Application of Transfer Functions to the Thermal Processing of Sweet and Sour Cherries Preserves: Influence of Particle and Container Sizes

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The conditions of thermal processing of fruit preserves packed in transparent glass containers have great importance from the point of view of the final product appearance. Process simulation can allow to predict the quality of the product and its possible degradation. This work applied the transfer function method to simulate the pasteurisation of whole sweet and sour cherries canned in glass containers, with a 25 °Brix sucrose solution as covering liquid, and the predicted results were experimentally tested. The influence of fruit and container diameters on the treatment times was analysed. Kinetic models for enzyme degradation were coupled to the prediction model as examples of the possibilities of optimising the whole pasteurisation process. The accuracy (average error in predicted temperatures: 2.1%) of the simulation method was satisfactory for practical purposes, its use resulted simple and fast, and it allowed adjusting of pasteurisation times, even during the process.

Key Words: thermal processing, transfer functions, simulation, kinetics, cherries, preserves

INTRODUCTION

Production and consumption of natural or "green" foods is having a steady increase in most developed countries. In the case of Argentina, natural foods production is very wide, including not only primary food products (meats, cereals, fruits and vegetables) but diverse elaborated foods (sugars, wines, oils, dairy products, preserves). Among preserves, the most representative are those based in fine fruits (sweet and sour cherries, strawberries, raspberries). These are generally produced in low volume lots by artisan food processors (CAPOC, 2002).

The conditions of thermal processing of fruit preserves, packed in transparent glass containers, have a great importance from the point of view of the sensory quality (overall appearance) of the product. If processing times and/or temperatures are overestimated the fruit will turn very soft, the peel break of whole fruits will increase (Márquez and De Michelis, 1997) as well as the degradation of its natural colour (Ochoa et al., 2001). These quality indexes (colour, texture and overall appearance) are of high importance when dealing with organic or natural fruits, since consumers always look for highest quality products that maintain most of the attributes of the fresh fruit.

Thermal processing must be sufficient for reducing the microbial charge to safety levels. Besides, since the whole fruit does not admit previous blanching, thermal inactivation of fruit enzymes is also required. If the treatment is insufficient, fermentation or deep colour changes will occur.

Therefore, thermal processing must be sufficient for reducing the microbial load at safety levels, and – eventually – to inactivate fruit enzymes. But simultaneously, to get a high-quality product, the lowest intensity of the treatment is required.

The transfer functions method that provides accurate results for the simulation of thermal processes, being the main advantage of this method its simplicity and ease of calculations that can be performed using simple programmable calculators (Sanz et al., 1986; Mascheroni et al., 1987; Salvadori, 1994; Salvadori and Mascheroni, 1994; Salvadori et al., 1994a,b; Márquez et al., 1998).

On the other side, its more important limitations are (Mitalas, 1978; Sanz, 1984; Ceylan, 1987; Salvadori, 1994; Salvadori et al., 1994a; Márquez et al., 1998): (i) it is only valid for linear systems, and (ii) it is always

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necessary showed that a previous experimental or calculation stage (analytical or numerical) be there, to find the response of the system to one known input signal.

This method has been widely proved and validated, generally applied to systems with conduction or preferentially conductive heat transfer (Salvadori, 1994; Salvadori et al., 1994a,b; Salvadori and Mascheroni, 1994; Virseda and Pinazo, 1998a,b; Dalmendray et al., 1999; Virseda et al., 2000). However, there is little information about its use for systems with different heat transfer mechanisms, where a combination of convection in the liquid phase and conduction in the solids occurs, like in the case under study in this work.

In this respect, Ryniecki and Jayas (1993) used the step-response formulation for automatic determination of parameters for computer control of canned food sterilizers. Likewise, in a previous work, the authors gave a detailed description of the theoretical principles of the transfer functions method. In that paper, transfer functions were used to simulate the sterilization of particulate products (raspberry preserves) immersed in a liquid medium of relatively low viscosity (Márquez et al., 1998).

In this work, the simulation method is applied to preserves of sweet and sour cherries canned in glass containers, using a low-concentration sucrose solution as covering liquid, and predicted values experimentally tested. The influence of fruit and container diameters on product thermal response and on processing time is studied. A microbial destruction kinetic and other enzymes degradation are both coupled to the method, as an example of the possibilities to improve the pasteurisation process for sour and sweet cherries preserves.

