MECHANICAL AND THERMAL CHARACTERISTICS OF FRUIT SPECIES STUDIED BY A FINITE ELEMENT METHOD

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Abstract. *The aim of this study was to investigate if it is possible to use Finite Element Model outputs to determine thermo-physical characteristics of fruit species. The experimental strategy was to construct small metallic modules where samples of apple (Pirus malus), melon (Cucumis melo) or mango (Mangifera indica) could be adjusted. The basic idea was to measure the temperature of each one of these samples during a cooling process, obtaining a temperature versus time curve. This experimental curve could then be compared with the corresponding results obtained by simulation using the Finite Element Method (FEM). Some simplification has been made to construct the model. The main one was to suppose the material homogeneity. Fruits are not homogeneous, of course. The presence of macroscopic fibres and seeds clearly indicates the in-homogeneity of this kind of material. However, the measurements were made using small pieces of fruit material obtained after the seeds have been extracted. Also, due the small sample dimension one expect that the presence of fibres had not any significant influence on the thermal phenomena under consideration. The FEM model parameters are the thermal characteristics (specific heat and conductivity) of the material under study. It was possible to adjust the FEM parameters, by using bi-dimensional Lagrange polynomials, produced by running the FE model over a range of randomly generated parameter values, to achieve the best determination to these thermo-physical characteristics (specific heat, and thermal conductivity)and the corresponding diffusivity (α) . These best values were obtained by means of an optimization method applied on theoretical data. The method works searching on the Lagrange polynomials values, in order to achieve the minimum difference between calculated and experimental data. We obtained* $\alpha=1,52*10^{-7} m^2/s$ *for the apple pulp material.*

Keywords: Thermal characteristics measurements, fruits, finite element method

1. INTRODUCTION

The physical characteristics of materials (mechanic, thermal and electric) are important parameters in almost all fields of Research and Development in Sciences and Technologies, since they are crucial factors to design instruments, machines, experiments and in measuring methodology development (Finey and Norris, 1998; Costell, Fiszman and Duran, 1997). These values are generally well known for homogeneous materials, as the main chemical element, crystals, the metals (and their alloys) and the plastic materials. However, in the case of non-homogeneous biological and/or composite materials the physical characteristics are hard to be determined since they are not constants. In fact, these values depend on chemical composition, on geometrical distribution in the crystalline structure, on temperature and on time (particularly for food).

In general, each time these physical characteristics must to be used, it is necessary to get mean or typical values (Rahman, 1995; Piovesana et al, 2006; Nogueira et al 2006). In technical literature (Rao et Rizvi, 1995; Verink, 1985) sometimes one get means with large standard deviations or even discrepant values.

These uncertainties affect some important activities, as the theoretical thermal calculation on freezing or cooking food. By the way, these food materials properties affect in a significant way characteristics as the flavor liberation, texture and hardness. In function of this, the benefit of material research in Food Engineering will be well knowing the relationship between the microscopic structure properties and the macroscopic behavior of food materials with important consequences on the industrials procedures used to processing aliments.

2. MATERIALS AND METHODS

In this section we explain the experimental set-up and the numerical methods we proposed to use, in order to measure the thermo physical characteristics of fruits and other vegetables. The experimental facility, acquired with grants from FAPESP (proc. N. 2006/04252), consists of thermo coupled thermometers that allow to measure the temperature of samples during a cooling process.

The samples can be cooled in a refrigerator and their temperatures can be monitored using "Kiltler Temperature Controller" model N322, interfaced to a micro computer by a USB – i485 converter. The "FieldChart NOVUS" software allowed the data acquisition and posterior analysis.

