A MODEL FOR THE HEAT TRANSFER PROCESS IN FOOD

Camila Perussello
Álvaro Amarante
Viviana Cocco Mariani
Mechanical Engineering Graduate Program – PPGEM
Pontifical Catholic University of Parana – PUCPR
80215-901 – Curitiba, PR, Brazil
e-mails: {camila_ea@yahoo.com.br, alvaro.amarante@pucpr.br, viviana.mariani@pucpr.br}

Abstract. *In the present work classical equations were found in the literature, which were reported to predict the initial freezing temperature, the thermal conductivity and specific heat of a food product in function of its composition and temperature. These equations were coupled to the Tchigeov's method, which predicts the ice fraction formed below the freezing point for a food material. This procedure enabled the development of the functions enthalpy and Kirchhof with respect to the temperature for the studied product by numerical integration. After was developed and implemented a computational code in finite differences to solve the transient heat transfer equation, transformed by the introduction of the enthalpy and Kirchhoff functions. With the objective to validate the code computational and to illustrate the use of the thermal properties prediction equations had been used surface heat transfer coefficients measured with fluxmeters. The previous knowledge of the heat transfer coefficients by convection mechanisms determined by using heat flux sensors coupled to temperature measurement devices had allowed to only have as variable the food thermal properties. The results show that the association of classical equations for predicting the thermophysical properties of a food, with the numerical solution of the modified transient heat transfer equation results in a useful method to predict the temperature evolution within a food product subjected to a freezing process.*

Keywords: *food, freezing, Tchigeov's method, transiente heat transfer, thermophysical properties, green beans pods.*

1. INTRODUCTION

Temperature is one of the most important factors for post harvest conservation of fruits and vegetables. When temperature is high the food metabolism is accelerated, leading to a faster deterioration, promoting a more intense transpiration and enabling an ideal environment to the growth of pathogenic microorganisms. The experimental and numerical investigation of the refrigeration or freezing of a food is then primordial for a better understanding of food conservation, in order to reduce the product metabolism, to decrease water loss and to control microorganism growth.

The numerical simulation of the transient heat transfer during the phase change, on the freezing or thawing of a food, has become a powerful tool for the management of the freezing chain of foods. The precise and instantaneous prediction of the temperature distribution within a food product is an indispensable step for the control strategies and the project of efficient refrigeration systems, attempting safety and quality. Because of the practical importance of these heat transfer problems, highly non-linear in the case of freezing, several researchers have been dedicating a lot of effort to develop physical models and advanced numerical techniques to solve them.

When considering the freezing and thawing problems of foods, the dominant mechanism is the heat transfer by conduction. The conduction problems involving phase change, called Stefan problems, belong to a more general class of free frontier problems. A first group of numerical methods to solve such problems is based on the treatment of the free frontier in the phase change using complicated techniques in order to locate the position of the interface at each new time step (Crank, 2004). Usually, these methods have a low convergence rate, leading to additional complications when multidimensional geometries are considered.

A second group of numerical methods, more flexible, does not track directly the exact position of the phase change front. This boundary condition is incorporated in the temperature dependant thermal properties. The governing equations are then solved in a fixed dominium. This will be the approach adopted in this work.

The phase change in solid/liquid foods occurs progressively at a finite and approximately well defined temperature interval. Both phases are not clearly separated and coexist in a finite fraction of the food in a given time. At this instant, the thermal properties, such as thermal conductivity (k) and specific heat (c) can be approximated by temperature dependant functions. Generally, both functions are discontinuous near the freezing temperature: the apparent specific heat exhibits a sharp peak near the phase change temperature and the thermal conductivity increases significantly below this temperature. Algebraic expressions for the thermal properties of some foods are frequently found in the literature in the form of tables (Alhama and Fernández, 2002; Zueco *et al*., 2004; Pham, 1996).

