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# Quality parameters assessment in kiwi jam during pasteurization. Modelling and optimization of the thermal process

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## ABSTRACT

This work focuses on the optimization of the pasteurization process in kiwi jams, considering the influence of the containers size on the quality parameters through experimental measurements and kinetic models. A numerical finite element model was developed with the purpose of simulating the energy transfer during the retort thermal processing of the product. The temperatures predicted by the simulations were successfully validated against experimental data (average relative differences < 5%). These temperatures were incorporated into the kinetic model that described the quality variations which corresponded well with the texture and colour variations experimentally measured. As a result the validated numerical model was used to design and evaluate equivalent thermal processes which allowed determine optimal operating conditions. These results could contribute to the optimization of thermal processing of kiwi jam in order to minimize quality losses, such as texture, colour and nutritional value.

*Keywords:* Thermal processing; Kiwi jam; Finite element analysis; Optimization; Quality parameters

## 1. Introduction

Kiwifruit (*Actinidia deliciosa*) is considered a highly nutritional fruit due to its high level of vitamin C and its strong antioxidant capacity due to its wide number of phytonutrients including carotenoids, lutein, phenolics, flavonoids and chlorophyll (Cassano et al., 2006). Kiwifruits have very short shelf-life since they are highly perishable (Kaya et al., 2010). The manufacturing of jams submitted to a thermal process, such as pasteurization, is a useful alternative to extend the shelf life and conservation period. However, during this process the original fruit loses some of its nutritional value acquiring undesirable characteristics in aroma, texture and colour. It has been previously determined that the thermal processing causes a browning that differs from the original fresh fruit colouring. This is possibly due to the degradation of chlorophylls involving a number of reactions causing enzymatic and/or nonenzymatic development of brown pigmented substances. During processing there is release of intracellular acids and enzymes, which can then come into intimate contact with chlorophyll-protein complexes, accelerating colour degradation (Cano and Marín, 1992).

Changes in the composition and organoleptic properties on canning of kiwifruit were reported by Beutel et al. (1976) and Cano and Marín (1992). Simmons (1978) investigated the drying of kiwifruit with particular reference to colour retention and gave a qualitative assessment of the candied product.

Also, it is important to remark that the visual quality and/or appearance are the main factors that consumers identify and relate with foods packed in glass jars (Marra and Romano, 2001). As a result, the correct design and optimization of the

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### Nomenclature

| | |
|---|---|
| $a^*$ | CIE colour space co-ordinate: degree of greenness/redness |
| $a_w$ | Water activity |
| $A$ | Area of the jar ($m^2$) |
| $b^*$ | CIE colour space co-ordinate: degree of blueness/yellowness |
| Cp | Specific heat ($J\,kg^{-1}\,K^{-1}$) |
| $D$ | Diameter of jar (m) |
| F | Sterilization value (min) |
| $H$ | Height of the jar (m) |
| $k$ | Thermal conductivity ($W\,m^{-1}\,K^{-1}$) |
| $L^*$ | CIE colour space co-ordinate: degree of lightness |
| $m$ | Number of experimental measures |
| QR | Quality retention |
| R | Radius of the jar (m) |
| T | Temperature (°C) |
| t | Time (min) |
| V | Volume of the jar ($m^3$) |
| VRT | Variable retort temperature |
| $(X_w^b)$ | Moisture content (g water/100-g sample) |
| $z_c$ | Thermal resistance factor (°C) |

*Greeks letters*

| | |
|---|---|
| $\Delta E$ | Total colour change |
| $\varepsilon$ | Relative average error (%) |
| $\rho$ | Density ($kg\,m^{-3}$) |

*Subscripts*

| | |
|---|---|
| ave | Average |
| $e$ | Experimental |
| ext | External |
| $f$ | Final |
| ref | Reference |
| s | Simulated |
| sur | Surface |
| 0 | Initial |

**Table 1 – Dimensions, *H/D* and *A/V* ratios of the glass jars used in the simulation models.**

| Volume ($cm^3$) | $H$ (cm) | $R$ (cm) | $H/D$ | $A/V$ ($m^{-1}$) |
|---|---|---|---|---|
| 660 | 13.7 | 4.4 | 1.6 | 74.3 |
| 360 | 12.0 | 3.5 | 1.7 | 110.8 |
| 240* | 7.7 | 3.8 | 1.0 | 117.6 |
| 240** | 13.4 | 2.8 | 2.4 | 117.7 |

thermal process of these types of products is a major issue when trying to minimize quality loses.

In order to evaluate the quality attributes and study the microbial population during the thermal process, the time temperature evolution in the product must be taken into account. In this sense, the numerical modelling of the process is an important tool that can predict the thermal histories over the entire domain, minimizing the experimental procedures and reducing time and costs for industrial processors (Martins, 2006).

Even though the technological advances in aseptic packaging and rotary retorts have substantially enhanced the quality of these food products decreasing the energy demand, these benefits were not observed in conductive foods (Durance, 1997). Variable retort temperature (VRT) thermal processing, in which the environment temperature within the retort is modulated during the process, has been recognized as an innovative method to improve quality and save process times (or energy) in these types of products (Chen and Ramaswamy, 2004). Some of the published works where this method has been implemented (Nadkarni and Hatton, 1985; Saguy and Karel, 1979; Teixeira et al., 1975) consisted in finding the optimal operating condition in order to obtain maximum volumetric retention of nutrients. Since the 1990s, several researchers (Almonacid-Merino et al., 1993; Banga et al., 1991; Durance et al., 1996; Noronha et al., 1993) have extended this technique to obtain other optimal options such as surface quality and process time or energy consumption, which are more meaningful to consumers and food industries. However, all the before mentioned works were developed for canned foods where the containers resistance to the heat penetration is negligible.