MATERIAL AND METHODS

Model

The dynamic behavior of any linear system can be characterized by a transfer function $F(z)$, that represents a one-to-one relationship between an input signal or perturbation and the corresponding response (Salvadori and Mascheroni, 1994).

The response of the studied system $R(z)$, to any perturbation $P(z)$, can be predicted knowing the coefficients f_i of transfer function $F(z)$ as (Salvadori, 1994; Márquez et al., 1998):

$$R(z) = F(z)P(z) \tag{1}$$

In the systems that are studied in this work, the perturbation is the external medium temperature. The desired response is the temperature of a characteristic point, the centre of the container or the centre of one fruit in the centre of the container (just in it), since they are the "coldest" points of the system.

So, the thermal centre temperature T_c is calculated at specified sampling intervals Δ, according to:

$$T_c(n\Delta) = T_i + R(n\Delta) \tag{2}$$

where:

$$\begin{aligned} R(n\Delta) = {} & P(0)f_{n+1} + P(\Delta)f_n + \cdots + P((n-1)\Delta)f_2 \\ & + P(n\Delta)f_1 \end{aligned} \tag{3}$$

Knowing the coefficients f_i and $P(i\Delta)$, that is to say, the coefficients of the transfer function $F(z)$ and the perturbation values in the intervals $n\Delta$, respectively, the temperature of the characteristic point can be calculated, in each interval $n\Delta$.

It is important to underline two points: (i) the calculated temperatures are not continuous functions but discrete values at fixed time intervals $n\Delta$; and (ii) the function $F(z)$ is an infinite series, but only a finite number of terms are used for the calculations. As a practical rule, the sum of the coefficients of the transfer function has to be, at least, equal to 0.99 (Salvadori, 1994).

The dependence of the thermal responses (experimental or predicted) on process time and fruit diameter, can be correlated by the following equation:

$$T^* = a \exp\left(\frac{-b\alpha(t - t_d)}{D_f^2}\right) \tag{4}$$

which is characteristic of thermal processes (Bimbenet and Michiels, 1974), with a time lag (t_d) correcting the true process time (Bimbenet and Michiels, 1974; Ryniecki and Jayas, 1993; Abril et al., 1998) where t is time, t_d delay time , α fruit thermal diffusivity, D_f is fruit diameter, a and b are regression constants, meanwhile T^* is a dimensionless temperature defined as:

$$T^* = \frac{T_{\text{hb}} - T_c}{T_{\text{hb}} - T_i} = \frac{P(n\Delta) - R(n\Delta)}{P(n\Delta)} \quad \text{at} \quad t = n\Delta \tag{5}$$

where T_{hb} is the heating bath temperature (external perturbation), T_c is the container centre temperature (response) and T_i the product initial temperature.

Once the temperature T_c for each interval is determined, it is possible to calculate the accumulated thermal effect in terms of a desired value of pasteurisation for the enzymatic degradation, according to:

$$L = \int 10^{(T_c(t) - T_{\text{ref}})/z_e} dt \tag{6}$$

where $T_c(t)$ is the calculated temperature for each time interval, z_e is the temperature increment for a tenfold reduction of the decimal reduction time D and T_{ref} is the reference temperature for z_e. In the same sense, any other type of kinetics may be coupled to the estimated thermal history (Márquez et al., 1998; Dalmendray et al., 1999).

Samples

Freshly hand-harvested fruit of 18 °Brix soluble solids content and of 0.014, 0.018, 0.023 and 0.028 m average diameter D_f were selected. Three different cylindrical glass containers were used: two of 360 cm^3 (0.0725 and 0.079 m external diameter D_c) filled with 0.200 kg of fruit and one of 660 cm^3 (0.088 m external diameter) with 0.450 kg of fruit. A 25 °Brix aqueous sucrose solution was added to fill the whole volume of the containers.

To allow for thermocouples collocation to measure temperatures during the thermal treatment, metallic lids perforated in their centre were used to close the containers.