The temperature dependence quoted in the earlier paragraph, as well as the boundary conditions of convection or radiation, make the prediction of the temperature history during freezing a non-linear problem. Some numerical methods based usually on the Fourier's transient heat conduction law and solved by finite differences or finite element techniques are used for both phases (Cleland and Özilgen, 1998). The use of the temperature as the dependent variable is limited by accuracy criteria, because the time increment must be minimal in order to avoid jumping of the sharp apparent specific heat peak (Pham, 1987).

Innovations have been introduced in the numerical modeling of Stefan's problems in order to minimize oscillations and improve accuracy, namely the use of the volumetric enthalpy and the Kirchhoff function (Fikiin, 1996). The use of enthalpy (*H*) as the dependant variable is based on the knowledge of the dependence of the enthalpy with temperature for the studied product (Mannapperuma and Singh, 1988). The temperature is calculated as a secondary variable. Another option, complementary to the enthalpic formulation, is the use of the Kirchhoff function, obtained through the integration of the thermal conductivity as a function of the temperature. These both functions permit the reduction of the oscillations of the computational results, especially in locations near the surface of the product.

The objective of this work is to validate and to illustrate the use of prediction equations of termophysical properties, combined with the numerical simulation of the temperature gradients within green beans pods during freezing processes at different convection conditions. The previous knowledge of the required parameters for simulation, namely the heat transfer coefficients for the air flow conditions in the experiments and the pods geometry, hypothetically may allow the validation of the thermal properties predicted by relations found in the literature .

2. EXPERIMENTAL CONDITIONS

A freezing chamber (MDF-U 20863, Sanyo, Japan) with inner dimensions 370 (w) x 490 (d) x 1200 (h) mm was used for the experiments. Air circulation in the range of 0 to 7 $m.s^{-1}$ inside the freezer was promoted by an axial fan (W2E 250 – CE 65-02, Airtechnic, France) equipped with electronic speed control and installed in the upper central portion of the freezer. Air speed was measured by means of a propeller anemometer (Miniair 64, range 0.3 – 20 $m.s^{-1}$, accuracy +/- 0.1 $m.s^{-1}$, Schiltknecht, Switzerland) placed 10 mm upstream from the surface of the products. Data was acquired and recorded every second by a SRMini® System (13-bit resolution, 24 channel, TCSA, France) connected to a PC running the supervision software Specview® (TCSA, France).

Green beans imported from Sacco Fresh Ltd (Kenya) selected for their straight and cylindrical form, whose extremities were trimmed off, diameter 6.0 ± 0.1 mm, length 80.0 ± 0.4 mm, 87.2 ± 0.1 moisture content, and mass of 0.00224 ± 0.00027 kg were used. Each sample was instrumented with a fluxmeter (Ref. 27036-3, nominal sensitivity 0.36 $\mu V.m^2.W^{-1}$, accuracy ± 2.5%, RdF Corporation, USA), adhered to the surface of the specimens by means of a thin layer of heat sink compound (k = 4.0 $W.m^{-1}.°C^{-1}$, CM 6018, Jelt, France). Thermocouples (type T, gained, diameter 0.5 mm, accuracy ± 0.2°C) were carefully placed at the thermal center and at the surface of the specimens, aligned horizontally and distant approx. 5 mm of the fluxmeter. The instrumented vegetable samples were accommodated in wire supports designed specially to hold them in the air stream. The contacts between the wires and the specimens were provided with small polystyrene pieces to reduce conduction heat transfer. The system composed by the instrumented vegetable and its support was placed inside the freezing chamber at –40°C. The air speed for each experiment was fixed at 0 (natural convection), 1, 3, 5, and 7 $m.s^{-1}$. Each essay condition was repeated at least three times. At every time interval *t*, the recorded heat flux, surface temperature and air temperature inside the freezing chamber were introduced in Eq. (1) and the heat transfer coefficient was straightforward calculated.

$$-k\frac{\partial T}{\partial x}\bigg)_S = q_s(t) = h(t)\left[T_\infty(t) - T_S(t)\right] \qquad (1)$$

3. MATHEMATICAL MODELLING

The following conditions were assumed for the formulation of the mathematical model used to predict the heat transfer:

a) Heat conduction is the predominant mechanism;
b) The pods are represented by an infinite cylinder with length *L* [m] and radius *R* [m] defined between [0; 0.03], where R << L, so the longitudinal heat transfer is neglected and the axial symmetry is considered;
c) The thermal conductivity is variable with the temperature during the freezing process;
d) The pods are considered homogeneous and the initial temperature is uniformly distributed in their interior.

