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MODELING HEAT TRANSFER DURING BLANCHING OF CUBIC PARTICLES OF LOCHE (*CUCURBITA MOSCHATA DUCH.*) AND POTATO (*SOLANUM TUBEROSUM L.*) USING FINITE DIFFERENCE METHOD

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ABSTRACT

The aim of this study was to model heat transfer during blanching of cubic particles of loche (*Cucurbita moschata* Duch.) and potato (*Solanum tuberosum* L.). The model included the variation of thermal properties based on temperature and the solution of the model was implemented by explicit finite difference method. Cube particles of $1 \times 1 \times 1$ cm^3, $2 \times 2 \times 2$ cm^3, and $3 \times 3 \times 3$ cm^3 were subjected to blanching at temperatures of 70, 80, and 90°C, each one, for 5 min. The heat transfer coefficient (h) was determined experimentally during heating of different sizes of aluminum cubes. The variation of the thermal diffusivity (α) was also determined according to the temperature increase, finding the minimum and maximum value of (α) for loche were: 1.55–1.61 $\times 10^{-7}$ m^2 s^{-1} and for potato were: 1.40–1.46 $\times 10^{-7}$ m^2 s^{-1}. A computer program in Visual Basic language was developed. The program includes the variation of the thermal diffusivity with respect to the increase of temperature with a second degree polynomial function. Experimental temperature profiles were compared with simulated ones, showing that an efficient convergence was achieved (RMSE: 0.329–5.119°C) for cubic particle of both vegetables.

PRACTICAL APPLICATIONS

The explicit finite difference scheme in three-dimensions (3D) developed in this research can be used to simulate heat transfer during heating of cubic particles of vegetables with variable thermal properties. Thermal properties of Loche (peruvian pumpkin) was reported for the first time and can be used for design and optimization of processes involving heating.

INTRODUCTION

The loche (*Cucurbita moschata* Duch.) is a high-quality landrace of cucurbitacea grown only on the northern coast of Perú and practically unknown elsewhere (Andres *et al.*, 2006), together with the potato (*Solanum tuberosum* L.) are potential vegetables to be processed and expended in different ways.

Blanching is one of the pretreatments to be subjected to these vegetables. It is a thermal treatment applied before freezing, frying, drying and canning, used mainly to (i) destroy enzymatic activity (Fellows, 2000; Chamorro and Vidaurreta, 2012), (ii) maintain the fresh color, stabilization of texture and nutritional quality (Abu-ghannam and Crowley, 2006; Jaiswal *et al.*, 2012); (iii) expel of air between the cells (Fellows, 2000); (iv) destroy the microorganisms to some extent (Morales-Blancas et al., 2002; Garrote *et al.*, 2004; Agüero *et al.*, 2008; Saldivar *et al.*, 2010).

The application of this heat treatment without adequate control may cause problems such as texture losses, nutrient losses, bioactive component losses and pigment modifications (Saravacos and Kostaropoulos, 2002; Galindo *et al.*, 2005; Latorre *et al.*, 2013; Martínez *et al.*, 2013).

Correct mathematical modeling is a very useful tool for studying the effect of process variables on the safety and quality-related attributes of food products (Palazoğlu and Erdoğdu, 2008). To simulate the heat distribution in a body, one can use analytical solutions; as long as they remain constant properties of the food and regular-shape body (Çengel, 2007; Erdoğdu and Turhan, 2008). Several studies, used numerical methods to simulate heat transfer, because these are useful for estimating the thermal behavior of foods under complex but realistic conditions such as variation in initial temperature, nonlinear and nonisotropic thermal properties, irregular-shaped bodies and time dependent boundary conditions (Wang and Brennan, 1995; Ansari, 1999; Delgado and Sun, 2003; Mohamed, 2003; Scheerlinck *et al.*, 2004; Betta *et al.*, 2009; Lespinard *et al.*, 2009; Loss *et al.*, 2011; Sakin-Yilmazer *et al.*, 2012; Lemus-Mondaca *et al.*, 2013).

Fasina and Fleming (2001) developed the method of finite differences to cucumbers of finite cylinder shape, in order to simulate heat transfer during blanching thereof, experimentally determining the values of thermal conductivity, specific heat and density of cucumbers for incorporation into the differential equation of heat diffusion. Finding an acceptable adjustment with real values, the maximum standard error of simulated temperatures of the cucumbers from experimental data was 4.5°C.

Loss *et al.* (2011) simulated the convective drying of papaya cubes $1 \times 1 \times 1$ cm^3, $2 \times 2 \times 2$ cm^3 and $3 \times 3 \times 3$ cm^3 at temperatures of 50, 60, and 70°C, using the scheme of explicit finite differences and the implicit method of Crank–Nicholson, finding explicit method that best fits the results for the cubes $2 \times 2 \times 2$ cm^3 and $3 \times 3 \times 3$ cm^3.

Palazoglu (2006), developed the method of finite differences in cubic particles using the concept of thermal resistance, validating the numerical solution with the analytical solution obtained in three dimensions, using potato cubes of 0.127 cm per side.

The inclusion of varying thermal properties of the food, with respect to temperature, was studied in the simulation of the freezing process, where a change of state of water is evident and therefore a drastic variation in the thermophysical properties in food. Recent research, like Lemus-Mondaca *et al.* (2013), simulated heat and mass transfer during drying of 3D cubes of papaya in a temperature range between 40 and 80°C, including the variation of the thermal properties depending on temperature increase by the numerical method of finite element; finding that the relative error of the simulated values on experimental data was <9.5% for temperature and 5.4% for moisture content using the 3D mathematical model. The quality of the predicted results illustrates that the 3D model of the coupled heat and liquid moisture transfer in solid food is satisfactory.

Scheerlinck *et al.* (2004) validated the finite element simulation of heat transfer during heating and cooling of strawberries at temperatures of 45 and 5°C, using thermal properties variables during heat transfer, although these properties were wholly obtained using of empirical equations, using the composition, RMSE values found were between 0.19 and 0.45°C. Hitherto, the agreement between predicted and measured values is very good, especially when taking into account some level of uncertainty on: (i) the shape of the food, (ii) exact measurement position, (iii) thermophysical properties, and (iv) the surface heat transfer coefficient (Scheerlinck *et al.*, 2004; Erdoğdu and Turhan, 2008; Loss *et al.*, 2011; Lemus-Mondaca *et al.*, 2013).

The aim of this study was to model and simulate the heat transfer during blanching of cubic particles of loche and potato, including the variation of thermal properties based on temperature, using explicit finite difference scheme.