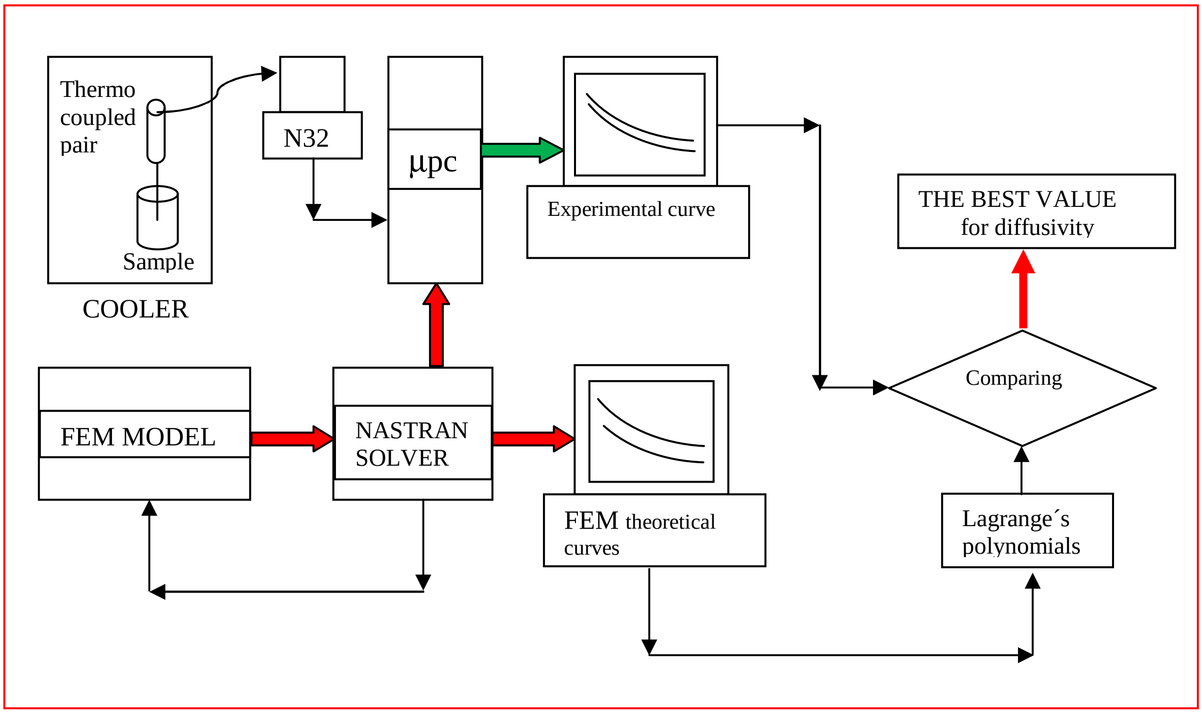

Figure 1: The method strategy: Measurements are compared with theoretical curves until the best values for parameters are achieved

By comparing the data obtained with this experiment with numerical results from a Finite Element Method (FEM) model (solved by NASTRAN software) it is possible to adjust the values for the sample diffusivity (conductivity, specific heat and density). The objective of our experiment was to measure simultaneously the conductivity and the specific heat of samples. We created a FEM model to simulate the thermal behavior of the experimental samples.

In order to solve the model an educational version of NASTRAN for Windows Software has been used. The parameters of the mathematical model are the physical characteristics (density, conductivity and the specific heat). By running the model for different values of conductivity (x_i) and specific heat (y_j), a network of possible theoretical results has been obtained and it was possible to fit a bi dimensional Lagrange´s Polynomial P(x, y) on the results (in our case this results were represented by the cooling rate adjusted to the temperature curves by least square method) the $\mathbf{f(x_i,y_i)}$).

$$P(x,y) = \sum_{i=0}^{n}\sum_{j=0}^{m} f(x_i, y_j)\ L_i(x)L_j(y) \qquad (1)$$

$$L_i(x) = \prod_{k=0,k\neq i}^{n} \frac{(x - x_k)}{(x_i - x_k)} \quad ; \quad i = 0, \dots, n \qquad (2)$$

$$L_j(y) = \prod_{k=0,k\neq j}^{m} \frac{(y - y_k)}{(y_j - y_k)} \quad ; \quad j = 0, \dots, m \qquad (3)$$

We then use this polynomial in an iterative procedure of optimization until the simulation results agree, as better as possible, with the experimental determination. We used this approach in validation tests and in preliminary measurements with samples of apples (*Pirus malus*).