The temperature diffusion process for $0 \le r \le R$ and $t > 0$ can be modeled by the partial differential equation that represents the transient heat conduction based on the Fourier's law, Eq. (2). The initial and boundary conditions are described, respectively, in Eqs. 3 to 5.

$$\rho(T(r,t))c_p(T(r,t))\frac{\partial T(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk(T(r,t))\frac{\partial T(r,t)}{\partial r}\right), \qquad (2)$$

where r is the radial component [m], t is the time [s], $T(r,t)$ is the temperature [^{o}C], $\rho(T(r,t))$ [kg/m^3] is the density, $c_p(T(r,t))$ [J/kg^{o}C] is the specific heat at constant pressure, $k(T(r,t))$ [W/m^{o}C] is the thermal conductivity. The following initial and boundary conditions are adopted,

$$T(r,t) = 26^oC,\ r > 0 \text{ and } t = 0, \tag{3}$$

$$k(T(r,t))\frac{\partial T(r,t)}{\partial r} = 0,\ r = 0 \text{ and } t > 0, \tag{4}$$

$$k(T(r,t))\frac{\partial T(r,t)}{\partial r} = h\left(T_\infty - T_S(r,t)\right),\ r = R \text{ and } t > 0, \tag{5}$$

where T_∞ [^{o}C] is the ambient temperature, T_S [^{o}C] is the temperature on the bean surface, h [W/m^{2o}C] is the heat transfer coefficient on the surface.

Executing a variable change on the Eq. (2), the density and the specific heat, which are temperature dependent parameters, can be replaced by the volumetric specific enthalpy, H [J/m^3],

$$H(T(r,t)) = \int_{T^*}^{T} \rho(T(r,t))c_p(T(r,t))dT\ , \tag{6}$$

where T^* [^{o}C] is the reference temperature that corresponds to the null value of H (Scheerlinck *et al.*, 2001). This change of variable results in the enthalpic formulation of the transient conduction heat transfer. In an analogous way, the thermal conductivity can be removed using the Kirchhoff transformation [W/m], (Fikiin, 1996),

$$E(T(r,t)) = \int_{T^*}^{T} k(T(r,t))dT\ . \tag{7}$$

Introducing Eq. (6) and (7) in the Eq. (1) the following expression is obtained,

$$\frac{\partial H(T(r,t))}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E(T(r,t))}{\partial r}\right). \tag{8}$$

By applying the same changes to Eq. (3) to (5), we obtain the initial and boundary conditions that match to Eq. (8):

$$H(T(r,t)) = H_0;\ r > 0 \text{ and } t = 0, \tag{9}$$

$$\frac{\partial E(T(r,t))}{\partial r} = 0;\ r = 0,\ t \geq 0, \tag{10}$$

$$\frac{\partial E(T(r,t))}{\partial r} = h(T_\infty - T_S(r,t));\ r=R,\ t\geq 0, \tag{11}$$

where H_0 [J/m^3] is the enthalpy known at the initial time obtained through the experiment.

4. NUMERICAL METHODOLOGY

The finite difference method was used to solve numerically Eq. (8). An energy balance over the nodal points of a finite uniform grid was developed. The geometry of the green beans pods, approximated by an infinite cylinder where $L >> r$, used in this work is presented in Fig. 1.