Methods

In all the tests, Cu-Constantan thermocouples were used and after their placement, the lids were sealed with high-temperature epoxy seal. In the experiences for the determination of $F(z)$, thermocouples were placed in the covering liquid around the fruits and in the centre of the container. In the experiences aimed at determining the influence of fruit size, thermocouples were fixed at the centre of a fruit of known diameter placed in the centre of the container. The temperature of the bath, T_{hb}, in which containers were immersed for the thermal treatment was also measured with Cu-Constantan thermocouples (0.8 mm probe sheath diameter).

All thermocouples were connected to a digital temperature-controller Cole Parmer Ind. Inc., Digi-Sense 8528-40 that allows making readings at user-selected time intervals.

Fruit weight was determined by using a digital balance Sartorius 1043 MP8-1.

Fruit diameter was measured with a micrometer in the transversal section to the peduncular insertion.

Sucrose concentration in the covering liquid was determined with an Atago Model 500 manual refractometer expresses as °Brix.

In order to obtain coefficients f_i of the transfer function $F(z)$, the containers were placed in a heating bath and it was provoked a step perturbation of the bath temperature. The response of the thermal centre of the container was measured every 0.5 min ($\Delta = 0.5$ min).

Moreover, several heating and cooling tests were carried out subjecting the containers to different thermal histories of the external bath.

All experiments were done in triplicate.

Calculation of the coefficients f_i of the transfer function and those belonging to the response ($R(i\Delta)$) for each system subjected to an external perturbation $P(z)$ were carried out by means of computer programmes developed in MS Quick Basic 4.5 (Salvadori et al., 1994b).

The dimensionless temperature T^* was correlated with time according to Equation (4), assuming a value of α of 1.32×10^{-7} m^2/s (Gaffney et al., 1980) and the regression constants a and b were obtained using the NonLin module from SYSTAT v.10.

The target pasteurisation value L was obtained by numerical integration, using an Excel Electronic Spreadsheet version 7.0 (Márquez et al., 1998). Parameters for pectinestearase inactivation ($L = 9.80$ min; $T_{ref} = 85$°C and $z_e = 14.8$°C (Silva and Silva, 1997)) were considered for the calculations.

RESULTS AND DISCUSSION

Determination of $F(z)$ for the Different Containers

The experimental response of liquid temperature in the thermal centre T_{cexp}, for 360 cm^3 containers and 660 cm^3 containers (Figure 1) subjected to a constant external perturbation (step) allowed to calculate the coefficients f_i of the transfer function $F(z)$. In both instances, the number of coefficients (30 for containers of 360 cm^3 and 59 for 660 cm^3, respectively) assured that

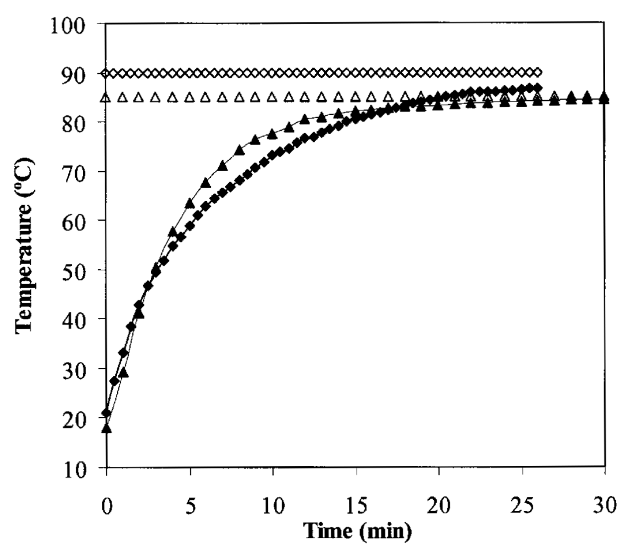

Figure 1. Experimental response of thermal center temperature, subjected to a constant external temperature T_{hb}. 360 cm^3 container: (π) T_{cexp}, (ρ) T_{hb}. 660 cm^3 container: (◆) T_{cexp}, (♬)T_{hb}.

their sum is higher than 0.99: 0.9955 and 0.9926 respectively.