MATERIALS AND METHODS

Conditioning and Blanching of Raw Materials

Loches and potatoes were obtained at the local market. Moisture content, protein, fat, fiber and ash were determined in triplicate and reported on wet weight basis using AOAC (2000) methods, while carbohydrate content was calculated for difference. Raw materials were carefully cleaned, peeled with a stainless steel knife and then cut into cubes of $1 \times 1 \times 1$ cm^3; $2 \times 2 \times 2$ cm^3; and $3 \times 3 \times 3$ cm^3, using digital Vernier calipers. One thermocouple type-K was inserted into the geometric central point of each cube, for cubes of $3 \times 3 \times 3$ cm^3 other thermocouple type-K were inserted close to the surface of raw materials. In most cases, this could not be achieved because of the soft nature of the vegetable tissue. Therefore, the actual locations of the thermocouple tips were obtained by cutting the raw materials after heating and measuring with the Vernier calipers.

Blanching was performed in a water bath of 15 L, at temperatures 70, 80, and 90°C for 300 s. As a control one thermocouple type-K remained immersed in the heating medium. Temperature was recorded, with an accuracy of ±0.2°C, every 1 s using a digital multimeter and this in turn connected to a personal computer (Fig. 1). Blanching experiments were conducted in triplicate.

Determination of Heat Transfer Coefficient (H)

The lumped heat capacity analysis method was used to determine h. Aluminum cubes $1 \times 1 \times 1$ cm^3; $2 \times 2 \times 2$ cm^3; and $3 \times 3 \times 3$ cm^3 were subjected to blanching temperatures at 70, 80, and 90°C and temperature were taken in the center of each cube. Assuming that the thermal properties of aluminum are: Density (ρ): 2707 kg m^{-3}; thermal conductivity (k): 204 W m^{-1} °C and heat capacity (c_p): 896 J kg^{-1} °C.

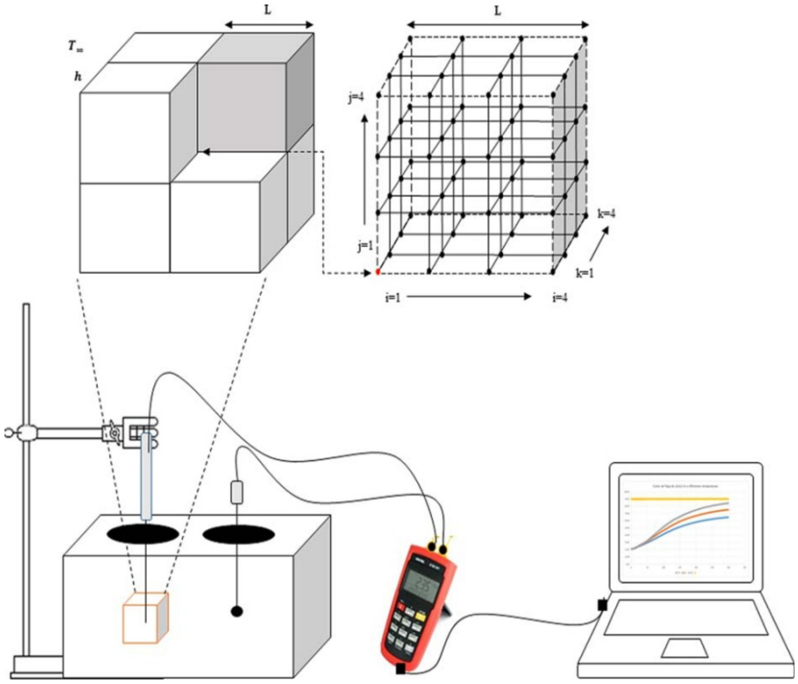

FIG. 1. SCHEMATIC OF THE EXPERIMENTAL SETUP AND NODE GENERATION IN A PARTICLE CUBIC

The h value was determined by application of Newton's law (Özişik, 1993; Singh and Heldman, 2014):

$$\frac{T-T_\infty}{T_i-T_\infty}=\exp\left[-\frac{hAt}{\rho V c_p}\right] \qquad (1)$$

where T is the temperature at the geometric center of object (°C), T_i the initial temperature of object (°C), T_∞ the temperature of blanching water (°C), A the surface area (m^2), and V is the volume (m^3). From the temperature history of the particle, plots of ln $[(T_c-T_\infty)/(T_i-T_\infty)]$ vs. time can be carried out to obtain the slope value; thus, the convective heat transfer coefficient may be calculated.

Determination of Variable Thermal Properties

Thermal diffusivity of loche and potato was determined by temperatures at 40, 50, 60, 70, 80, and 90°C, in order to obtain a mathematical function relating the thermal diffusivity with respect to temperature. Loches and potatoes samples were introduced into a hollow aluminum cylinder (15 cm effective length and 0.0595 cm radius). A thermocouple type K was inserted it in the center of the sample and the tube ends were capped with rubber as insulating material. Thermal diffusivity was calculated using the method described by Baïri *et al.* (2007) who used 1D analytical solution of the heat transfer equation of an infinite cylinder.

Where the analytical solution of the 1D Fourier's equation in cylindrical co-ordinates, using the method of separation of variables can be written as (Erdoğdu and Turhan, 2008):

$$\frac{T_{(x,t)}-T_\infty}{T_i-T_\infty}=\left[\frac{2\cdot J_1(\mu_n)}{\mu_n\cdot[J_0^2(\mu_n)+J_1^2(\mu_n)]}\cdot J_0\left(\mu_n\cdot\frac{r}{R}\right)\right]\cdot\exp\left(-\mu_n^2\frac{\alpha\cdot t}{R^2}\right) \qquad (2)$$

at the center where $r=0$, $Jo(0)=1$, then calling A to the constant part of this equation and taking natural logarithm of both sides, it becomes

$$\ln\frac{T_{(x,t)}-T_\infty}{T_i-T_\infty}=\ln A+\left(-\mu_n^2\frac{\alpha\cdot t}{R^2}\right) \qquad (3)$$

Graphically Eq. (3) is a straight line, where the slope $\left(-\mu_n^2\frac{\alpha}{R^2}\right)$ was used to determine the effective thermal diffusivity (α) for each experimental temperature, using the first root of the characteristic equation ($\mu_n=2.045$).