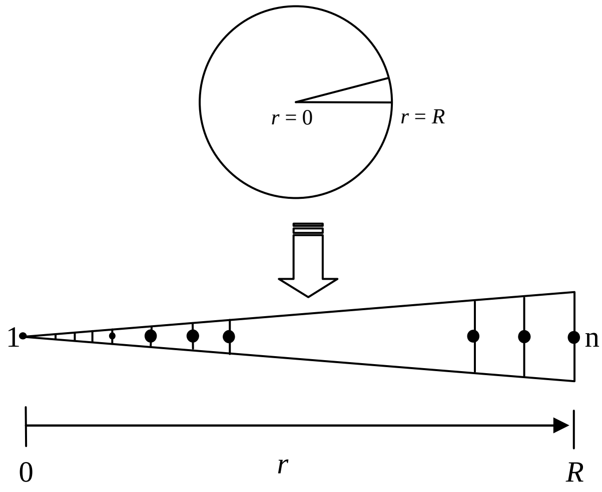


Figure 1 – Radial representation of the green bean pods.

The energy balance for every i^{th} element located inside the numerical grid ($2 \leq i \leq n$-1) and between the time steps j to $j+1$ can be written using the development of Smith (1985) in the form of Maclaurin series, as expressed by Eq. (12).

$$\frac{H^{j+1} - H^{j}}{\Delta t} = \frac{1}{r_i \Delta r^2}\left[r_{i+1/2}\left(E_{i+1} - E_i\right) - r_{i-1/2}\left(E_i - E_{i-1}\right)\right]. \tag{12}$$

For the nodal points i = 1 (center) and i = n (external surface) we used the same development, considering respectively the symmetry condition, Eq. (10) and the convection condition, Eq. (11).

$$\frac{H^{j+1} - H^{j}}{\Delta t} = \frac{4}{\Delta r^2}\left(E_{i+1} - E_i\right). \tag{13}$$

For the nodal point i = n (on the bean) it is considered the convection condition, Eq. (10), which results in,

$$\frac{H^{j+1} - H^{j}}{\Delta t} = \frac{1}{r_i \Delta r^2}\left[r_{i+1/2}\Delta r h\left(T_\infty - T_S\right) - r_{i-1/2}\left(E_i - E_{i-1}\right)\right]. \tag{14}$$

At each j^{th} time step, the temperature profile within the product is straightforward determined by application of the previously developed $H(T)$ relationship, using the local calculated enthalpy values. A numerical code was developed using Matlab 4.0 to implement the presented solution.

5. PREDICTION OF THE THERMAL PROPERTIES

Attempting to predict the thermal properties required by the mathematical model, a literature survey was conducted to collect equations with this purpose. We considered fundamentally relations involving temperature and composition (protein, lipid, carbohydrate, fiber, ash, water and ice) dependency, in order to cover a broader range of conditions. The equations found are generally recommended for homogeneous, non porous and low fat products.

The thermal properties are significantly affected by the ice fraction formed under the initial freezing temperature. This temperature was predicted by Eq. (15) (Pham, 1996), based on regression analysis (R^2 = 0.92) of data for several products.

$$T_f = -4.66(X_o / X_{wtot}) - 46.4(X_m / X_{wtot}) \tag{15}$$

To calculate the ice fraction formed below the initial freezing temperature, it was used the Tchigeov's (1979) method, Eq. (16), which is generally accepted and recommended by ASHRAE (2002).

$$X_{ice} = \frac{1.105 \cdot X_{wtot}}{1 + \dfrac{0.8765}{\ln(T_{cc} - T + 1)}} \tag{16}$$

where X_{ice} is the mass fractions of the ice formed in the temperature T [°C], X_{wtot} is the total mass fraction of the water of the product in the unfrozen state and T_{cc} [°C] is the initial freezing temperature.