3. RESULTS AND DISCUSSION

3.1. **Experimental thermal analysis.**

Figure 1 represents the experimental structure mounted for the accomplishment of the experimental measures. A small metallic tube containing a sample of fruit composes the experimental module. The sample of the fruit was initially at room temperature (25º C). A thermo-coupled pair attached inside de sample material was capable to monitor the temperature. The experimental module was then introduced in the refrigerator and the thermo coupled signal was continually send to a microcomputer in order to register the cooling curve, allowing to monitoring the experiment over a large time interval (some hours), with a very good time resolution (one measure each second) and with sensitivity of 0.1 ºC.

Once the cooling process were finished (i.e once the sample reach the temperature of the refrigerator), the data was converted to an adequate format allowing the mathematical handling.

In Figure 2 is possible to see the cooling curve (data in blue) for an experiment made with an apple sample.

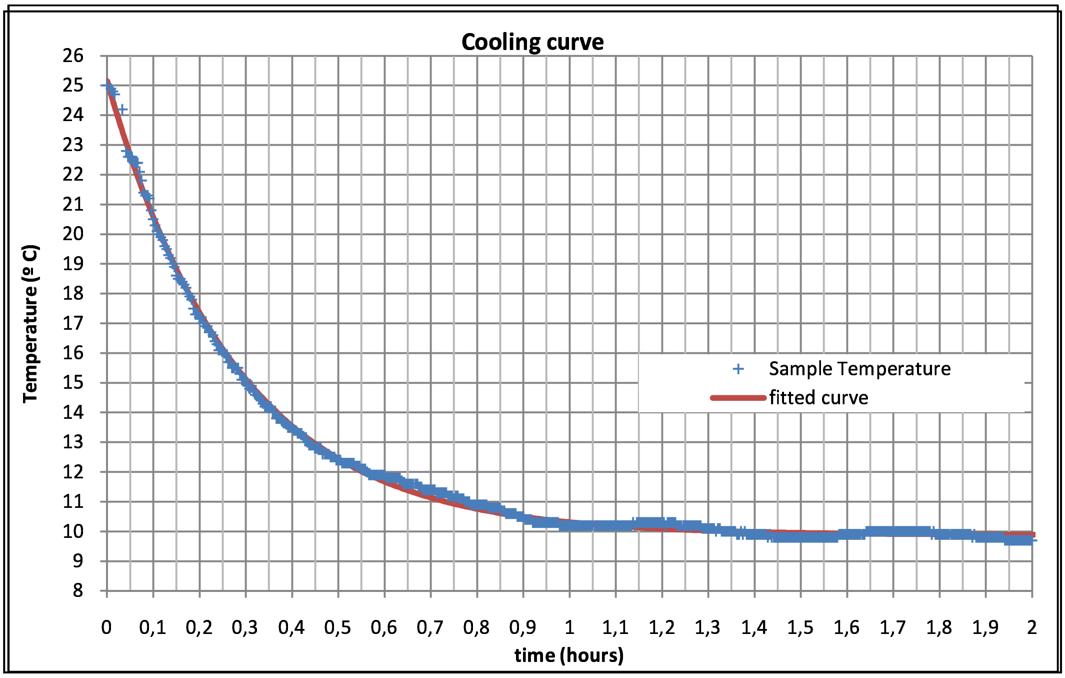

Fig.2: Cooling process experimental and numerical data

Based in a root mean square approach and using the software Solver Excell (Fylstra et al , 1998), we adjusted the experimental data to the following 3 parameters function:

$T(t) = a_0 + a_1 . \exp(-a2.t)$,

where $\mathbf{a_0}$ corresponds to the sample final temperature, $(\mathbf{a_0} + \mathbf{a_1})$ corresponds to the sample (initial) temperature and $\mathbf{a_2}$ determines the cooling rate which depends on the thermal characteristics of material (diffusivity).