Thermal conductivity was predicted using the equations proposed by Choi and Okos (1986) (Eq. (4)) using the food components as functions of temperature.

$$k=\sum\left(k_{si}\,\frac{\frac{X_i}{\rho_i}}{\sum\left(\frac{X_i}{\rho_i}\right)}\right) \qquad (4)$$

Modeling Heat Transfer Using Finite Difference in 3-Dimensional (3D)

Heat conduction equation in Cartesian coordinates in three dimensional (Eq. (5)) was numerically modeled with the initial and boundary conditions presented in Eq. (6) (Fasina

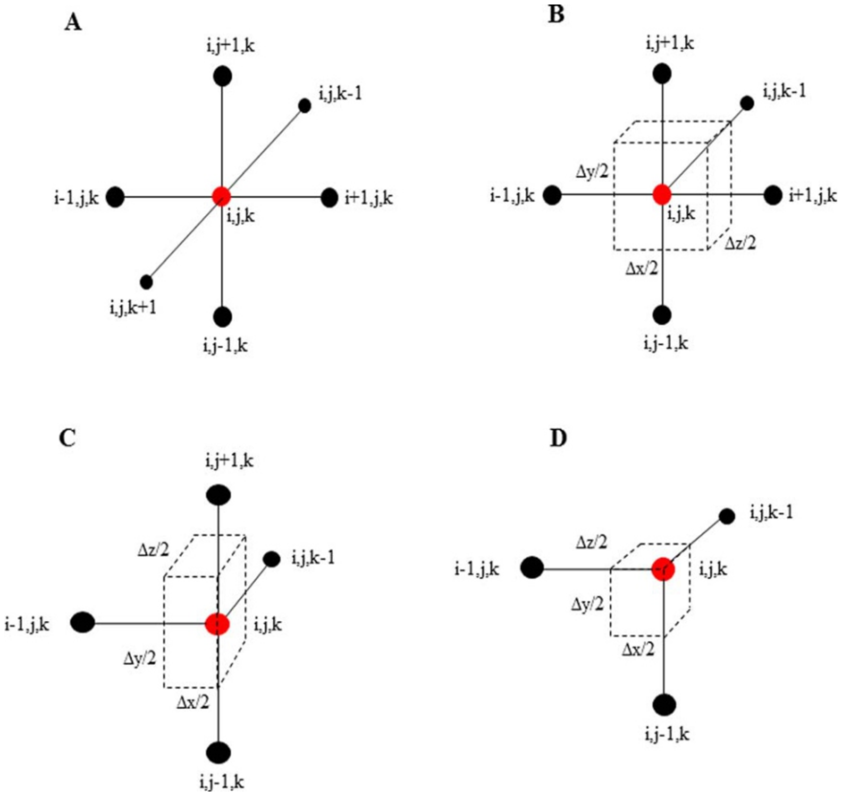

FIG. 2. NODAL CONNECTION (I, J, K). (A) INTERNAL NODE CONNECTED WITH SIX NODES; (B) EXTERNAL NODE CONNECTED WITH FIVE NODES; (C) EXTERNAL NODE CONNECTED WITH FOUR NODES; (D) EXTERNAL NODE CONNECTED WITH THREE NODES

and Fleming, 2001; Palazoglu, 2006; Lespinard *et al.*, 2009; Chamorro and Vidaurreta, 2012).

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{5}$$

As mentioned by Palazoglu (2006), numerical modeling of the heat transfer in cubic geometry can be performed only for 1/8 of the whole particle volume (shaded volume in Fig. 1), since thermal symmetry about the geometric center of particle exists due to the same boundary conditions at all surfaces.

The explicit finite difference program was written in programming language Visual Basic 2013 (Microsoft Corporation), where internal nodes were programmed to transfer heat by conduction, considering the six nodal connections that may have an internal node (Fig. 2A).

For internal nodes the new temperature for each time step, $T^{t+1}_{\mathrm{i,j,k}}$, was calculated as follows:

$$\begin{aligned} T^{t+1}_{\mathrm{i,j,k}} = {} & (1-2F1-2F2-2F3)T^{t}_{\mathrm{i,j,k}} + F1\left(T^{t}_{\mathrm{i+1,j,k}} + T^{t}_{\mathrm{i-1,j,k}}\right) \\ & + F2\left(T^{t}_{\mathrm{i,j+1,k}} + T^{t}_{\mathrm{i,j-1,k}}\right) + F3\left(T^{t}_{\mathrm{i,j,k+1}} + T^{t}_{\mathrm{i,j,k-1}}\right) \end{aligned} \tag{6}$$

$$\text{where}: \ F1 = \frac{\alpha\Delta t}{\Delta x^2}, F2 = \frac{\alpha\Delta t}{\Delta y^2} \ \text{y} \ F3 = \frac{\alpha\Delta t}{\Delta z^2}$$

The stability of Eq. (6) was obtained making positive the quotient$(1 - 2F1 - 2F2 - 2F3)$. Considering $\Delta x = \Delta y = \Delta z$, the stability criterion for nodes with conductive heat transfer, was: $F1 = F2 = F3 \leq 1/6$.

External nodes were programmed to transfer heat by convection using energy balance method, three particular cases were found, as shown in Fig. 2B–D.

The Eqs. (7–9) show how the new external temperatures were determined for each period of time, for nodes with five, four, and three connections, respectively.

$$\begin{aligned} T^{t+1}_{\mathrm{i,j,k}} = {} & (1-F4N_{\mathrm{Bi}}-5F4)T^{t}_{\mathrm{i,j,k}} + F4N_{\mathrm{Bi}}(T_\infty) \\ & + F4\left(T^{t}_{\mathrm{i+1,j,k}} + T^{t}_{\mathrm{i-1,j,k}} + T^{t}_{\mathrm{i,j+1,k}} + T^{t}_{\mathrm{i,j-1,k}} + T^{t}_{\mathrm{i,j,k-1}}\right) \end{aligned} \tag{7}$$

$$\begin{aligned} T^{t+1}_{\mathrm{i,j,k}} = {} & (1-2F5N_{\mathrm{Bi}}-4F5)T^{t}_{\mathrm{i,j,k}} + 2F5N_{\mathrm{Bi}}(T_\infty) \\ & + F5\left(T^{t}_{\mathrm{i-1,j,k}} + T^{t}_{\mathrm{i,j+1,k}} + T^{t}_{\mathrm{i,j-1,k}} + T^{t}_{\mathrm{i,j,k-1}}\right) \end{aligned} \tag{8}$$

$$\begin{aligned} T^{t+1}_{\mathrm{i,j,k}} = {} & (1-3F6N_{\mathrm{Bi}}-3F6)T^{t}_{\mathrm{i,j,k}} + 3F6N_{\mathrm{Bi}}(T_\infty) \\ & + F6\left(T^{t}_{\mathrm{i-1,j,k}} + T^{t}_{\mathrm{i,j-1,k}} + T^{t}_{\mathrm{i,j,k-1}}\right) \end{aligned} \tag{9}$$

where: $F4 = F5 = F6 = \frac{\alpha\Delta t}{\Delta x^2/2}$ and $N_{\mathrm{Bi}} = \frac{\Delta x \ h}{k}$; considering that $\Delta x = \Delta y = \Delta z$

TABLE 1. PROXIMAL COMPOSITION OF LOCHE AND POTATO PER 100 G

Component	Loche (*Cucurbita moschata* Duch.)	Potato (*Solanum tuberosum* L.)
	Content (%)	Content (%)
Water	75.72 ± 0.97	81.00 ± 1.02
Protein	1.82 ± 0.01	1.34 ± 0.03
Fat	0.14 ± 0.03	0.06 ± 0.02
Carbohydrate	19.29 ± 0.04	16.38 ± 0.03
Crude fiber	1.72 ± 0.02	0.47 ± 0.01
Ash	0.32 ± 0.01	0.74 ± 0.02

The stability of Eqs. (7–9) was obtained making positive the quotient of $T^{t}_{\mathrm{i,j,k}}$, for: $\mathrm{F4} \leq 1/((\mathrm{N_{Bi}}+5))$; $\mathrm{F5} \leq 1/((2\mathrm{N_{Bi}}+4))$ and $\mathrm{F6} \leq 1/((3\mathrm{N_{Bi}}+3))$.