The prediction of the properties thermal conductivity *k(T)* and specific heat *c(T)* were primarily based on the equations of these properties for the isolated components of the product (proteins, lipids, carbohydrates, fibers, ash, water and ice) obtained from Choi and Okos (1986). The final *k(T)* of the product was obtained using the mean value between the conductivity calculated using the series and parallel models according to the methodology presented by Murakami and Okos (1989) and expressed by Eq. (17). The ice fraction was taken into account as a component under the initial freezing temperature, as calculated by Eq. (16).

$$k(T) = \frac{1}{2}\left\{\sum X_y^v(T)k_y(T) + \frac{1}{\sum\left[X_y^v(T)/k_y(T)\right]}\right\} \tag{17}$$

For the determination of *c(T)* it was used an additive model, which considered the conductivity of each isolated component multiplied by its mass fraction in the product. The apparent specific heat, including the evolution of latent heat of fusion of water with the ice fraction formed was calculated by Eq. (18).

$$c_{app}(T) = X_{ice}(T) + X_{wl}(T)c_w(T) + X_{MS}c_{MS}(T) + H_L\frac{dX_{ice}(T)}{dT} \tag{18}$$

The knowledge of the function *c(T)* allowed to develop the enthalpy function *H(T)* using Eq. (19) (Heldman, 1992).

$$H(T) = X_{MS}\int_{-40}^{T} c_{MS}dT + X_{wl}\int_{Tf}^{T} c_w dT + \int_{-40}^{Tf} X_{wl}(T)c_w(T)dT + X_{ice}(T)H_L + \int_{-40}^{Tf} X_{ice}(T)c_{ice}(T)dT \tag{19}$$

A code containing all algebraic equations was then developed in Matlab to predict the thermal properties of the product and their variation with temperature in the range of -40°C to 30°C, given only the mass fractions of the components. Food properties and their complete variation with temperature are scarce in the literature. The simulated properties were compared with collected punctual literature data.

5. NUMERICAL RESULTS

The regular analysis conducted in our laboratory resulted in the following composition for the green beans: 92.2% moisture content, 1.3% protein, 0.2% fat, 3.1% carbohydrates, 0.7% ash and 2.5% fiber content. This composition data was introduced in the calculation routine developed in Matlab with the intent to predict the thermal properties of the product (Strapasson *et al.*, 2006). Fig. 2a presents the thermal conductivity as a function of the temperature. The obtained conductivities for -6°C and 5°C are in accordance with literature data (Martins and Silva, 2003), being the standard error respectively 3.1% and 6.8%.

The predicted initial freezing temperature was -0.71°C, while the mean value found in our experiments was 0.8°C. Under the initial freezing temperature, the routine used showed a progressive increase in the thermal conductivity, as the result of the increasing ice content in the product. The mean value between the parallel and the serial conductivities is apparently a good approximation for the thermal conductivity of the tested product. It was noticed that the serial model underestimates the conductivity, while the parallel model overestimates it. This effect is much more pronounced under the initial freezing temperature. The integration of the thermal conductivity with temperature resulted in the Kirchhoff function, Fig. 2b. This latter function is continuous, as compared with the thermal conductivity, and will probably contribute for more stable numerical simulation of the freezing process.

Fig. 3a shows the apparent thermal capacity of the beans. Again, as the result of a great increase in the ice content and the corresponding evolution of latent heat under the initial freezing temperature, we observe a fine peak characterizing a region of discontinuity in this property. Thus, the use of Eq. (2) to simulate the freezing process of the beans may implicate in numerical oscillations and peak jumping. The development of the enthalpy function, Fig. 3b by integration of the apparent thermal capacity with temperature results in a smoother behavior. When the predicted enthalpy is compared with literature data a good agreement (R^2 = 0.97) is obtained. The data from Toumi *et al.* (2004) were measured experimentally by differential scanning calorimetry (DSC) using the same supplier and variety as for the green beans used in this work. The freezing experiments allowed the acquisition of the heat fluxes on the surface, and the center and surface temperature of the pods. Fig. 4 displays the heat fluxes for the different air speed used. The attached table indicates the heat transfer coefficients at each freezing condition calculated by Eq. (1). These coefficients were compared in a previous work (Amarante and Lanoisellé, 2006) with values obtained by *Nu-Re* relations for the conditions of the experiments with good agreement (mean standard error of estimation = 5,5%).