The fitted a curve (also shown (in red) in the figure 2) corresponds to $\mathbf{a_0}$ = 10ºC, $\mathbf{a_1}$ = 15ºC and $\mathbf{a_2}$ = 3.57 s^{-1}**.** The mathematical parameters for this curve basically correspond to the initial (25ºC = 10ºC + 15ºC), the final (10ºC) temperatures and the cooling rate and so are related with the thermal characteristics of the sample material.

3.2. **Numerical analysis.**

The thermal modules, containing a sample of the fruit material, are represented by a Finite Element model in order to calculate the solutions of the thermal equations and to obtain the temperatures inside the material during a cooling process in each in case and for each type of sample. It is then possible to compare the numerical solutions (see Fig.3) with the results obtained with the described experimental apparatus in the previous item.

A simulation sequence procedure allows obtain optimized values to the parameters of the model (conductivity, specific heat, density, viscosity etc). With the results of the successive calculations it is possible to carry out statistical studies in order to consider, for example, the effect of the variation of the parameters of the model on the calculated cooling time of the experiment in question. This procedure generates points in a two-dimensional space (for example, in the present case, specific heat versus conductivity) resulting in a bi-dimensional function (z=f[x,y]) which corresponds to a surface. Statistic analysis allows to delimit the variation intervals in which the values of the physical characteristics of the sample is contained and, therefore, to find the optimum range where looking for the best configuration and to guide the successive iterations speeding up the convergence of the method.

The modeling and simulation were made using softwares of CAD (to draw the modules), and the "solver" NASTRAN to solve the equations of the thermal systems and post processing the solutions graphically.

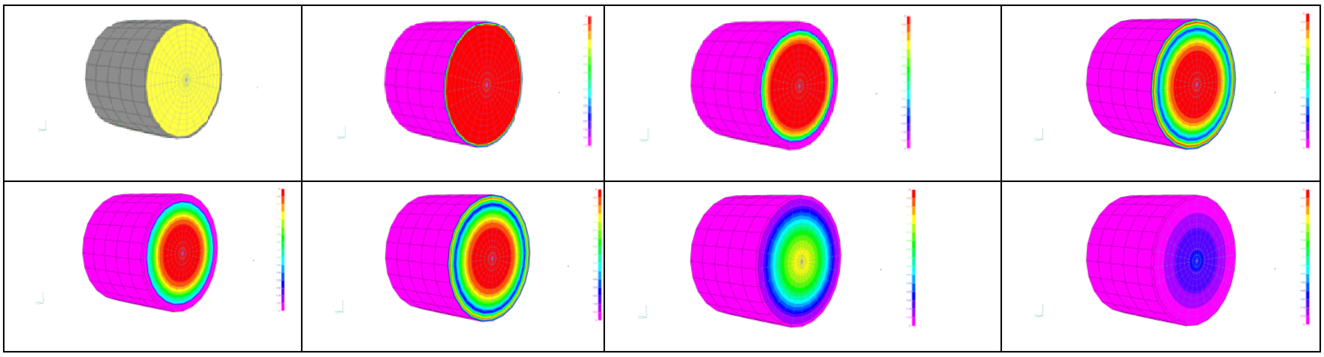

Fig3. FEM model and outputs for the thermal module and sample during the cooling time. The colors represent temperatures. The aluminium cylinder is supposed to be always at the refrigerator temperature (10 ºC) while the sample temperatures change between 25 ºC (red) and 10 ºC (pink) as the heat goes from inside to outside (left to right/up to down) .

3.3. Strategy to obtain the best values for thermal characteristics

The FEM model has been solved for diverse values of physical characteristics. Specific heat and conductivity values have been changed +/- 10% around a first trial initial value in order to construct a bi dimensional network of results for the thermal modules cooling times. The same strategy has been used to obtain this kind of network (we named it "meta-model") for each thermal module (Table 1). Each one of these meta-models has been fitted by a correspondent Lagrange Polynomial. The Polynomials corresponds to a surface in 3D-space. One of these surfaces is shown in the figure 4 bellow.

Using the experimental apparatus, we got a value to the cooling time characteristic for each case and it was possible to investigate (fig 5) where is the point in the Lagrange's surface that best fits the experimental values. This point corresponds to the best determination for the parameters "specific heat and conductivity". We have programmed the Lagrange's polynomial in the EXCELL for Windows software and use again the SOLVE optimization routine (Fylstra et al, 1998) to obtain the best values for the parameters.