Validation of the Prediction Method

Once coefficients f_i were determined, they were used to predict the thermal response of the different containers to diverse operating conditions, for which experimental thermal histories were also determined. So, the accuracy of the transfer function method could be verified in a wide range of possible operating conditions for homemade pasteurized preserves.

With variable bath temperature: This situation is quite frequent for regional low-volume manufacturers of organic fruit preserves. They use batch systems for thermal treatment. During production peaks the pasteurizer is often overloaded, making its temperature to decrease during the loading period, taking some time to recover the predetermined condition.

With two periods of constant and different bath temperatures: These experiments tried to simulate container heating plus immediate cooling stages. As it is known, the cooling stage is important in terms of accumulated microbial destruction and, at the same time, avoids unnecessary overcooking on the product. First, the containers were placed in a water bath at constant temperature set to 95°C and, 14 min later they were quickly transferred to another bath also at constant temperature set to 65°C.

With one heating and two cooling stages: This condition is convenient when preserves are processed in glass containers, because if the thermal jump between heating and cooling stages is very high, the container can break.

For all these conditions, the adequacy of the proposed calculation method (Equation (2)) to predict thermal responses was verified (Márquez, 2000) confirming the results obtained by Márquez et al. (1998) for raspberry preserves. Furthermore, in these new tests we worked using shorter sampling intervals and, consequently, a higher number of coefficients than previously (Márquez et al., 1998) and higher accuracy of predictions. This good agreement between simulated and experimental responses showed a maximum error of 6.2% and an average error of 2.1% in predicted temperature variation.

Nevertheless, at the end of the process that included a cooling stage, the transfer function (obtained only for heating stages) predicted temperature values lower than the experimental ones. These differences, more significant than those observed in heating curves, did not limit the applicability of the method. At those long times, the product already presented low temperatures and no practical cooking phenomena or microbial death occured.

Differences in predicted temperatures (T_{csim}) of the pasteurisation bath against experimental ones presented were less than 6.8% (Figure 2). The highest differences between experimental data and predicted values responses as a function of the initial temperature of preserves, T_i (Figure 3) were observed in the curves with the highest initial temperature (62 °C), an unusual situation in low volume productions. Probably due to the evolution of system fluid-dynamics implied in the determination of $F(z)$. The transfer functions were