This work aims to

(i) Evaluate the influence of container size using glass jars on the quality attribute of kiwi jams during the pasteurization process by using experimental measurements.
(ii) Simulate the heat transfer phenomenon applying a numerical algorithm to predict the time-temperature evolution inside the product and consequently the variation of the quality parameters through the coupling of the kinetic model.
(iii) Design and evaluate, through the numerical model previously validated, the equivalent thermal process needed to optimize the food process.

## 2. Materials and methods

### 2.1. Sample preparation

Fresh kiwi fruits (*Actinidia deliciosa* var. Hayward) obtained in a local market store were selected for the preparation of the jams, which were immediately processed. Processing consisted in peeling, cutting and grinding with further cooking until reduction of one third of the initial volume was obtained. Sugar was added until a 65 °Brix soluble solid concentration was reached, ensuring that the national legislation regulations established by the Código Alimentario Argentino (CAA or Argentine Food Code, 1971) were upheld.

Finally, a gelling agent (high methoxyl pectin) was added and cylindrical glass jars of different volumes and characteristic dimensions, as shown in Fig. 1, were filled. After filling the jars with the product to be heated, their metal lid were fixed and sealed with silicon. The containers tested were of three different volumes (240, 360, and 660 $cm^3$) and those of 240 $cm^3$ included two different aspect ratios (240* and 240**). So, four different types of jars (240*, 240**, 360 and 660 $cm^3$) were studied in this work. The volume and dimensions of those glass jars are detailed in Table 1.

These containers sizes were selected to include the range of jar sizes being used in the food industry today as well as to enable us to observe effects of different *A/V* ratios.

### 2.2. Thermal processing

A vertical stainless steel batch retort was used to carry out the thermal process. This retort is furnished with an automatic

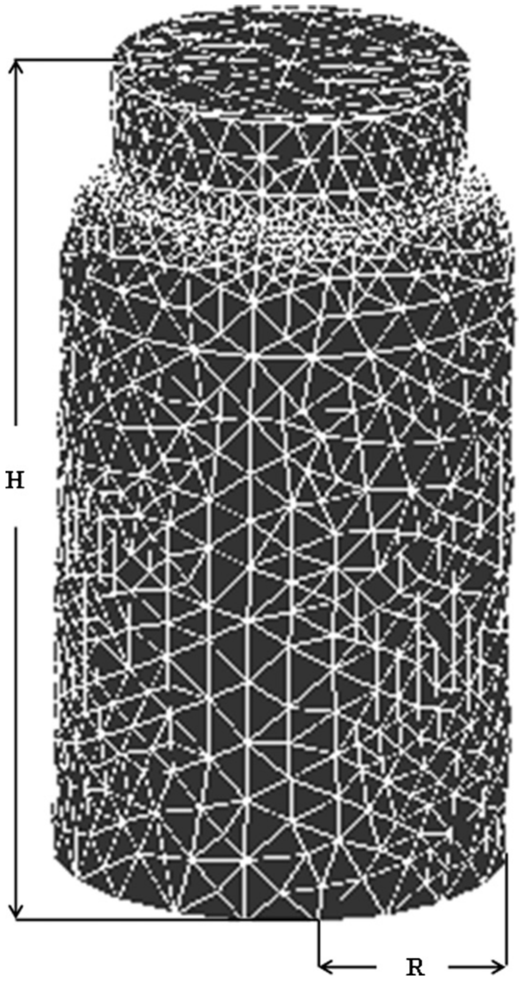

**Fig. 1 – Diagram of the cylindrical glass jar (360 cm$^3$), characteristic dimensions and the spatial discretization of the domain used for the simulation.**

security valve that opens at the pressure of 2 atmospheres, reaching and maintaining a final temperature of approximately 118 °C. The heating media consists of the initial air contained in the retort plus an increasing amount of water vapour generated by the heated water contained in the bottom of the retort (see Fig. 2).

Three layers of nine jars containing water were placed in the retort. Three jars with kiwi jam were placed in the centre of the middle layer (slowest heating zone)–instead of the water- filled jars - and equipped with thermocouples (see Fig. 2).

The process was divided into three steps: (a) come-up (without venting), (b) holding and (c) cooling. The initial heating stage (come-up period) consisted in approximately 30 min (come-up time) where the retort temperature ($T_{ext}$) increased from ambient room temperature to a final temperature of 118 °C. The second stage maintained this temperature, followed by a cooling period where there is a pressure relief inside the retort reaching a temperature of 100 °C. Then the jars were submerged into a 60 °C thermostatic water bath to rapidly cool down the product. This procedure, type of retort and working temperature are typical to little-volume processors.