Validation of Finite Difference Method

Analytical solution was used to validate the numerical solution (Cai et al., 2006; Erdoğdu and Turhan, 2008; Palazoğlu and Erdoğdu, 2008). It was obtained by employing the first six terms of the infinite series solution for the three-dimensional cubic particle with a convective boundary at the surface (Eq. (10)).

$$\left(\frac{T_{(\mathrm{x,y,z,t})}-T_{\infty}}{T_{\mathrm{i}}-T_{\infty}}\right)_{3D}=\sum_{n=1}^{6}\left[\frac{2\cdot sin\left(\mu_{\mathrm{n}}\right)}{\mu_{\mathrm{n}}+sin(\mu_{\mathrm{n}})\cdot cos(\mu_{\mathrm{n}})}\cdot \exp\left(-\mu_{n}^{2}\frac{\alpha t}{L^{2}}\right)\right]^{3} \tag{10}$$

The degree of fitting numerical simulations with analytical solution were compared using known thermal properties of potato ($\rho = 1090$ kg m^{-3}; $k = 0.554$ W m^{-1} °C; $c_{\mathrm{p}} = 3515$ J kg^{-1} °C), at the maximum temperature of blanching (90°C), using the estimated coefficient of heat transfer, in order to determine the number of nodes and time steps so that the simulation is stable and convergent.

Simulation Heat Transfer During Blanching Including Variable Thermal Properties

Using the model of finite difference in three-dimensional (3D) validated, a subroutine was incorporated to vary the thermal properties of each node, according to temperature increase. According to Lemus-Mondaca *et al.* (2013) and Wu *et al.* (2004), the new mathematical model was expressed as follows:

$$\rho(T)C_{\mathrm{p}}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) \tag{11}$$

The initial temperature is uniform and equal to:

$$t=0;\ \ T(x,y,z,0)=T_{\mathrm{o}} \tag{12}$$

To validate the proposed new model, experimental data of blanching of loche and potatoes were compared with explicit finite difference simulation with variable thermal properties.

Statistical Analysis

As suggested by Scheerlinck *et al.* (2004) and Uyar and Erdogdu (2012), to evaluate the fit of quality of the simulations, either to validate the simulation by finite difference in 3D, as well as to validate the simulation with variable thermal properties in 3D with experimental data, root mean square error (RMSE, Eq. (13)) was used.

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T-T_{\mathrm{simulation}}\right)^{2}} \tag{13}$$

RESULT AND DISCUSSION

Characterization of Raw Materials

Table 1 shows the results of proximal composition of loches and potatoes. In the case of loche, the values found are similar to those reported by García *et al.* (2009). The proximal loche analysis also confirms that reported by Indecopi (2010), who notes that this vegetable is characterized by its high fiber content. With respect to the proximal composition of the potato variety "Yungay," is very similar to those reported by Obregón La Rosa *et al.* (1998).

TABLE 2. HEAT TRANSFER COEFFICIENT (*H*) AT SURFACE OF DIFFERENT SIZES OF ALUMINUM CUBES, SUBJECTED TO DIFFERENT HEATING TEMPERATURES

	Heat transfer coefficient (W m^{-2}°C)		
Aluminum (cm^3)	70°C	80°C	90°C
1 x 1 x 1	655.34 ± 30.35^{a}	745.55 ± 22.76^{a}	1083.65 ± 61.15^{b}
2 x 2 x 2	655.62 ± 19.47^{a}	712.92 ± 17.36^{a}	986.08 ± 41.90^{b}
3 x 3 x 3	691.49 ± 59.74^{a}	793.86 ± 22.18^{a}	972.33 ± 89.82^{b}

^{a,b}Letters indicate significant difference at $P < 0.05$.

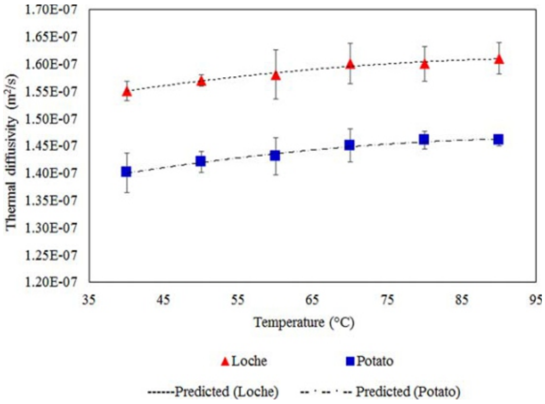

FIG. 3. THERMAL DIFFUSIVITY OF LOCHE AND POTATO AT DIFFERENT TEMPERATURES

Heat Transfer Coefficient During Blanching

Table 2 shows the values of the heat transfer coefficients found; as can be seen, there was not a significant difference between the different sizes of cubes ($P > 0.05$), but there was a significant difference between heating temperatures ($P < 0.05$). This was corroborated by Sablani (2008); Hahn and Ozisik (2012) and Singh and Heldman (2014), who noted that this property depends primarily on the conditions of the heating medium. In research conducted by Alhamdan and Sastry (1990) and Awuah and Ramaswamy (1993) they noted that the concentration of carboxymethvl cellulose (CMC) in the fluid and the heating temperature, have a great impact on (h). Noting that (h) increases as the temperature rises and decreases with increasing viscosity of the heating medium.

Similar values are reported by different researches; Palazoglu (2006) uses the value of 1000 W m^{-2}°C to simulate the heat transfer potato cubes of 1.27 × 1.27 × 1.27 cm^3 subjected to 100°C for 100 s. Scheerlinck *et al.* (2004) determined that (h) was 590 W m^{-2}°C when strawberries were heated to 45°C. Alhamdan and Sastry (1990) found values of (h) between 75 and 310 W m^{-2}°C, when food of irregular shapes are heated in water with CMC (carboxymethyl cellulose) and samples are heated in water, found values of (h) between 652 and 850 W m^{-2}°C. Lamberg and Hallström (1986) simulated cylinder heat transfer during blanching potatoes (6-cm diameter and 1.8-cm thick) to 75° C, and found a good correlation between simulated and experimental data when the coefficient heat transfer was 750 W m^{-2}°C.