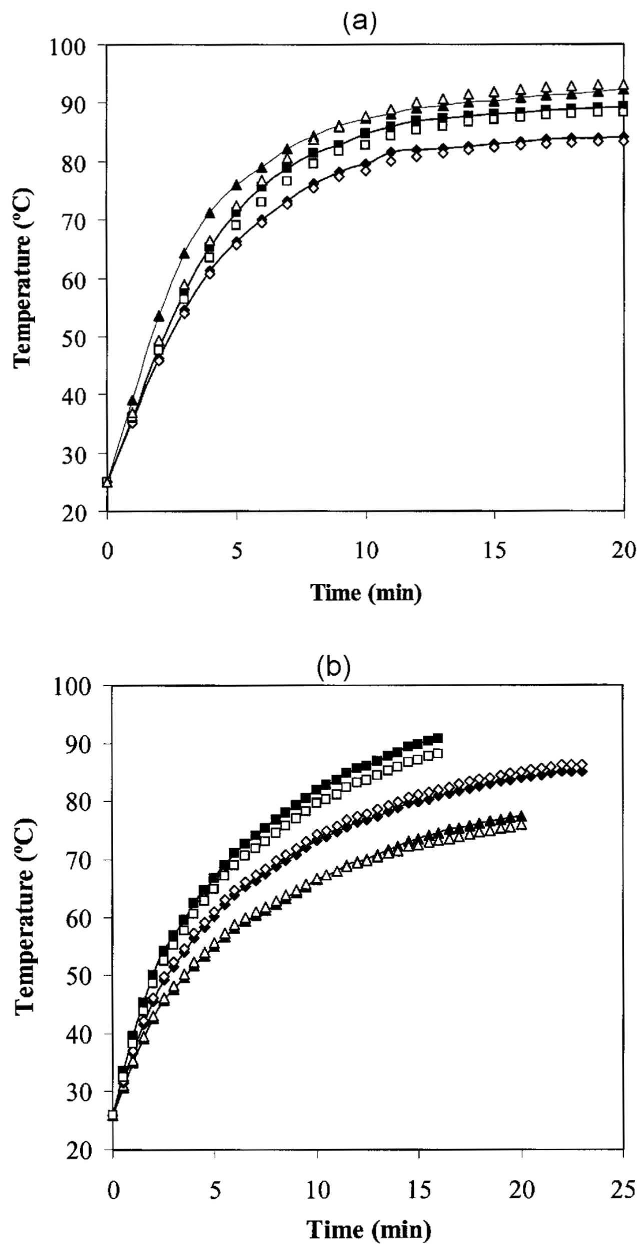

Figure 2. Experimental (T_{cexp}) and simulated (T_{csim}) temperatures for three different bath temperatures $T_{hb.}$ (a) 360 cm^3 container: (◆) T_{cexp}, $T_{hb} = 85$°C; (■) T_{cexp}, $T_{hb} = 90$°C; (▲) T_{cexp},$T_{hb} = 95$°C; ♬ T_{csim}, $T_{hb} = 85$°C; ⊠ T_{csim}, $T_{hb} = 90$°C; ρ T_{csim},$T_{hb} = 95$°C. (b) 660 cm^3 container: (▲)T_{cexp}, $T_{hb} = 80$°C; (◆) T_{cexp},$T_{hb} = 90$°C; (■) T_{cexp},$T_{hb} = 97$°C; (ρ) T_{csim}, $T_{hb} = 80$°C; (♬) T_{csim},$T_{hb} = 90$°C; (⊠) T_{csim},$T_{hb} = 97$°C.

obtained from experiences with low initial temperature, where convective currents gradually arise and contribute to internal heat transfer as the process develops. However at high initial temperatures, the system reaches from the beginning the final fluid dynamic condition, therefore convection – and hence heat transfer rate – is higher than the predicted one using coefficients determined at lower average temperatures.