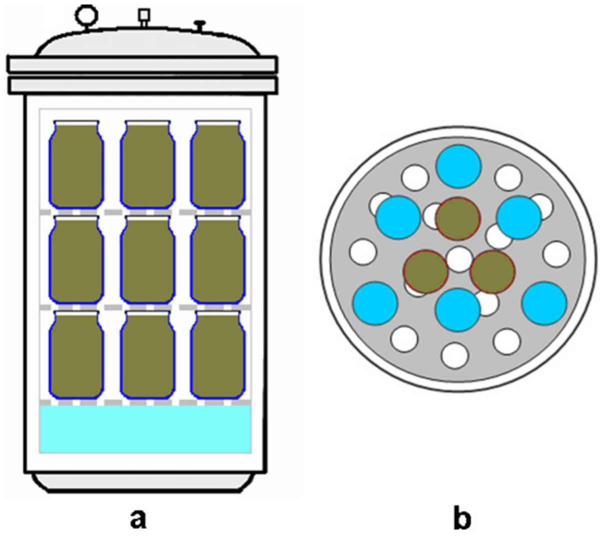

**Fig. 2 – Diagram of (a) front view of the retort and (b) top view showing the distribution of the glass containers (●) filled with water and (●) kiwi jam in each layer.**

These test processes were specifically designed to determine the time needed to reach at the cold spot a sterilization value ($F_{93.3}^{8.3}$) of 10 min (Eq. (1)), as recommended by Townsend et al. (1954) for foods with pH lower than 4.5.

$$F = \int_{t_0}^{t_f} 10^{(T-93.3)/8.3} dt \qquad (1)$$

To this end, simulation experiments were carried out varying the length of second stage (constant temperature) in order to reach this final sterilized value (F-value).

In the same manner, several different thermal processes were numerically designed to optimize the process. Some of the simulations considered that the system reached its maximum external temperature instantaneously, i.e. without come-up time. Then two types of equivalent processes (with same F-value) were analyzed, one with variable retort temperature (VRT), and another where the retort temperature was maintained constant (CRT).

### 2.3. Simulation model

Heat transfer in kiwi jams during pasteurization is a general transient heat conduction problem and the second Fourier Law can describe it. The cylindrical geometry of jar dictates the axis-symmetrical heat transport phenomena in a cylindrical glass jar. The head space was not considered in the mathematical model. Some preliminary calculations indicate that the use of either domain (“with” or “without head space”) in the simulation model results in differences lower than 3.41% for quality retention and of 0.54% for lethality.

This approach was also used by Erdogdu et al. (2010) who showed that the assumption of zero head space did not affect the simulation results.

Thus for cylindrical shaped jars the energy transport equation can be described as follows (Bird et al., 1976):

$$\rho Cp \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \qquad (2)$$

**Table 2 – Thermal properties of kiwi jam (24.75 g/100 g w.b., moisture content) and of glass wall of the jar.**

| Material | Property | Value | Unit | Source |
|---|---|---|---|---|
| Kiwi jam | Density ($\rho$) | 1200 | $\mathrm{kg\,m^{-3}}$ | This work |
| | Specify heat ($Cp$) | 2280 | $\mathrm{J\,kg^{-1}\,K^{-1}}$ | Riedel (1969) |
| | Thermal conductivity ($k$) | 0.337 | $\mathrm{W\,m^{-1}\,K^{-1}}$ | Fikiin (1974) |
| Glass | Density ($\rho$) | 2243 | $\mathrm{kg\,m^{-3}}$ | |
| | Specific heat ($Cp$) | 963 | $\mathrm{J\,kg^{-1}\,K^{-1}}$ | Hayes (1987) |
| | Thermal conductivity ($k$) | 1.125 | $\mathrm{W\,m^{-1}\,K^{-1}}$ | |

### 2.3.1. *Initial conditions*

A uniform initial temperature $T_0$ over the entire domain was assumed for the simulation:

$$T(x, y, z, t = 0) = T_0 \tag{3}$$

### 2.3.2. *Boundary conditions*

At the glass jar boundary: two thermocouples were fitted outside close to the samples in order to register the temperature of the surrounding steam and their average was considered as boundary condition in the heat transfer model (Eq. (4)).

$$T = T_{\mathrm{wall}}(t) \tag{4}$$

Thus essential boundary conditions were considered and the effect of surface heat transfer coefficient was neglected. In this sense, Richardson et al. (1988) observed that the experimental and predicted temperatures were in better agreement when the surface temperature of the object was measured, instead of that of a point in the heating medium. Therefore, the effect of the surface heat transfer coefficient was eliminated, particularly during the cooling stage.

The thermal properties of the jam were assumed constant and calculated based on theoretical models taking into account their moisture content (24.75 g/100 g wet basis, w.b.) (Table 2).

The heat transfer resistance of the jar wall was accounted in the simulation model and an average value of 0.004 m obtained from destructive glass thickness tests was considered as the thickness of the container wall, to assess the possible effect of the glass walls on heating rates. The thermo physical properties of glass wall of the jars used in the model are given in Table 2.

The partial differential equations that establishes the mathematical model were solved, for defined dominium and associated boundary conditions, using the finite element method with the software COMSOL Multiphysics version 3.2 (COMSOL AB, 2005) in a P.C. with Intel Pentium 4 2.40 GHz, 1.98 GB RAM. The transient calculations were carried out using a backward Euler scheme, with variable time step size.

## 2.4. *Mesh and time step details*

The boundary layer occurring at the heated walls and its thickness are the most important parameters for the numerical convergence of the solution. Temperatures have their largest variations in this region. To adequately resolve this boundary layer flow i.e. to keep discretization error low, the mesh should be optimized and a large concentration of grid points is needed in this region. If the boundary layer is not resolved adequately the simulation will be erroneous. On the other hand, in the rest of the domain where the variations of temperature are small, the use of a fine mesh will lead to increases in the computation time without any significant improvement in accuracy. Thus a non-uniform grid system is necessary.