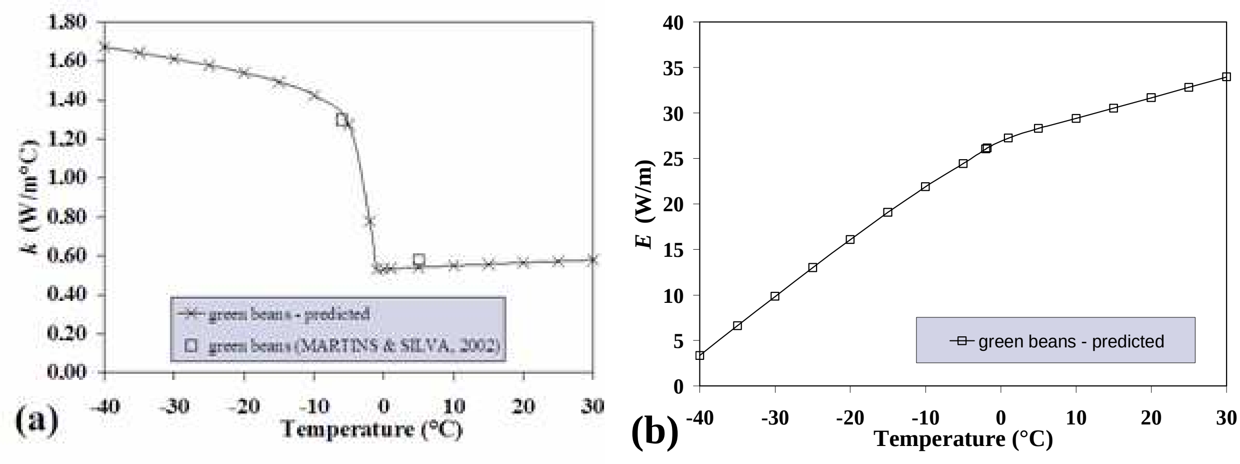


Figure 2 – Thermal conductivity (a) and Kirchhoff function (b) of the green beans.

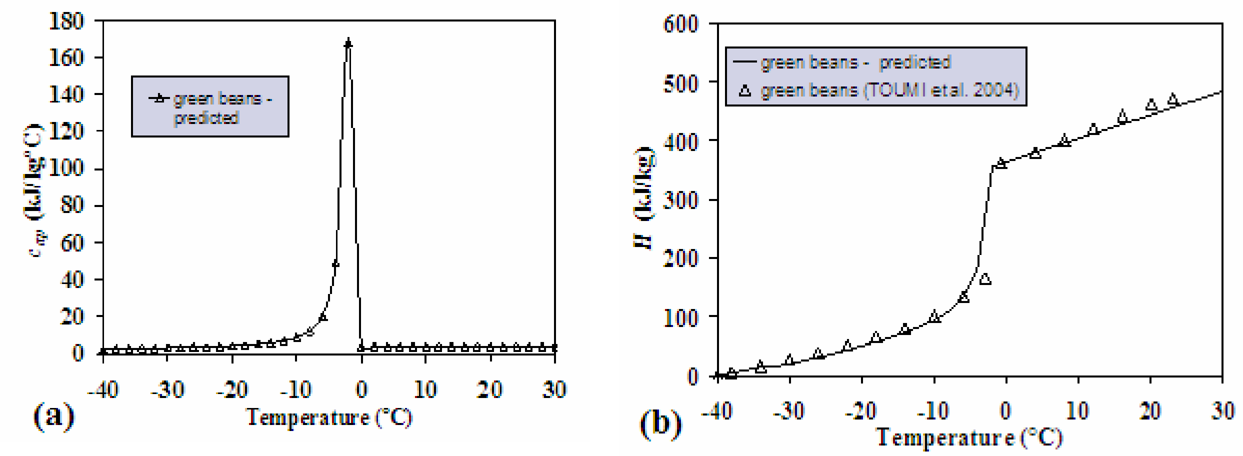
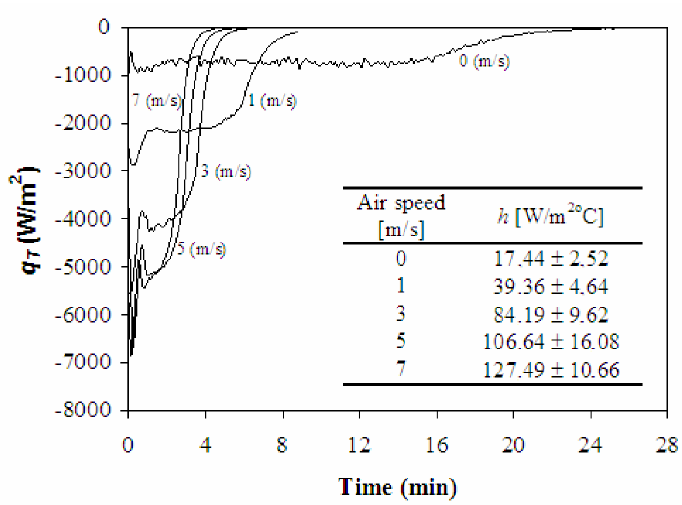