Thermal Properties of Raw Material

Figure 3 shows the relationship of thermal diffusivity of loche and potato with respect to temperature. As expected, the thermal diffusivity increases with respect to temperature increase, to find that the minimum and maximum values of (α) for loche was 1.55×10^{-7} and 1.61×10^{-7} m^2 s^{-1}, respectively, and for potato, the minimum and maximum value of (α) found was 1.35×10^{-7} and 1.47×10^{-7} m^2 s^{-1}, respectively.

The heat diffusion of loche was faster than that of the potato and both fit a quadratic function (Ec. (14) and (15)) with R^2: 0.979 for loche and R^2: 0.983 for potato.

$$\alpha_{Loche} = 1.61\ x\ 10^{-12}\left(T^2\right) + 3.26\ x\ 10^{-10}\ (T) + 1.45x\ 10^{-7} \tag{14}$$

$$\alpha_{Potato} = 1.79\ x\ 10^{-12}\left(T^2\right) + 3.58\ x\ 10^{-10}\ (T) + 1.28x\ 10^{-7} \tag{15}$$

Thermal diffusivity of loche, found in this study, are similar to those reported in the literature, their counterparts as squash and pumpkins. Ahromrit and Nema (2010), reported an apparent thermal diffusivity value of 1.62×10^{-7} m^2 s^{-1} to squash, containing 72% water, subjected to frying at 180°C. Likewise Gaffney *et al.* (1981) reported a thermal diffusivity value of 1.71×10^{-7} m^2 s^{-1} for pumpkins subjected to a heating temperature of 47°C.

Similarly to the case of potatoes, thermal diffusivity values found in this research were similar to those reported in other studies, such as the work done by Rice *et al.* (1988) who studied the effect of temperature on the thermal properties of the potato (76.3% moisture), subjected to heating from 40 to 90°C and found that the thermal diffusivity increases with temperature until a maximum value 1.34×10^{-7} m^2 s^{-1} at 70°C, and then decreased to 1.32×10^{-7} m^2 s^{-1} at 90°C, which could be due to starch gelatinization which may alter the structure of the potato as has been indicated by Rao *et al.* (1975). Murakami (1997), studied the variability of the thermal properties of the potatoes and carrots subjected to different processes, finding that (α) decreases after the sterilization process and increases during cooking. Reporting values (α) of 1.44×10^{-7} m^2 s^{-1} for potatoes with 77.8% moisture. Recent research also report the low thermal diffusivity of potatoes, as in the work of Cariño-Sarabia and Vélez-Ruiz (2013) who used the value 1.34×10^{-7} m^2 s^{-1} when potato cubes are 2 × 2 × 2 cm^3 heated to temperatures of 70–85°C. Palazoglu (2006) and Yildiz *et al.* (2007)

TABLE 3. COMPARISON OF NUMERICAL AND ANALYTICAL SOLUTIONS OBTAINED FOR CUBIC PARTICLES

	Temperature at center node (°C)		
Cube (cm^3)	Numerical	Analytical	RMSE
1 x 1 x 1	85.8	85.7	0.142
2 x 2 x 2	39.3	39.2	0.062
3 x 3 x 3	21.7	21.7	0.074

T_o=20°C; T_∞=90°C; *Time*=100 s; h=1000 *W* *m*−2°C.

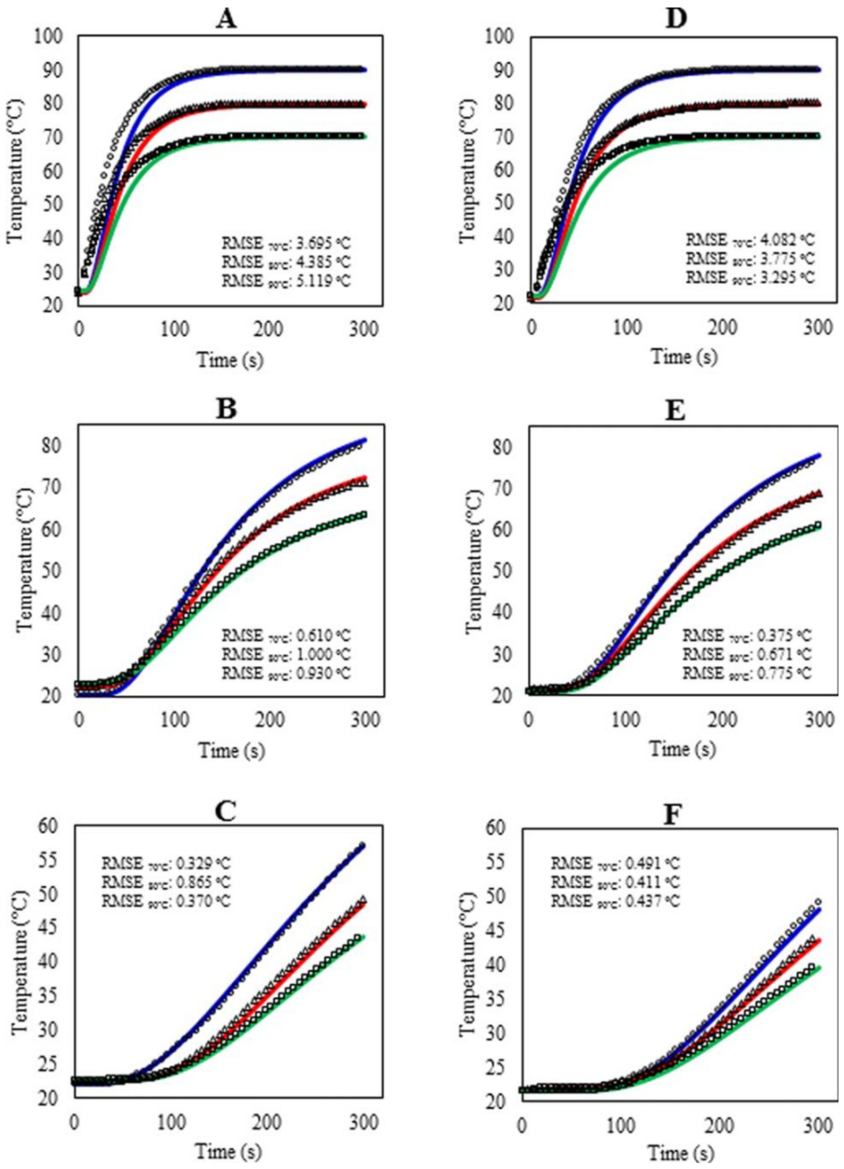

FIG. 4. COMPARISON BETWEEN EXPERIMENTAL DATA AND SIMULATED CENTER TEMPERATURE PROFILES DURING BLANCHING AT 70°C (○), 80°C (Δ) AND 90°C (□). (A) LOCHE OF 1 × 1 × 1 CM^3; (B) LOCHE OF 2 × 2 × 2 CM^3; (C) LOCHE OF 3 × 3 × 3 CM^{3}3; (D) POTATO OF 1 × 1 × 1 CM^{3}3; (E) POTATO OF 2 × 2 × 2 CM^3; (F) POTATO OF 3 × 3 × 3 CM^3

use the value of (α) of 1.45×10^{-7} m^2 s^{-1} to simulate frying and heating of potato.