As shown in Fig. 1 describes the dominium of a 360 cm$^3$ jar ($H/D$ = 1.7) – a non-uniform grid system was used in the simulations. An unstructured mesh with 9708 nodes and 51082 tetrahedral elements was developed, graded in both directions with a finer grid near the wall. To achieve this meshing, a maximum element size of 1.5 mm in the food boundary and an element growth rate of 1.25 were specified. This will give the adequate number of elements near the wall. The use of finer mesh showed no significant effect on the accuracy of the solution (data not shown).

The thermal processing, for that jar, was simulated for 7800s. It took 100 time steps to achieve the first 975s, another 100 steps to reach 2280s and 440 steps for the total of 7800s of heating. Solutions have been obtained using a variety of grid sizes and time steps, and the results show that the solutions are time-step independent and weakly dependent on grid variation. Similar meshing and time steps were used for the different containers analyzed in this work.

## 2.5. *Numerical model validation*

The temperature evolution at surface of the jar and geometrical centre of the container was measured each 15 s, using Copper-Constantan type T thermocouples and a multichannel data acquisition system (KEITHLEY model AS-TC, USA) connected to a PC. The temperature measurement inside the jars was performed by inserting a thin thermocouple through a small hole in the metallic lid. A high-temperature resistant seal was used to secure air tightness around the thermocouple in the lid.

The numerical model was validated by comparing the time-temperature curves with the experimental measurements and calculating the relative average error (Eq. (5)) and $F_{\mathrm{model}}/F_{\mathrm{experimental}}$ ratio, obtained from the ratio of model and experimental $F$ (Eq. (1)).

$$\varepsilon_{\mathrm{ave}}(\%) = \frac{1}{m}\sum_{i=1}^{m}\frac{|T_s - T_e|}{T_e}100 \tag{5}$$

The evaluation by $F$-values, instead of only by temperature values, is important as due to the exponential relationship of microbial inactivation with the temperature. Even small deviations in temperatures along the process can be critical in microbial reduction (Augusto et al., 2009).

## 2.6. *Quality indexes*

### 2.6.1. *Physicochemical properties*

Moisture content was determined using AOAC 20103 method (1980). Soluble solids were determined by measuring the °Brix at 25 °C (Bellingam-Stanley Limited refract meter). Water activity ($a_w$) was measured by using a dew point hygrometer (Decagon Inc.) and for pH analysis a pH-meter with a puncture electrode (HANNA Inc., pH 211) was used. The pH-meter was standardized by a two-point method against standard buffers of pH 4.0 and 7.0. Each analysis was carried out in triplicate.

### 2.6.2. *Texture*

We evaluated the consistency – in terms of maximum force (N) – of the jam samples using a compression test, with an

**Table 3 – Measured physical-chemical properties (mean ± standard deviation, three replicates) of traditional kiwi jam (without and with thermal processing) and of two available commercial kiwi jam[a].**

| Sample | °Brix | $a_w$ | $X_w^b$ | pH |
|---|---|---|---|---|
| TKJ | 70.1 ± 0.4 | 0.777 ± 0.006 | 28.8 ± 1.0 | 3.21 ± 0.02 |
| CDKGJ | 37.1 ± 0.1 | 0.939 ± 0.001 | 60.4 ± 0.1 | 3.20 ± 0.01 |
| CDKJ | 33.5 ± 0.0 | 0.929 ± 0.002 | 64.6 ± 0.2 | 3.70 ± 0.01 |
| TPTKJ 660 $cm^3$ | 69.4 ± 0.2 | 0.763 ± 0.001 | 25.62 ± 0.16 | 3.19 ± 0.16 |
| TPTKJ 360 $cm^3$ | 70.1 ± 0.1 | 0.762 ± 0.002 | 25.64 ± 0.77 | 3.21 ± 0.01 |
| TPTKJ 240 $cm^3$ | 71.1 ± 0.3 | 0.759 ± 0.001 | 22.94 ± 0.03 | 3.22 ± 0.01 |

[a] TKJ, traditional kiwi jam before processing; CDKGJ, commercial dietetic kiwi-grapefruit jam; CDKJ, commercial dietetic kiwi jam; TPTKJ 660 $cm^3$, TPTKJ 360 $cm^3$ and TPTKJ 240 $cm^3$: traditional kiwi jam after thermal processing in jars of different volumes.

acrylic cylindrical probe P/05R (0.5 in. radius) for gels and a test speed of 2 mm/s, of the texture analyzer TA.XA2i (Stable Micro Systems Ltd., Godalming, Surrey, UK). Each reported value corresponded to the mean of ten measurements, for unprocessed as well as processed samples.

### 2.6.3. *Colour*

A CIE 1976 $L^*a^*b^*$ system was used to describe the spatial 3D colour representation with a Minolta CR300 Colorimeter. The colour measurements were taken at the surface by placing the Colorimeter at several points on the jars surface. The volumetric colour (inner filling) was measured first by mixing the jam and then creating a 3 cm film on a Petri dish. The $L^*$: lightness; $a^*$: redness and $b^*$: yellowness parameters were determined for ten samples before and after being thermally treated and for each process type.

To evaluate the pasteurization process in jams, the total colour change using Eq. 6 was applied:

$$\Delta E = \sqrt{\Delta L*^2 + \Delta a*^2 + \Delta b*^2} \qquad (6)$$

where $\Delta L^*$, $\Delta a^*$ and $\Delta b^*$, are the differences in $L^*$, $a^*$ and $b^*$ parameters of the jam during the thermal process.