Figure 3 – Apparent thermal capacity (a) and Enthalpy (b) of the green beans.



Air speed [m/s]	h [W/m^{2}°C]
0	17.44 ± 2.52
1	39.36 ± 4.64
3	84.19 ± 9.62
5	106.64 ± 16.08
7	127.49 ± 10.66

Figure 4 – Heat fluxes on the surface of the pods during freezing at different air speed.

The numerical solution was obtained by the utilization of an explicit finite difference method. A numerical grid formed by ten nodal points was used. It was assumed that the accuracy of the numerical solution was not significantly influenced by the adoption of the explicit method, nor by the number of nodal points chosen, according to the conclusions of Cleland and Earle (1984) regarding this subject. When using the explicit method sufficiently small time and space steps were chosen in order to overcome truncation problems due to stability criteria. Fig. 5 illustrates the numerical and experimental behavior of the freezing process using 1 m/s air speed. In this case, the result obtained using the Kirchhoff function Eq. (8) is quite similar to that using directly the thermal conductivity in the model's equation. We attribute the similarity of both solutions to the small time steps used in the simulations (0,025s).

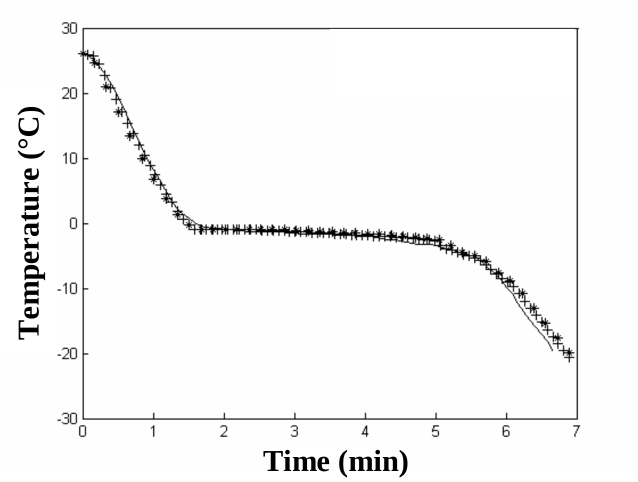


Figure 5 – Numerical simulation using the thermal conductivity (*) or the Kirchhoff function (+), as compared wit the experimental (-) temperature history (1 m/s air speed).

Fig. 6 summarizes a complete series of freezing experiments and simulations applying the heat transfer coefficients obtained by calorimetry and the thermal properties predicted using solely composition data of the beans. It is observed that the enthalpic formulation using the Kirchhoff function can predict satisfactorily the experimental results for the covered conditions. From these curves one can notice small discrepancies between simulated and experimental temperatures, mainly in the phase change region. In one hand the beginning of the water freezing is dependant on kinetic factors (nucleation), which are not taken into account by the numerical model. On the other hand, as a result of the small diameter and the tenderness of the green beans internal tissues, little displacement of the thermocouples tips is likely to occur. This may cause significant experimental error. Nevertheless, the predicted temperature values fit well to experimental ones ($R^2 > 0.95$ for all runs). The Fig. 7 illustrates the behavior of the temperature in the product for the null velocity of the freezing air.