Table 1: FEM results ; Cooling Time in function of specific heat (cp) and conductivity (k)

Cooling Time s^{-1}		k (W/mK) conductivity				
		3.00	3.30	3.60	3.90	4.20
cp Specific Heat KJ/kg.K	0.20	3.20	3.25	3.41	3.45	3.48
	0.30	3.23	3.32	3.45	3.48	3.66
	0.40	3.25	3.33	3.49	3.61	3.81
	0.50	3.32	3.45	3.59	3.52	3.72
	0.60	3.38	3.49	3.61	3.62	3.66

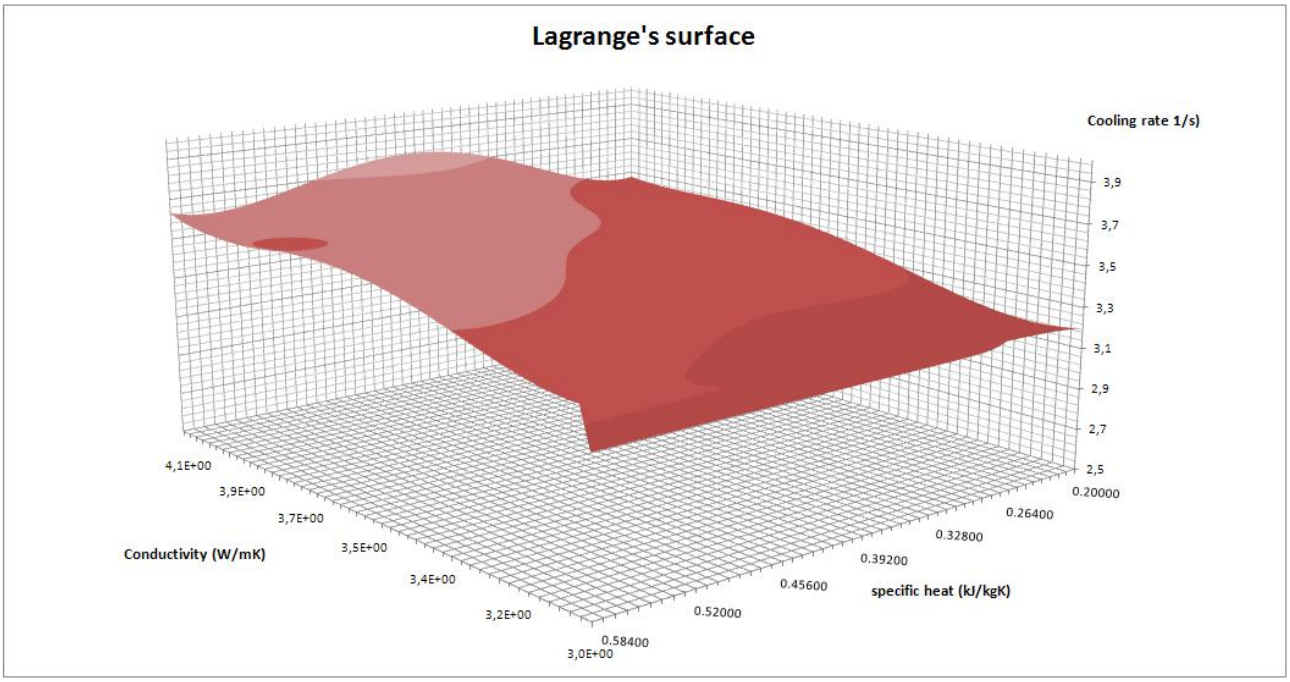

Fig5. Lagrange's Surface fitted to experimental data.