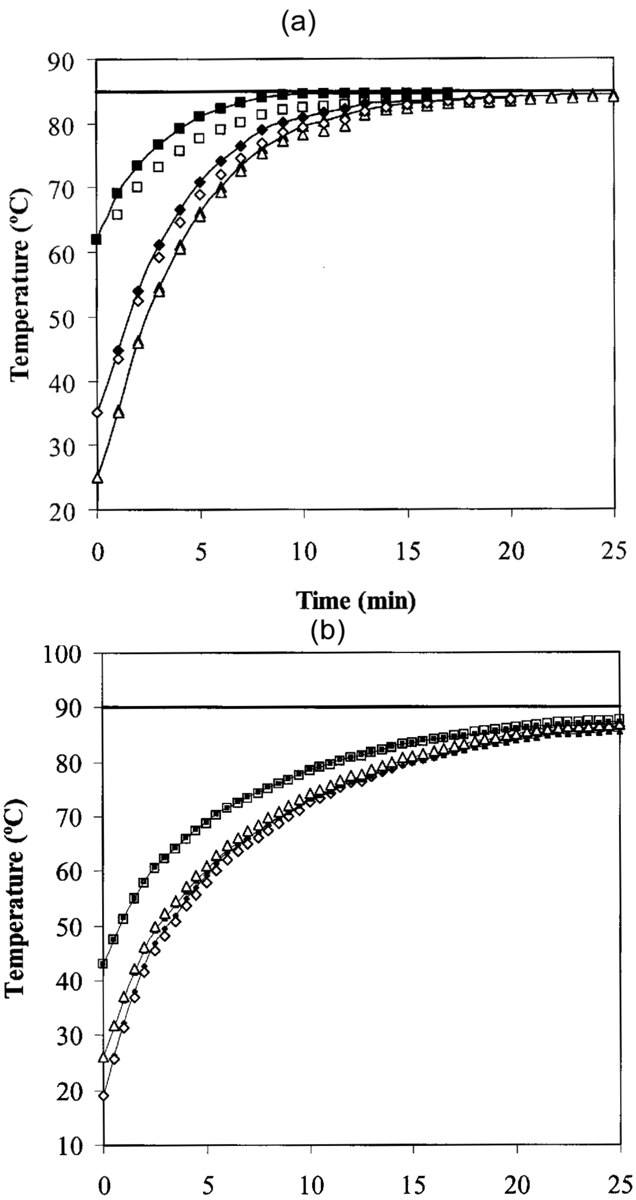

Figure 3. Experimental (T_{cexp}) and simulated (T_{csim}) temperatures for three different initial temperatures T_i. (a) 360 cm^3 container: (▲) T_{cexp},$T_i = 25$°C; (◆) T_{cexp},$T_i = 35$°C; (■) T_{cexp}, $T_i = 62$°C; (ρ) T_{csim}, $T_i = 25$°C; (♬) T_{csim},$T_i = 35$°C; (⊠) T_{csim},$T_i = 62$°C; — T_{hb}. (b) 660 cm^3 container: (◆) T_{cexp},$T_i = 19$°C; (ρ)T_{cexp} ,$T_i = 26$°C; (■)T_{cexp}, $T_i = 43$°C; (♬) T_{csim},$T_i = 19$°C; (ρ) T_{csim},$T_i = 26$°C; (⊠) T_{csim}, $T_i = 43$°C; — T_{hb}.

Evaluation of the Influence of Fruit and Container Diameter

As observed in preliminary experiments (Márquez, 2000), the thermal responses obtained for sour cherries and sweet cherries of the same diameter did not differ as a function of the type of fruit.

The temperature in the centre of the fruit remained constant for different periods depending on fruit diameter. The longer the diameter, longer is the measured delay. These times will be known hereafter as delay time, t_d (Figure 4). Based on the experimental results given in Figure 4, simulations of different processing conditions were carried out using transfer functions, as example Figure 5 displays the influence of fruit diameter for 360 cm^3 containers (container-diameter D_c: 0.0725 m), the perturbation temperature is 80°C and the product initial one is 30°C.

Experimental delay times for each type of container presented an almost lineal dependence with fruit and container diameters (Figure 6). Therefore, t_d variation was correlated according to:

$$t_{\rm d} = cD_f D_c + e \qquad (7)$$

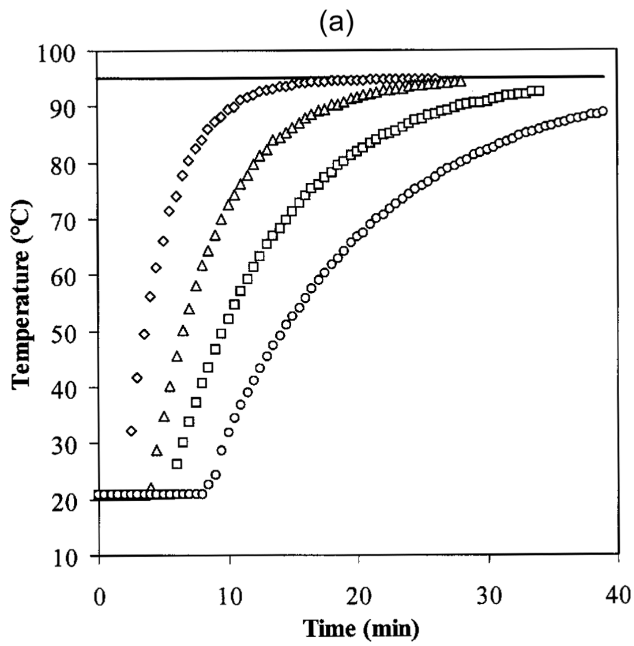

Figure 4. Experimental temperatures for different fruit diameter D_f,. (a) $D_c = 0.0725$ m and 360 cm^3 container. (♬) T_{cexp}, $D_f = 0.014$ m; (ρ) T_{cexp}, $D_f = 0.018$ m; (⊠) T_{cexp}, $D_f = 0.023$ m; (○)T_{cexp}, $D_f = 0.028$ m; — T_{hb}. (b) $D_c = 0.079$ m and 360 cm^3 container: (♬) T_{cexp}, $D_f = 0.014$ m; (ρ) T_{cexp}, $D_f = 0.018$ m; (⊠) T_{cexp}, $D_f = 0.023$ m; (○) T_{cexp}, $D_f = 0.028$ m; —T_{hb}. (c) $D_c = 0.088$ m and 660 cm^3 container: (♬) T_{cexp}, $D_f = 0.014$ m; (ρ) T_{cexp}, $D_f = 0.018$ m; (⊠) T_{cexp}, $D_f = 0.023$ m; (○) T_{cexp}, $D_f = 0.028$ m; — T_{hb}.