### 2.6.4. *Sensory quality retention*

The average sensory quality retention of the jam ($QR_{ave}$) and its surface sensory quality retention ($QR_{sur}$) were determined by Eqs. 7 and 8, respectively. A reference temperature ($T_{ref}$) of 100 °C, a $D$-value ($D_{ref}$) of 12.5 min and a $z_c$ of 26 °C were used based on the sensory quality changes kinetics reported in Toledo (2007).

$$QR_{ave} = \left(\frac{Q}{Q_0}\right)_{ave} = \frac{1}{V}\int_0^V 10^{\left[-1/D_{ref}\int_0^t 10^{(T-T_{ref})/z_c dt}\right]} dV \qquad (7)$$

$$QR_{sur} = \left(\frac{Q}{Q_0}\right)_{sur} = \frac{1}{S}\int_0^S 10^{\left[-1/D_{ref}\int_0^t 10^{(T-T_{ref})/z_c dt}\right]} dS \qquad (8)$$

## 3. Results and discussion

### 3.1. *Quality parameters*

Table 3 shows the physical-chemical properties of kiwi jam before and after the thermal process, including those of two commercial jams obtained at a local market store. The total soluble solid content, water activity ($a_w$), pH and moisture content ($X_w^b$) of the traditional kiwi jam (unpasteurized) (TKJ) and commercial jams (CDKGJ and CDKJ), resulted in agreement with data published by García-Martinez et al. (2002). The experimental values obtained for the physical chemical properties ($a_w$, pH and $X_w^b$) for the jams processed in the different jar sizes and shapes (TPTKJ) assure that an adequate conservation procedure is achieved for its long-time storage.

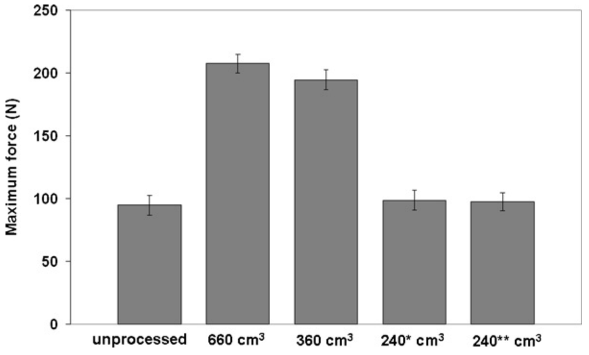

**Fig. 3 – Maximum force values of kiwi jam after the thermal process for the different sizes and dimensions of the glass jars.**

Moreover, the pH results for all cases showed values inferior to 4.5, which validate the use of Eq. 1 to calculate the pasteurization time.

Fig. 3 presents the maximum force (N) parameter of the product before and after the process for the different jar sizes showing the effect of the VRT treatment on the textural properties of the kiwi jam. In all cases studied, an increase of the consistency was observed compared to the unprocessed jams. The increase of firmness after thermal processing could be due to the activation of an enzyme: pectin-methyl-esterase (PME) during part of the heating process. Such enzyme is activated at 50 °C and is inactivated at temperatures higher than 70 °C (Aguilar et al., 1997). For most fruits and vegetables, texture depends on the presence of pectic substances, which are part of the intercellular material (Baduí, 1993). Pectic enzymes affect these substances and, therefore, the overall texture. Among the pectic enzymes, PME hydrolyzes the methyl ester bonds, producing methyl alcohol (Bonner, 1936; Kertesz, 1951), pectin and polygalacturonic acid, and lowering pH (Balestrieri et al., 1990). The PME produces free carboxylic groups which can react with divalent ions present in the tissues, e.g. calcium and magnesium, creating more rigid structures and increasing the firmness (Bartolome and Hoff, 1972).

Some studies have been reported on the effect of low-temperature blanching on texture of different vegetables, and a very marked increase in firmness has been observed. This increase persisted through processing such as canning and sterilization (Stanley et al., 1995).

This tendency was more marked for those jars with low A/V ratio (660 and 360 $cm^3$), whereas it was minor in those jars with high A/V ratio (240* $cm^3$ and 240** $cm^3$). This could

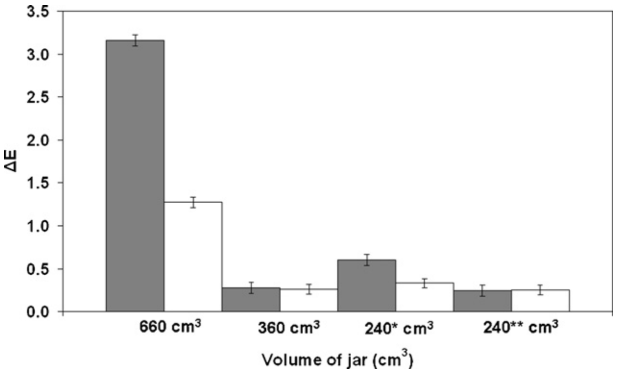

**Fig. 4 – Total colour change (ΔE) of kiwi jam after the thermal process (■) at the surface and (□) volumetric for the different jars sizes.**

be related to the fact that in the jars of 660 cm$^3$ and 360 cm$^3$ the product remains within the optimal activation range of PME (50–70 °C) during a larger time period that for the other sizes and shapes.

From Fig. 3 it can also be observed that the influence of volume is more significant than that of the diameter of the jar since containers with the same volume and different diameter (240* cm$^3$ and 240** cm$^3$) experimented the same firmness variation meanwhile jars with almost equal diameter and different sizes (240* cm$^3$ and 360 cm$^3$) showed important differences in their consistency.