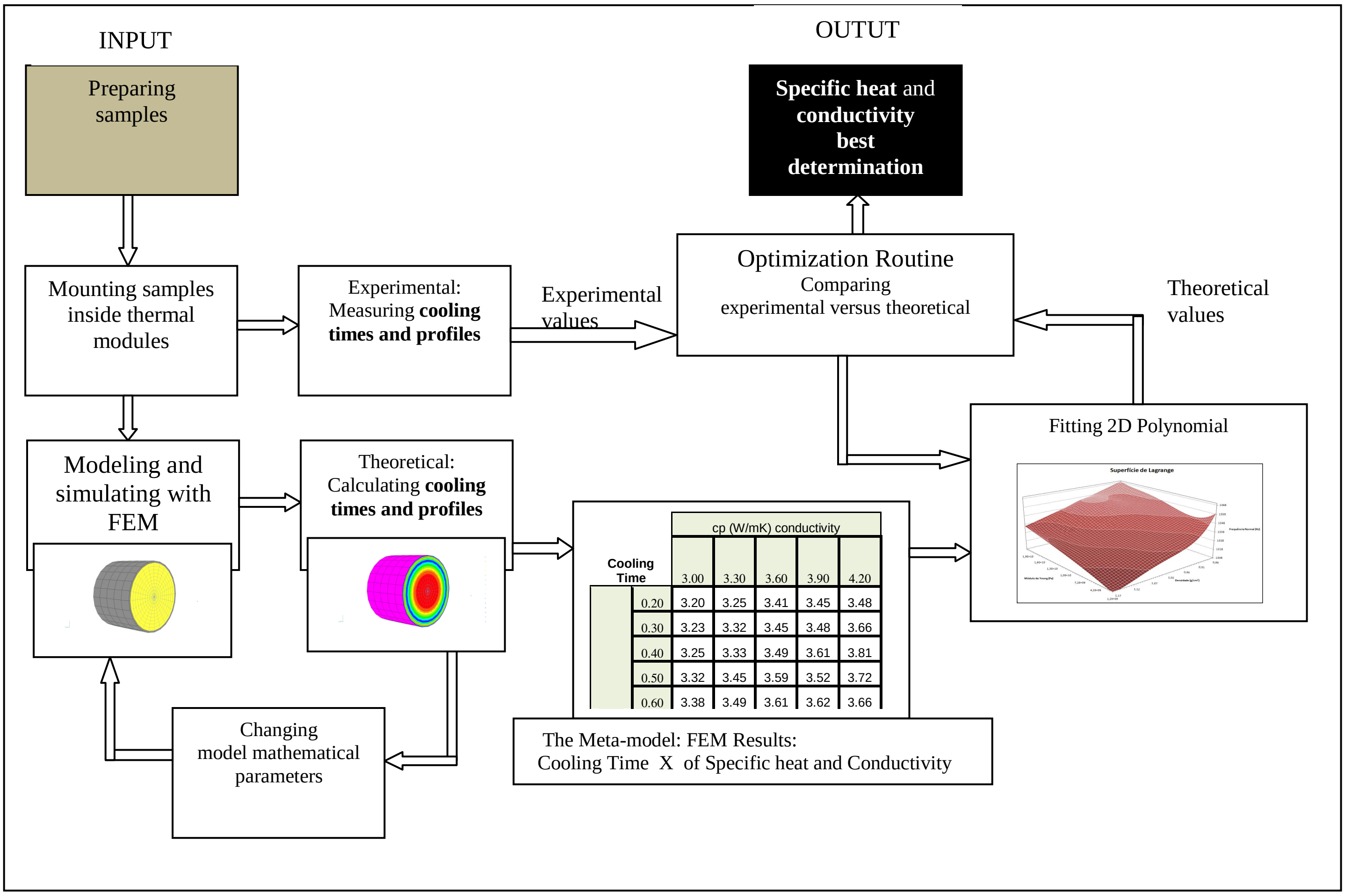

Fig5. The method strategy: Measurements are compared with theoretical curves until the best values for thermo physical parameters are achieved

Once the experimental cooling rate value is 3.57 s^{-1}, we obtained the best values for specific heat (cp = 3.68 kJ/kg.K) and conductivity (k= 0.488 W/mK). Figure 6 shows our results, allowing to compare the theoretical results (the blue points obtained from FEM model) and the experimental curve (the red line fitted on our data). Using these results it was possible to calculate the thermal diffusivity (α=1.52*10^{-7} m^2.s) for the *Pirus malus*.