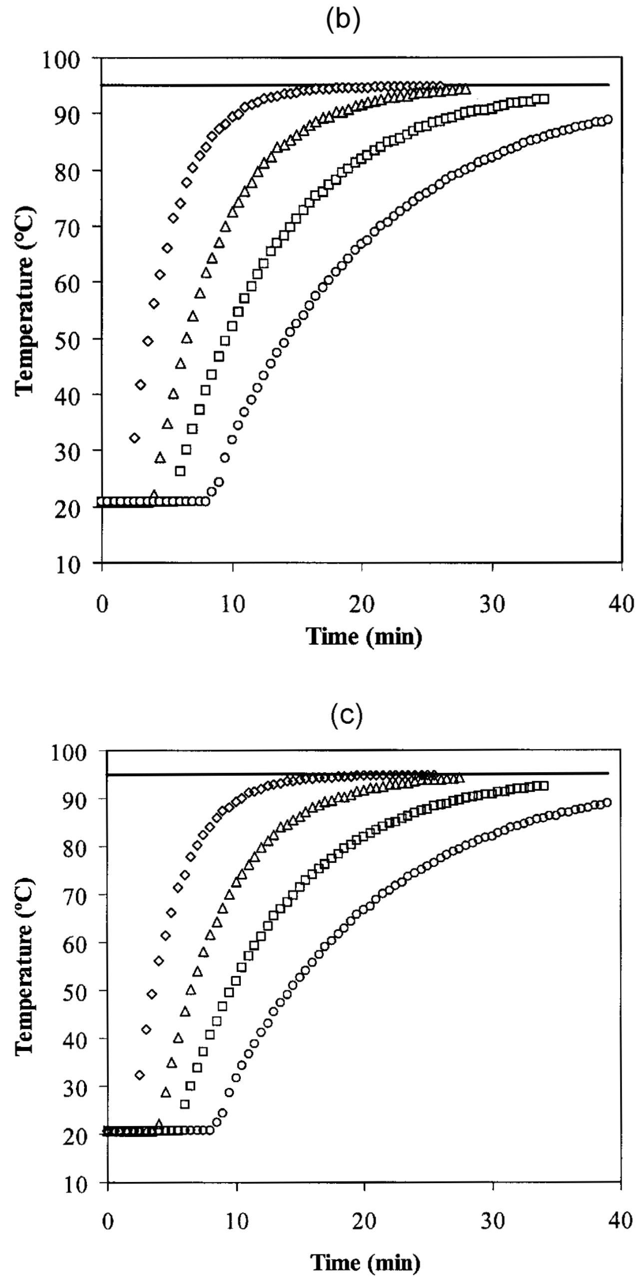

Figure 4. Continued.

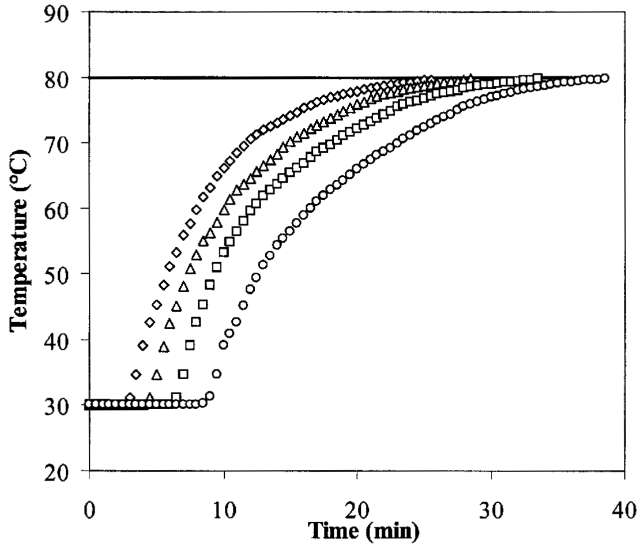

Figure 5. Simulated temperatures for different fruit diameter D_f, for 360 cm^3 containers and $D_c = 0.0725$ m. (♬) T_{csim}, $D_f = 0.014$ m; (ρ) T_{csim}, $D_f = 0.018$ m; (☒) T_{csim}, $D_f = 0.023$ m; (○) T_{csim} $D_f = 0.028$ m; — T_{hb}.