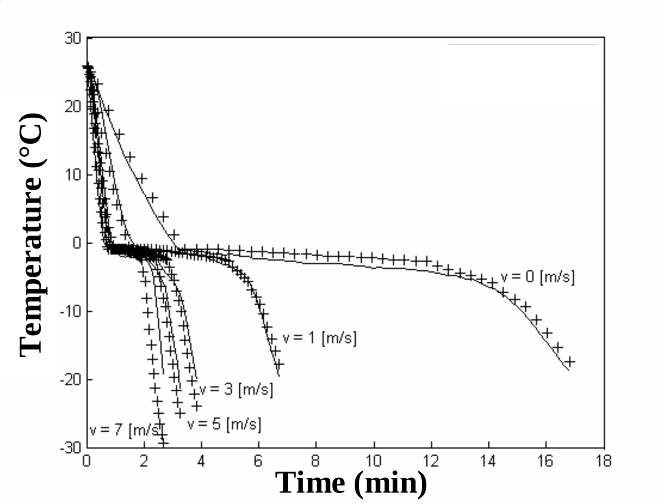


Figure 6 – Experimental (-) and numerically simulated (+) temperature profiles during the freezing of green beans pods using different air speed

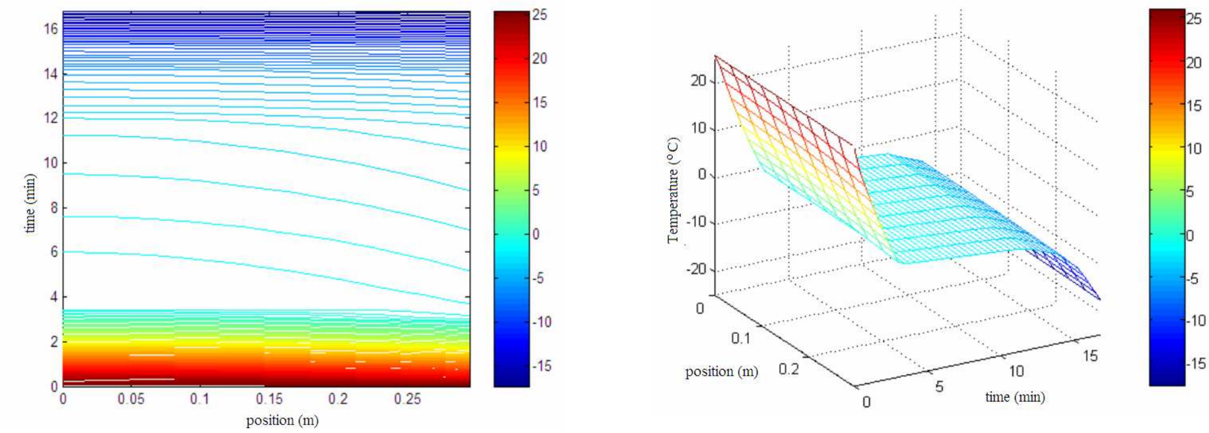


Figure 7. Temperature profiles during the freezing along the bean radius for v = 0 [m/s].

6. CONCLUSIONS

A group of relations based exclusively on the composition were selected and used to determine thermal properties of the chosen food specimen used in this work, associated with an equation to predict the ice fraction formed below the freezing temperature. The simulated properties are in agreement with values found in the literature. Moreover it was possible to establish the continuity of the studied properties with temperature. The good results are attributed to homogeneous internal structure of the chosen food product. The use of these functions, associated with the numerical computational code to solve the heat conduction equation on a transient basis with phase change, showed to be possible to predict with reasonable precision the evolution of the temperature in a food under different freezing conditions. It is believed that the combined modeling of the thermal properties and the evolution of temperature during freezing is an interesting and relatively accurate method for engineering purposes.

7. ACKNOWLEDGEMENTS

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