With respect to thermal conductivity, the predicted values for the loche were: 0.59 W m^{-1} °C for 70, 80, and 90°C and for potato, the predicted thermal conductivity values were: 0.60 W m^{-1} °C for 70 and 80°C, and 0.61 W m^{-1} °C to 90°C. The values found in this research, are similar to those reported in other studies. Rao *et al.* (1975) reported values of thermal conductivity of five varieties of potatoes, which ranged from 0.533 to 0.571 W m^{-1} °C. Rice *et al.* (1988), reported that the thermal conductivity remains at a constant value of 0.56 W m^{-1} °C when potatoes are heated at 80–90°C. Murakami (1997) mentions that blanching potatoes for 10 min had a negligible effect on the thermal conductivity remaining constant at a value of 0.577 W m^{-1} °C.

Mathematical Model Validation

To validate the mathematical model and the numerical solution procedure, blanching was simulated of different cubic particle of potato at 90°C. A close agreement between the results of simulation numerical and analytical was found, when cubes of 1 × 1 × 1 cm^3 used 10 nodes in each direction and for cubes of 2 × 2 × 2 cm^3 and 3 × 3 × 3 cm^3 when used 20 nodes in each direction, for all cases with time step of 0.125 s (Table 3).

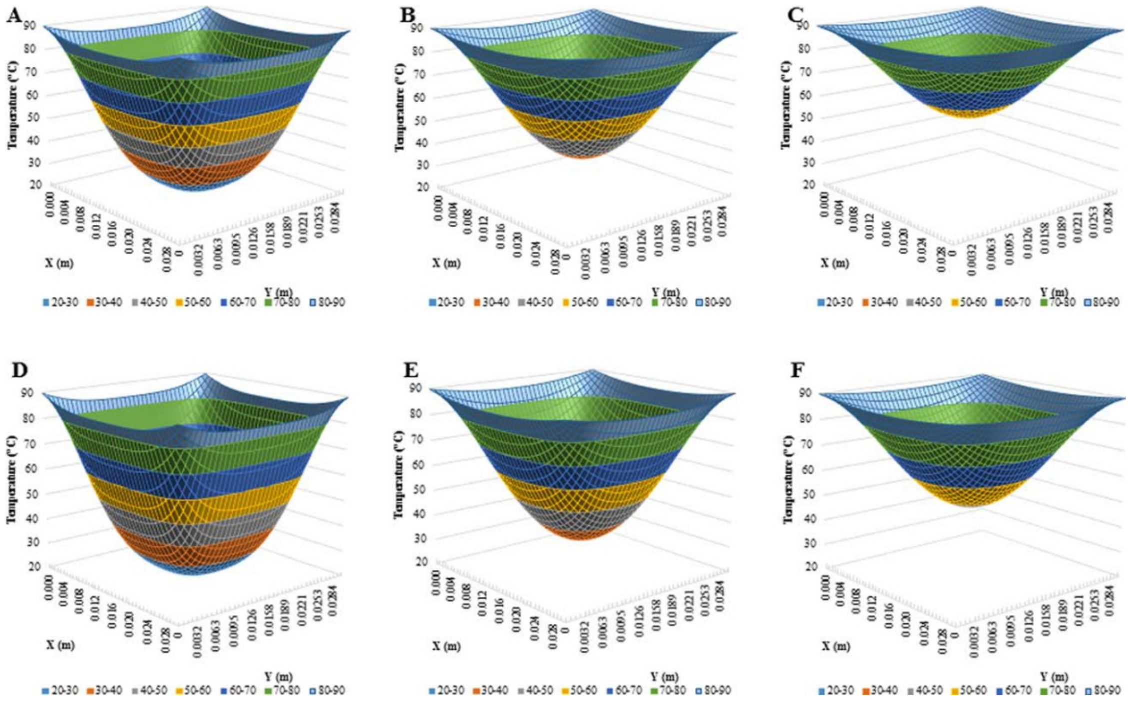

FIG. 5. PREDICTED TEMPERATURE DISTRIBUTION DURING BLANCHING AT 90°C OF LOCHE AT TIME: (A) 100 S, (B) 200 S, AND (C) 300 S; AND POTATO AT TIME (D) 100 S, (E) 200 S, AND (F) 300 S, DIMENSIONS 3 × 3 × 3 CM^3 (PLOT IS FOR *X–Y* PLANE LOCATED AT *Z* = 1.5 CM)

Blanching Process With Variable Thermal Properties

During blanching of both vegetables, some problems were encountered by trying to keep the thermocouple suspended in the center of the cubes 1 × 1 × 1 cm^3, due to the small size of the shape and the drilling that should be done to enter the thermocouple. All of these counterproductive factors, resulted in inaccuracies in the record of the temperature at the center point of the hub, as seen in Fig. 4A,D. For the case of cubes of loches and potatoes of 2 × 2 × 2 cm^3 and 3 × 3 × 3 cm^3 were easier to maintain the thermocouple at the center position, this can be reflected in the degree of adjustment of the simulations, as shown in Fig. 4B,C,E,F.

RMSE values for loche and potato cubes of 1 × 1 × 1 cm^3 were elevated, and this suggests that the experimentally obtained temperature record was not at center point. With regard to the problems obtained in the form of cubes of 1 × 1 × 1 cm^3 of loche and potato, similar problems were reported by Loss *et al.* (2011), who conducted the finite difference simulation of heat transfer during drying of papaya cubes, finding problems trying to achieve accuracies during data collection. Erdoğdu and Turhan (2008) mentions that in the validation studies of heat transfer, knowledge of the location of the thermocouple, it is extremely important to correlate the simulation results with experimental data.

To verify the fitting of the proposed model, the temperature record at the distance of 0.75 cm from the center point in loche and potato cubes of 3 × 3 × 3 cm^3 was considered. A network of 20 nodes each axis was used for the simulation, so the specific coordinate to compare with experimental data was (10, 1, 1). Simulations of temperature at the coordinate (10, 1, 1) fitting properly experimental values for both loche cubes as potato cubes, achieving smaller RMSE values.

Similar values were reported by Uyar and Erdogdu (2012), who found RMSE values between 0.26 and 0.49°C. Scheerlinck *et al.* (2004), found RMSE values are between 0.19 and 0.45°C. Lemus-Mondaca *et al.* (2013), also simulated heat and mass transfer during drying of papaya 3D cubes in a temperature range between 40 and 80°C, including the variation of the thermal properties depending on temperature increase, by finite element method; finding that the simulated values fit neatly into the experimental values with 6% deviation.

