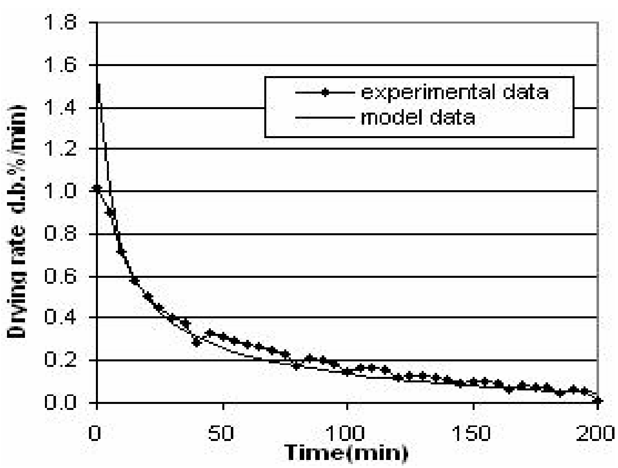
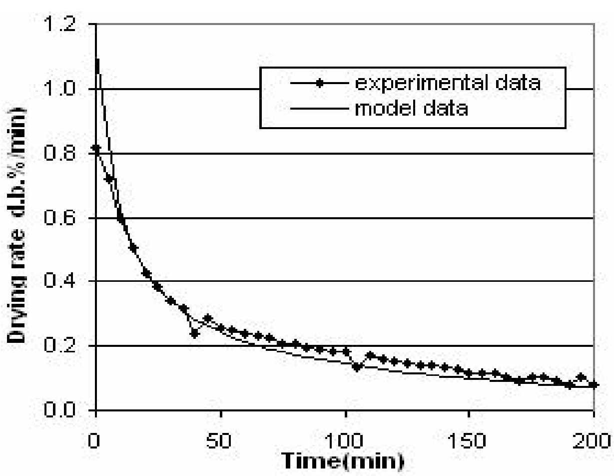


Fig. 3. Variation of drying rate with drying time and initial moisture content of 55.28% (d.b.), T = 70°C and RH = 5%



a bit higher than the experimental values and this trends was reversed afterwards. Similar trends during the first 25 min were shown for the drying air temperature of 70°C and after that the predicted values were lower than the experimental values. Drying decreased rapidly for the first 15 min and was slowed down thereafter.

From the practical point of view, it is important to know the temperature and moisture distributions of nuts during drying, because combinations of moisture and temperature gradients would produce greater stress levels in nut. In order to examine the moisture and thermal stresses in details, it is imperative to find the temperature and moisture distributions of nuts (Fortes *et al.,* 1981; Haghighi & Segerlind, 1988). Fig. 4 and 5 show the moisture content distributions inside the nuts at five selected times (5, 50, 100, 200 & 400 min) under drying air temperatures of 55 and 70°C, respectively. At initial stage of drying, nut's surface moisture content was decreased quickly and then

Fig. 4. Moisture distributions inside pistachio nuts at selected drying times for X_i= 59.13% (d.b.), T = 55°C and RH = 5%

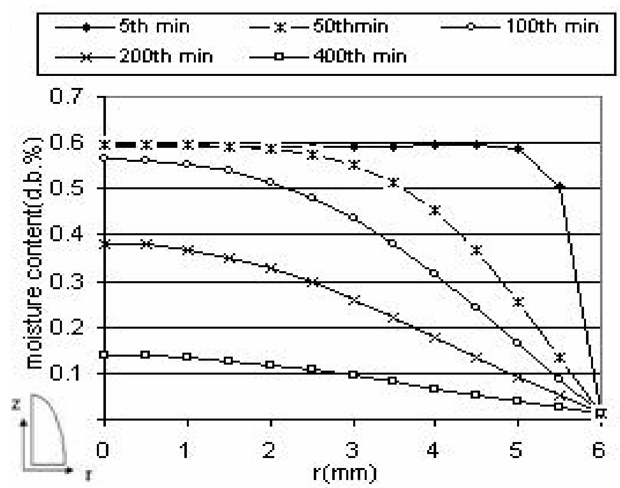
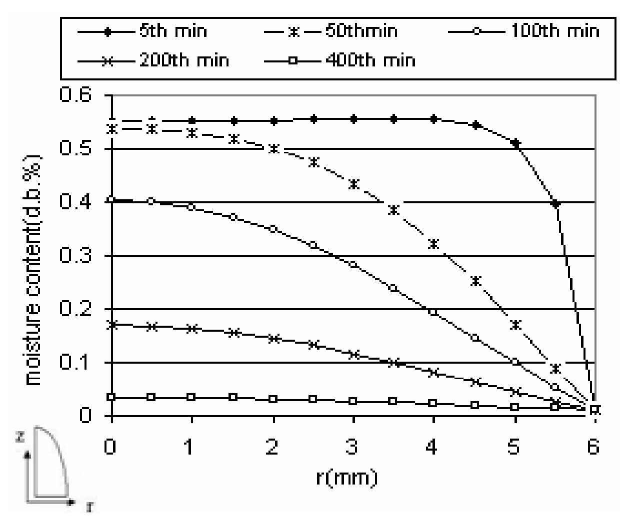


Fig. 5. Moisture distributions inside pistachio nuts at selected drying times for X_i = 55.28% (d.b.), T = 70°C and RH = 5%



slowly. But nut's center moisture content in first stage was constant and then decreased. The moisture distribution for different drying times was reported within a single kernels of wheat (Jia *et al.,* 2000), maize (Nemenyi *et al.,* 2000) and barley (Haghighi *et al.,* 1990).

CONCLUSIONS

The simulated moisture content of the pistachio nut's center showed that the times to reach 10% moisture content (from initial moisture content at drying air temperatures of 55 & 70ºC) were 1660 and 640 min, respectivly. The moisture content distribution of the pistachio nut's surface becomes dry very rapid and that of nut's center is slow. Therefore, it cause wide moisture gradient in the nut.

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