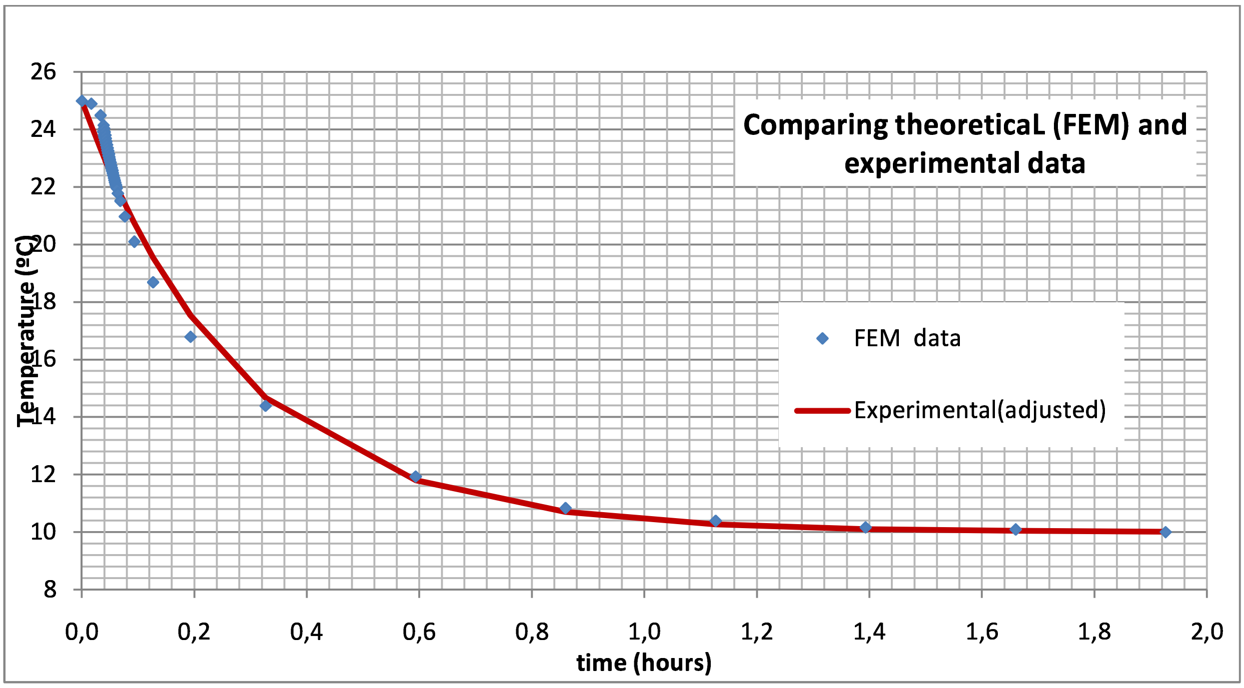

Fig. 6. Comparing the curves.

3.4 **Discussion**

The results showed that the proposed method is useful even if some simplifications, as material homogeneity, have been supposed in the model. Since the vegetables to be studied with this method are industrially important these results can represent strategic economical information. In fact physical characteristics of these fruits can influence agro-industrial processes as refrigeration, cooking, fermentation, etc.

These results show that the method we proposed is really capable to get a relatively precise experimental determination for the values of physical characteristics of materials. Both mechanical and thermal data can be obtained with symilar procedures. The same facility could also be used to measure characteristics of dental tissues (Esteves-Oliveira et al, 2008; da Ana, Velloso and Zezell, 2008) in order to analyse the effect of temperature on the mechanical behavior (elasticity, hardness, specific heat etc) of dental tissues (enamel and dentin).

4. ACKNOWLEDGEMENTS

This work has been supported by grants from FAPESP (Proc.n. 06/04252-0; 09/09206-5; 09/07036-5), from CNPq and from Pró-Reitoria de Pesquisa of the University of São Paulo - USP.

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