Figure 5 shows temperature distributions during blanching at 90°C of loche and potato cubes after 100 s, 200 s, and 300 s, respectively. The temperature contours in the cube present elliptic profiles due to the shape of the blanching product. The trends of temperature distributions agreed with those reported by Zhou et al. (1995) and Dincer (2010).

CONCLUSIONS

The heat transfer during the blanching process of cubic particles of potato and loche was modeled and simulated using finite difference method, including the variation of thermal properties based on temperature. Thermal diffusivity of loche and potato was determined experimentally at different temperature, as the heat transfer coefficient at different temperatures and sizes of cubic particles. A computer program in Visual Basic language was developed to implement the model. The RMSE of the simulated values on experimental data was <5°C in cubic particle of loche and potato of 1 × 1 × 1 cm^3, 2 × 2 × 2 cm^3, and 3 × 3 × 3 cm^3. In addition, this model provides a better understanding of the heat transfer inside the samples.

NOMENCLATURE

Symbols

A	solid surface area (m^2)
c_p	specific heat (kJ kg^{-1} °C)
h	heat transfer coefficient (W m^{-2}°C)
I	components number
i, j, k	nodal connotation in x,y,z direction
I	components number
J_0, J_1	Bessel function of first kind zeroth and first order
k	thermal conductivity (W m^{-1} °C)
L	half thickness of cubic particle and radius of an infinite cylinder (m)
N	Number of data
N_{Bi}	Biot number (dimensionless)
N_{Fo}	Fourier number (dimensionless)
R	radius of an infinite cylinder (m)
r	distance from the center ($0 \leq r \leq R$)
s	solid (food)
T	temperature at any time (°C)
T_∞	ambient temperature (°C)
T_i	initial temperature (uniform) (°C)
$T^t_{i,j,z}$	temperature at node (i, j, k) at time step (°C)
$T^{t+1}_{i,j,k}$	temperature at node (i, j, k) at time step +1 (°C)
t	time (s)
V	volume (m^3)
X	mass fraction of each component
Δx	distance between nodes in x-direction (m)
Δy	distance between nodes in y-direction (m)
Δz	distance between nodes in z-direction (m)
Δt	incremental time step (s)

Greek Letters

α	thermal diffusivity (m^2 s^{-1})
μ	roots of the characteristic equation
ρ	density (kg m^{-3})

REFERENCES

ABU-GHANNAM, N. and CROWLEY, H. 2006. The effect of low temperature blanching on the texture of whole processed new potatoes. J. Food Eng. *74*, 335–344.

AGÜERO, M.V., ANSORENA, M.R., ROURA, S.I. and VALLE, C.E. 2008. Thermal inactivation of peroxidase during blanching of butternut squash. Food Sci. Technol. *41*, 401–407.

AHROMRIT, A. and NEMA, P.K. 2010. Heat and mass transfer in deep-frying of pumpkin, sweet potato and taro. J. Food Sci. Technol. *47*, 632–637.

ALHAMDAN, A. and SASTRY, S. 1990. Natural convection heat transfer between non-newtonian fluids and an irregular shaped particle. J. Food Process. Eng. *13*, 113–124.

ANDRES, T.C., UGÁS, R. and BUSTAMANTE, F. 2006. Loche: A unique pre-Columbian squash locally grown in North Coastal Peru, in: *Proceedings of Cucurbitaceae* 2006. Raleigh, North Carolina, USA., pp. 333–340.

ANSARI, F.A. 1999. Finite difference solution of heat and mass transfer problems related to precooling of food. Energy Convers. Manag. *40*, 795–802.

AOAC. 2000. *Official Methods of Analysis*, 17th ed., Association of Official Analytical Chemists, Gaithersburg, MD.

AWUAH, G. and RAMASWAMY, H. 1993. Surface heat transfer coefficients associated with heating of food particles in CMC solutions. J. Food Process *16*, 39–57.

BAÏRI, A., LARAQI, N. and DE MARÍA, J.M.G. 2007. Determination of thermal diffusivity of foods using 1D Fourier cylindrical solution. J. Food Eng. *78*, 669–675.

BETTA, G., RINALDI, M., BARBANTI, D. and MASSINI, R. 2009. A quick method for thermal diffusivity estimation: Application to several foods. J. Food Eng. *91*, 34–41.

CAI, R., GOU, C. and LI, H. 2006. Algebraically explicit analytical solutions of unsteady 3-D nonlinear non-Fourier (hyperbolic) heat conduction. Int. J. Therm. Sci. *45*, 893–896.

CARIÑO-SARABIA, A. and VÉLEZ-RUIZ, J.F. 2013. Evaluation of convective heat transfer coefficient between fluids and particles in suspension as food model systems for natural convection using two methodologies. J. Food Eng. *115*, 173–181.

ÇENGEL, Y.A. 2007. *Transferencia de Calor y Masa*, 3rd Ed., Mc Graw Hill, D.F, México.

CHAMORRO, P.V. and VIDAURRETA, C.A. 2012. Blanching of fruits and vegetable products. In *Operations in Food Refrigeration*, pp. 93–112, R.H. Mascheroni, ed.), CRC Press, Boca Raton, FL.

CHOI, Y. and OKOS, M. 1986. Effects of temperature and composition on the thermal properties of foods. In *Food Engineering and Process Applications*, pp. 93–101, Vol. *1*, (M. Le Maguer, P. Jelen, eds.), Transport Phenomena, Elsevier Applied Science, London.

DELGADO, A.E. and SUN, D.W. 2003. One-dimensional finite difference modelling of heat and mass transfer during thawing of cooked cured meat. J. Food Eng. *57*, 383–389.

DINCER, I. 2010. Heat and mass transfer during food drying. In *Mathematical Modeling of Food Processing*, pp. 253–300, (M.M. Farid, ed.), CRC Press, Boca Raton, FL.

ERDOǦDU, F. and TURHAN, M. 2008. Analytical solutions in conduction heat transfer problems, In *Optimization in Food Engineering*, pp. 19–29, (F. Erdogdu, ed.), CRC Press, Boca Raton, FL.

FASINA, O.O. and FLEMING, H.P. 2001. Heat transfer characteristics of cucumbers during blanching. J. Food Eng. *47*, 203–210.

FELLOWS, P. 2000. *Food Processing Technology. Principles and Practice*, 2nd ed. CRC Press LLC, Boca Raton, FL.

GAFFNEY, J., BAIRD, D. and ESHLEMAN, D. 1981. Review and analysis of transient method for determining thermal diffusivity of fruits and vegetables. ASHRAE Trans *86*, 261–280.