Fig. 4 shows the total colour change (ΔE) at the surface and volumetric for the different jar dimensions analyzed in this work, the highest value of ΔE occurred for the largest jars diameters (660 cm$^3$ and 240* cm$^3$). This tendency was observed in the global colour change as well as at the surface. On the other hand, the difference between both parameters also was higher for these jar dimensions. This fact might be explained because there is a less uniform heating inside the product in those containers of major diameter (660 cm$^3$ and 240* cm$^3$), causing overcooking of the jam at the surface.

The degradation of kiwi pigments observed through the total colour change (ΔE) parameter can be attributed to the pasteurization process. This thermal process resulted in important colour changes, inducing a yellow brownish colouring, which is very different to that of the unpasteurized product. According to Cano and Marín (1992), who studied pigment composition in fresh and conventional canned slices of kiwi fruit, this colour change is due to the development of chlorophyll degradation compounds such as pheophytin, pyropheophytin and pyropheophorbides. Moreover, was reported that several decomposition reactive products occur via the degradation of vitamin C and these compounds may combine with amino acids, thus resulting in formation of brown pigments (Burdurlu et al., 2006). In this sense, Hydroxymethylfurfural (HMF) is one of the decomposition products of ascorbic acid (Eskin, 1990; Solomon et al., 1995) and suggested that is a precursor of brown pigments.

### 3.2. *Temperature profile – model validation*

Fig. 5 shows the experimental and predicted thermal histories at the geometrical centre of the kiwi jam for different glass containers during the thermal processing. The temperature, at the external fluid inside the retort, the external cooling fluid in the thermostated bath, and the jars surface (boundary condition) are also shown in the same figure. The great differences at the beginning of the process between the temperature at the surface of the jar and the fluid inside the retort can be attributed to the presence of air in the heating medium. As the thermal process takes place, there is an increase in the vapour content inside the retort, which helps the convective energy transport, decreasing the temperature difference.

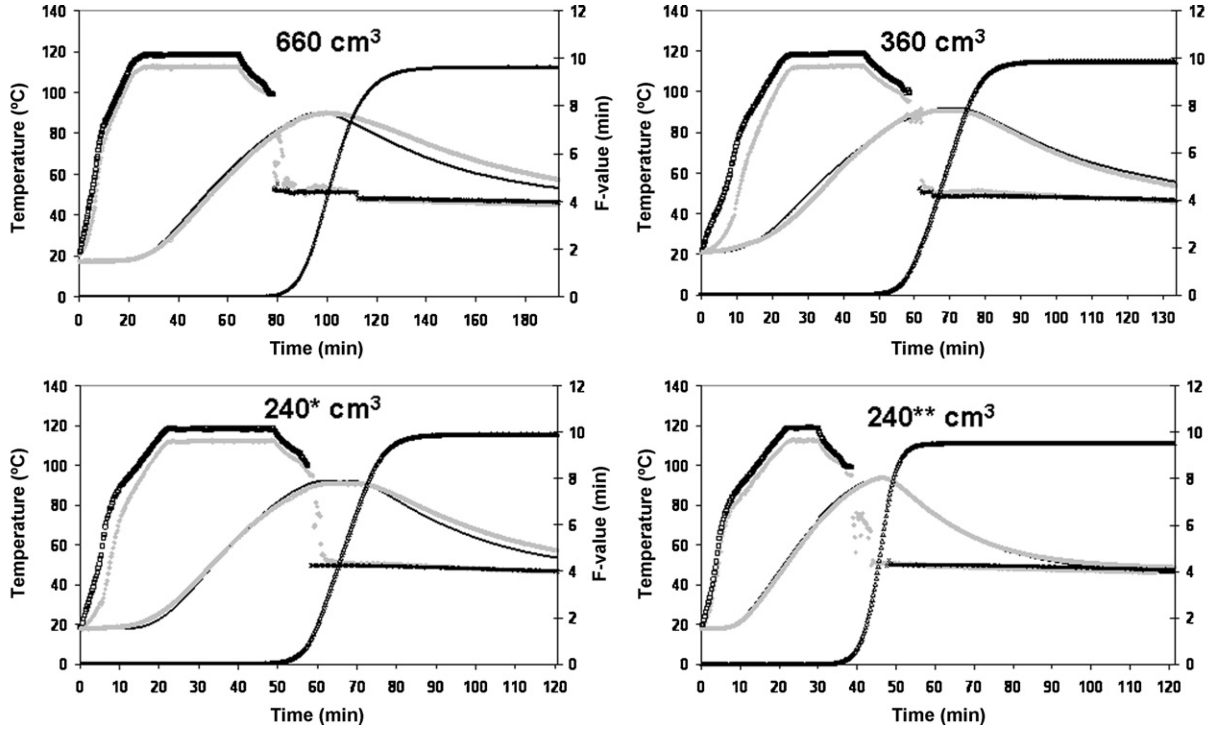

**Fig. 5 – Time-temperature evolutions of the kiwi jam in the different glass jars used in this work. (□) retort temperature, (♦) surface jar temperature, (×) thermostatic bath, (●) experimental centre temperature, (-) simulated centre temperature, (Δ) experimental *F*-value.**