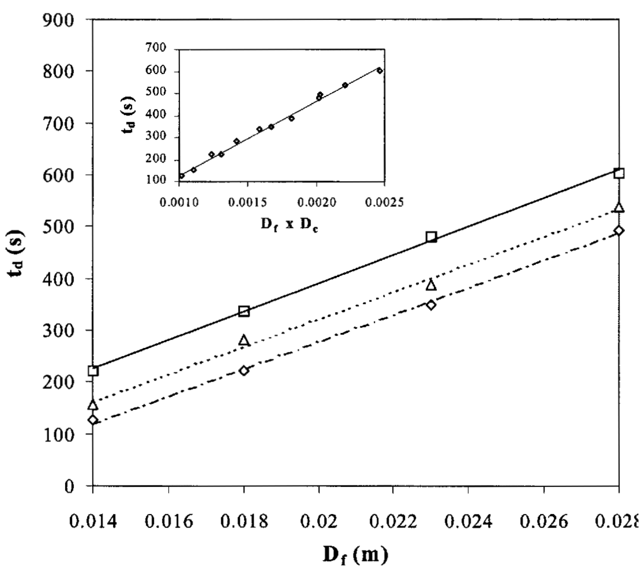

Figure 6. Experimental time delays t_d vs. fruit diameter D_f, for the three sizes of glass containers D_c. (♬) Container 360 cm^3, $D_c = 0.0725$ m; (ρ) Container 360 cm^3, $D_c = 0.079$ m; ☒ Container 660 cm^3, $D_c = 0.088$ m.

In Equation (7), c and e are regression constants. Bimbenet and Michiels (1974) and Abril et al. (1998), among others, showed that the delay due to heat transmission through the container liquid is proportional to the relation [(product mass)/(product area)], that is, to fruit size (diameter). Furthermore, for glass containers, Abril et al. (1998) found an additional delay due to the resistance to heat conduction across the container wall. This delay is proportional to the relation [(container mass)/(container external area)] that is, to its external diameter.

From the values of correlation coefficients and average errors (Table 1) it may be concluded that the fitting of experimental data to Equation (7) enable an accurate prediction of t_d for different types of containers and fruit sizes.

As an example of on-line adjustment of process time, Figure 7 displays the results for pasteurisation with variable process conditions. It can be noticed that the prediction of temperatures – even with three consecutive steps in bath temperature – was very precise, and that the prediction of L adequately considers temperature changes along the process.

Table 1. Constants for Equations (4) and (7) obtained by correlation of experimental and/or simulated data.

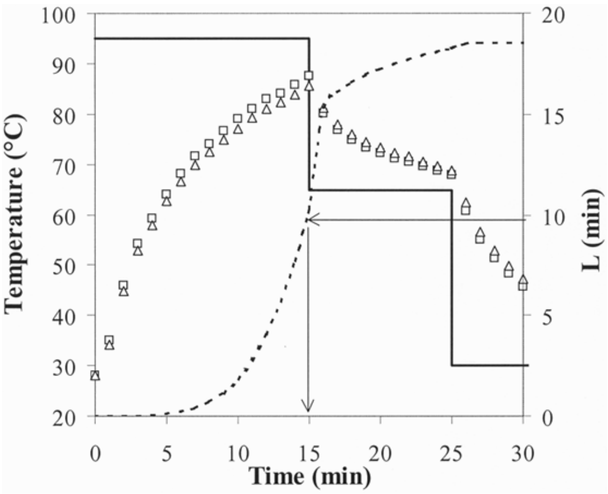

Figure 7. On-line adjustment of process time. Experimental and simulated temperatures under variable bath temperature, and pasteurization value L for enzyme inactivation (target $L = 9.80$ min). (⊠) T_{cexp}; (ρ) T_{csim}; (—) T_{hb}; ($\cdots$) L.

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