GALINDO, F.G., TOLEDO, R.T. and SJÖHOLM, I. 2005. Tissue damage in heated carrot slices. Comparing mild hot water blanching and infrared heating. J. Food Eng. *67*, 381–385.

GARCÍA, M.R., PRIETO, I.G.S., BARRIENTOS, C.E., REBATTA, F.B. and MORÓN, L.G. 2009. *Tablas Peruanas de composición de alimentos*, 8th ed. Ministerio de Salud, Instituto Nacional de Salud, Lima.

GARROTE, L., SILVA, E.R. and BERTONE, R.A. 2004. Predicting the end point of a blanching process. Food Sci. Technol. *37*, 309–315.

HAHN, D. and OZISIK, M. 2012. *Heat Conduction*, 3th ed. Wiley, New Jersey.

INDECOPI. 2010. *Appellation of Origin Butternut Squash (Cucurbita moschata Duch.)*, Presidency of Councils of Ministers, Lambayeque, Peru.

JAISWAL, A.K., GUPTA, S. and ABU-GHANNAM, N. 2012. Kinetic evaluation of colour, texture, polyphenols and antioxidant capacity of irish york cabbage after blanching treatment. Food Chem. *131*, 63–72.

LAMBERG, I. and HALLSTRÖM, B. 1986. Thermal properties of potatoes and a computer simulation model of a blanching process. J. Food Technol. *21*, 577–585.

LATORRE, M.E., PLÁ, M.F.D.E.E., ROJAS, A.M. and GERSCHENSON, L.N. 2013. Blanching of red beet (*beta vulgaris* L. Var. Conditiva) root. Effect of hot water or microwave radiation on cell wall characteristics. Food Sci. Technol. *50*, 193–203.

LEMUS-MONDACA, R.A., ZAMBRA, C.E., VEGA-GÁLVEZ, A. and MORAGA, N.O. 2013. Coupled 3D heat and mass transfer model for numerical analysis of drying process in papaya slices. J. Food Eng. *116*, 109–117.

LESPINARD, A.R., GOÑI, S.M., SALGADO, P.R. and MASCHERONI, R.H. 2009. Experimental determination and modeling of size variation, heat transfer and quality indexes during mushroom blanching. J. Food Eng. *92*, 8–17.

LOSS, R.D., SANTOS, I.P., MUNIZ, E.P., PROVETI, J.R.C. and PORTO, P.S.S. 2011. Finite difference solutions for heat transfer during drying of cubic papaya particles. Proc. Food Sci. *1*, 753–761.

MARTÍNEZ, S., PÉREZ, N., CARBALLO, J. and FRANCO, I. 2013. Effect of blanching methods and frozen storage on some quality parameters of turnip greens ("grelos"). Food Sci. Technol. *51*, 383–392.

MOHAMED, I.O. 2003. Computer simulation of food sterilization using an alternating direction implicit finite difference method. J. Food Eng. *60*, 301–306.

MORALES-BLANCAS, E.F., CHANDIA, V.E. and CISNEROS-ZEVALLOS, L. 2002. Thermal inactivation kinetics of peroxidase and lipoxygenase from broccoli, green asparagus and Carrots. J. Food Sci. *67*, 148–164.

MURAKAMI, E.G. 1997. The thermal properties of potatoes and carrots as affected by thermal processing. J. Food Process. Eng. *20*, 415–432.

OBREGÓN LA ROSA, A.J., PEÑAFIEL, C.E and REPO-CARRASCO, R. 1998. Estudio técnico para la obtención de un enlatado de papas a partir de variedades nativas. Anal. Científic. UNALM *35*, 174–196.

ÖZIŞIK, M.N. 1993. *Heat Conduction*, 2nd ed. Wiley, New York.

PALAZOGLU, K. 2006. Influence of convective heat transfer coefficient on the heating rate of materials with different thermal diffusivities. J. Food Eng. *73*, 290–296.

PALAZOǦLU, T.K. and ERDOǦDU, F. 2008. Numerical solutions: Finite difference methods. In *Optimization in Food Engineering (F.* Erdogdu, ed.), CRC Press, Boca Raton, FL.

RAO, M., BARNARD, J. and KENNY, J. 1975. Thermal conductivity and thermal diffusivity of process variety squash and white potatoes. Trans. ASAE *18*, 1188–1192.

RICE, P., SELMAN, J.D. and ABDUL-REZZAK, R.K. 1988. Effect of temperature on thermal properties of "record" potatoes. Int. J. Food Sci. Technol. *23*, 281–286.

SABLANI, S.S. 2008. Measurement of surface heat transfer coefficient. In *Food Properties Handbook (*M.S. Rahman, ed.), CRC Press, Francis and Taylor Group, pp. 698–716, Boca Raton, FL.

SAKIN-YILMAZER, M., KAYMAK-ERTEKIN, F. and ILICALI, C. 2012. Modeling of simultaneous heat and mass transfer during convective oven ring cake baking. J. Food Eng. *111*, 289–298.

SALDIVAR, X., WANG, Y., CHEN, P. and MAUROMOUSTAKOS, A. 2010. Effects of blanching and storage conditions on soluble sugar contents in vegetable soybean. Food Sci. Technol. *43*, 1368–1372.

SARAVACOS, G.D. and KOSTAROPOULOS, A.E. 2002. *Handbook of Food Processing Equipment*, Springer Science, Business Media, New York.

SCHEERLINCK, N., MARQUENIE, D., JANCSÓK, P.T., VERBOVEN, P., MOLES, C.G., BANGA, J.R. and NICOLAÏ, B.M. 2004. A model-based approach to develop periodic thermal treatments for surface decontamination of strawberries. Postharvest Biol. Technol. *34*, 39–52.

SINGH, R.P. and HELDMAN, D.R. 2014. *Introduction to Food Engineering*, 5th ed. Elsevier Publishing, London.

UYAR, R. and ERDOGDU, F. 2012. Numerical evaluation of spherical geometry approximation for heating and cooling of irregular shaped food products. J. Food Sci. *77*, E166–E175.

WANG, N. and BRENNAN, J.G. 1995. A mathematical model of simultaneous heat and moisture transfer during drying of potato. J. Food Eng. *24*, 47–60.

WU, B., YANG, W. and JIA, C. 2004. A three-dimensional numerical simulation of transient heat and mass transfer inside a single rice kernel during the drying process. Biosyst. Eng. *87*, 191–200.

YILDIZ, A., KORAY PALAZOĞLU, T. and ERDOĞDU, F. 2007. Determination of heat and mass transfer parameters during frying of potato slices. J. Food Eng. *79*, 11–17.

ZHOU, L., PURI, V.M., ANANTHESWARANB, R.C. and YEHH, G. 1995. Finite element modeling of heat and mass transfer in food materials during microwave heating—Model development and validation. J. Food Eng. *25*, 509–529.