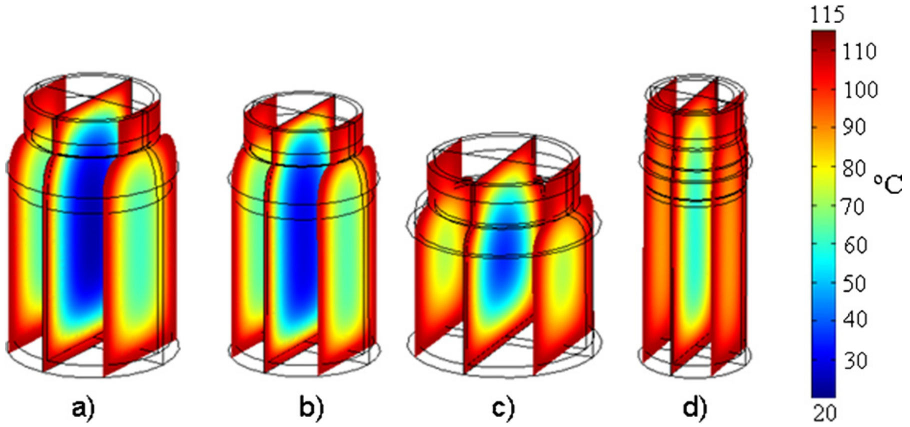

Fig. 6 – Temperature distribution of kiwi jams after 1500s of the thermal process considering the following jars volumes: (a) 660 cm$^3$, (b) 360 cm$^3$, (c) 240* cm$^3$ and (d) 240** cm$^3$.

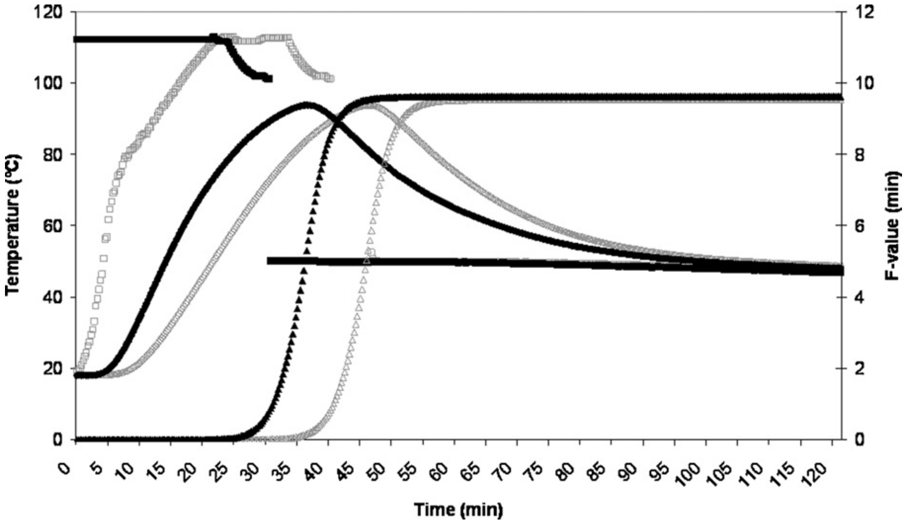

Fig. 7 – Temperature evolution during the thermal process in a 240** cm$^3$ container for the following processes: CRT (■) retort-bath, (●) thermal centre, (▲) F-value and VRT (□) retort-bath, (○) thermal centre, (△) F-value.

Fig. 5 illustrates how the thermal centre maintains a continuous increase in its temperature, even during the cooling period, due to the great thermal inertia of these types of systems. The complete microbial inactivation of the process (F-value) occurs mainly during the cooling period where the highest contribution was observed with the jars that have the largest diameter.

Predicted temperatures were found to be in satisfactory agreement with experimental measurements. Relative average errors for the predicted temperatures, calculated according to Eq. (5), were lower than 5% assessing the validity of the simulation model.

The values of $F_{\text{model}}/F_{\text{experimental}}$ obtained were always close to the unit (in the range of 0.81–1.27), indicating high correlation among experimental and simulated data.

Fig. 6 shows the temperature distribution in the product after 1500s inside the retort, for the different containers analyzed in this work. It can be noted that the coldest point in the product is practically near the geometric centre, which is the expected characteristic of pure conductive foods.

However, the coldest point rigorously is just below the geometric centre, which is probably caused by the shape of the jar neck and the asymmetry of thermal conductivities between the bottom and metallic lid material.

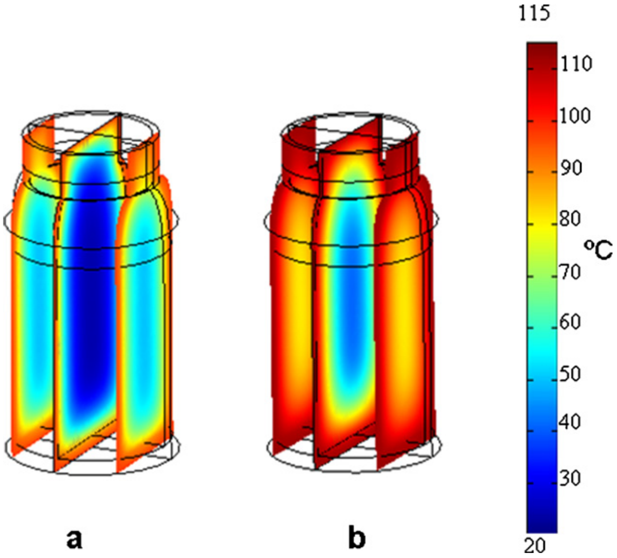

Fig. 8 – Temperature distribution of kiwi jams after 1200s of the thermal process considering a glass jar of 360 cm$^3$ volume for two different processes: (a) VRT and (b) CRT.

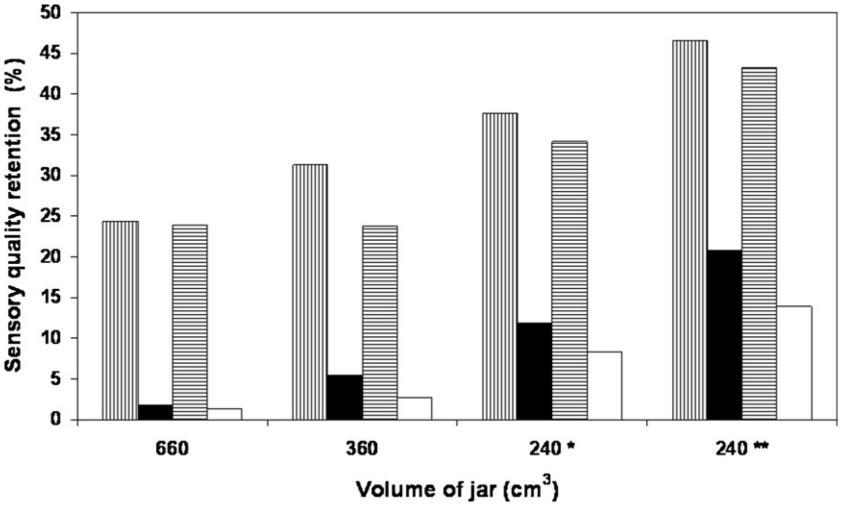

Fig. 9 – Sensory quality retentions for the different jar sizes and thermal processes: VRT (▥) $C_{ave}$, (■) $C_{sur}$ and CRT (▤) $C_{ave}$, (☐) $C_{sur}$.

Moreover, a slower heating rate was observed in containers that have a larger volume (Fig. 6a and b), meanwhile for those of equal volume (see Fig. 6c and d) that of lower diameter and larger height (high *H*/*D* ratio), experimented a higher heating rate (240** cm$^3$).

### 3.3. *Equivalent thermal processes. Analysis and optimization*

As an example in Fig. 7 the predicted temperatures for the coldest point of a jam in a 240** cm$^3$ jar for the VRT and CRT processes are shown.

The heating rate of the product submitted to the CRT reached an inactivation value ($F = 10$ min) much faster than the VRT process, approximately 10 min earlier. The figure also shows that – irrespective of the heating regime – in both cases most of microbial inactivation occurs during the cooling stage.

Fig. 8 shows the temperature distribution over the whole domain of the kiwi jams contained in 360 cm$^3$ jars, after 1200s of being submitted to the thermal process for both processes (VRT and CRT). Even though CRT produces shorter processing times and therefore lowers energy demand, there is a less uniform heat distribution inside the product, causing higher overcooking of the jam at the surface. Similar behaviours were encountered for the other jar sizes.

Fig. 9 presents the average quality retention and the surface quality retention calculated for the different jar sizes and equivalent process types applied (VRT and CRT).

The major differences in average quality retention and quality retention values were obtained for the CRT process, which is in accordance with the less uniform heating for this process. For all jars sizes the average quality retention and surface quality retention resulted in higher values when the VRT treatment was applied.

In fact, the implementation of the VRT increases the volumetric quality retention between 2.04% and 31.66%; while the surface quality retention accomplished a 33.16–98.58% increase.

These results are in agreement with those published by Chen and Ramaswamy (2002), where a 7–10% surface cooking value reduction was obtained when a VRT process was implemented with respect to the CRT process. Additionally, Banga et al. (1991) found similar results and they incorporated an optimization algorithm using three objective functions: maximum nutrient retention, maximum surface quality retention, and minimum processing times. These authors concluded that the variable temperature process was a beneficial aspect in order to maintain an acceptable quality level at the products surface. In the same manner, Noronha et al. (1993) found a 20% increase of the surface quality parameter for the VRT process with respect to the CRT.

On the other hand the quality retention suffered a reduction in their value as the volume of the jar increased, while studying jars with the same volume (240 cm$^3$) this parameter was lower for the containers with the largest diameter and shorter height (240* cm$^3$). Teixeira et al. (1975) also observed this behaviour for the thiamin retention in solid foods. They reported that as the height/diameter ratio increased from 1.71 to 13.75, for equal volume containers, the retention increased from 43% to 63%.

The sensory quality retention obtained through the time-temperature prediction for the VRT process corresponded with the textural and colour parameters measured experimentally. This validates the implementation of the numerical model and allows the correct optimization of the process.

Thus, the experimental and theoretical study showed that optimization using VRT profiles represents a valuable approach when the minimization of quality degradation for more than one component is of interest.

On the other side, the evaluation of the influence of container size on the quality allowed develop a model that can be very practical especially in low volume productions, where sterilization is discontinuous and is usual to work with successive batches of jars of different sizes.

Finally the validated numerical model can be used for the design and optimization of the thermal process, minimizing the experimental procedures and reducing time and costs for industrial processors.

## 4. Conclusions

This work assessed the influence of the jars sizes on the colour and textural variations of kiwi jams during the thermal process. It was established by the results that the *A*/*V* ratio is the main factor that influences the firmness variations, increasing its value as the A/V ratio decreases. On the other hand, the diameter of the jar has an important effect on the colour variations; it was concluded that as the diameter of the jar increases the total colour change increases. These quality factors resulted in agreement with the quality retention determined by means of temperature predictions using numerical simulations. This enables the application of the numerical models for the prediction of quality losses during different process schedules. The implementation of the numerical model resulted in a useful tool for the design and optimization of the thermal process. The model showed that the variable retort temperature (VRT) allowed obtain products with higher quality parameters (both at the surface and over the entire volume) for conductive products in glass jars compared to CRT processes.

The developed calculation software is of general use and can be applied to different solid products and processing conditions (material of the container, size and shape).

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