Application of Transfer Functions to Canned Tuna Fish Thermal Processing

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Design and optimization of thermal processing of foods need accurate dynamic models to ensure safe and high quality food products. Transfer functions had been demonstrated to be a useful tool to predict thermal histories, especially under variable operating conditions. This work presents the development and experimental validation of a dynamic model (discrete transfer function) for the thermal processing of tuna fish in steam retorts. Transfer function coefficients were obtained numerically, using commercial software of finite elements (COMSOL Multiphysics) to solve the heat transfer balance. Dependence of transfer function coefficients on the characteristic dimensions of cylindrical containers (diameter and height) and on the sampling interval is reported. A simple equation, with two empirical parameters that depends on the container dimensions, represented the behavior of transfer function coefficients with very high accuracy. Experimental runs with different size containers and different external conditions (constant and variable retort temperature) were carried out to validate the developed methodology. Performance of the thermal process simulation was tested for predicting internal product temperature of the cold point and lethality and very satisfactory results were found. The developed methodology can play an important role in reducing the computational effort while guaranteeing accuracy by simplifying the calculus involved in the solution of heat balances with variable external conditions and emerges as a potential approach to the implementation of new food control strategies leading not only to more efficient processes but also to product quality and safety.

Key Words: thermal processing, transfer functions, canned fish

INTRODUCTION

Canned fish is a popular elaborated food that is produced since the 19th century. However, optimization of canned fish thermal processing, in terms of quality retention and energy consumption is still a pending task, despite the existence of some work in this area (Banga et al., 1993; Durance et al., 1997; Teixeira and Tucker, 1997; Erdogdu et al., 1998; Jaczynski and Park, 2003; Simpson et al., 2004, 2006; Miri et al., 2008). Besides, implementation of optimization routines as well as intelligent on-line control requires the use of mathematical heat transfer models capable of predicting accurately the internal product cold spot temperature in response to any dynamic temperature experienced by the retort during the process (Balsa-Canto et al., 2002a,b; Mohamed, 2003; Simpson et al., 2007).

Thermal process calculations in which process times at specified retort temperatures are calculated in order to achieve safe levels of microbial inactivation (lethality) should be carefully carried out to ensure public health safety. Therefore, the accuracy of methods used for this purpose is highly relevant for food science and engineering professionals working in this field (Holdsworth, 1997).

Since the beginning of the canned industry, the process time was calculated according the well-known formulae method. This first method, designed for the prediction of food temperature during thermal processing, relied on the use of empirical formulae to describe heat penetration curves (Holdsworth, 1997). The great advantage of these empirical methods is their simplicity and wide applicability independently of the mode of heat transfer involved. Today these methods are still

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widely applied for the design and evaluation of thermal processes. The principal disadvantage is that they were developed considering a constant heating medium temperature and cannot handle time-variable boundary conditions, although empirical rules have been suggested and used to handle different come up times (Ball, 1923).

Considering that the thermal processing of low-acid foods must ensure 12 decimal reductions (assuming *Clostridium botulinum* spores as target microorganisms) and that in general microorganisms are less resistant to heat than other quality parameters (such as nutrients, texture and color), the optimization of the process is possible by controlling its thermal evolution. In this sense, variable retort temperature (VRT) thermal processing has been recognized as an innovative method to improve food product quality and save process times (Almonacid-Merino et al., 1993; Noronha et al., 1993; Chen and Ramaswamy, 2004). Therefore, to estimate the degree of sterilization and to implement an optimization routine, it will be necessary to know the thermal history in one or more positions inside the can for different external variable conditions, which discards the use of the formula method.

For pure conductive heating foods, where the heat transfer is described by Fourier's partial differential equation, several analytic solutions allow the prediction of the transient temperature history for different geometries and boundary conditions. A more general approach is the development of numerical methods (finite differences and finite elements), which provide a more precise perspective to solve the problem. The finite difference method has been widely applied for the prediction of sterilizing values and nutrient retention during the sterilization of conduction heating of foods (Teixeira et al., 1969; Tandon and Bhowmik, 1986; Simpson et al., 1989; Tucker, 1991; Tucker and Holdsworth, 1991).

Although the potential of mathematical modeling is extraordinary, it is frequently recognized that in many situations these methods must be performed by trained users, for this methods are nor trivial neither simple. These methods are not restricted to simple bodies, and variable thermal properties can be conveniently introduced during calculations. Results, however, are specific for the particular thermal history, not allowing generalizations and requiring complex mathematical algorithms in order to be solved.

Several researchers have tried to obtain simplified models that are simpler to solve, while trying to retain the predictive accuracy of the previous models. Studies have been presented dealing with semi-empirical models (Noronha et al., 1995; Kim and Teixeira, 1997). In particular, the application of transfer functions in food systems, have proved to be a very valuable mathematical tool in the resolution of linear problems of heat transfer with variable boundary conditions, which can be found in many typical operations of food processing, i.e., refrigeration, pasteurization and sterilization (Salvadori et al., 1994; Vírseda and Pinazo, 1997; Abril et al., 1998; Márquez et al., 1998, 2003). The approach presents several advantages. First, it takes into consideration the whole thermal history and not only the range of temperatures for which the semi-log plot of temperature versus time is linear; second, it involves only algebraic equations; third, initial conditions are automatically included in the solution of the equations; finally, it may be used with different forcing functions in the surroundings temperature (Ziemer et al., 1993; Glavina et al., 2006). In conclusion, the major characteristics of this methodology are its simplicity and the fact that the transfer function can be easily applied in several food processing operations in which temperature evolution is involved.

However, a systematic study that analyzes the dependence of transfer function coefficients on the particular characteristics of each process (product size, thermophysical properties and boundary conditions) has not been carried out.

The objective of this work is to characterize the thermal response of canned tuna fish, processed in batch retorts, by its discrete z-transfer function; and to determine the dependence of transfer function coefficients on the dimensions of the cylindrical containers (diameter and height) and on the sampling interval. Finite element modeling was used to calculate the transfer function coefficients, which were adjusted by a simple equation, with two empirical parameters that depend on the container dimensions. Experimental runs with different size containers, different canned seafood (mackerel) and different external conditions (constant retort temperature (CRT) and VRT) were performed to validate the developed methodology.

MATERIALS AND METHODS

Transfer Function Theory

The dynamic behavior of a linear system, with time invariant properties, can be characterized by its transfer function, $F(s)$ or $F(z)$, respectively, if continuous or discrete variables are used. The transfer function of a system represents a biunivocal relationship between an input signal or perturbation and the system's evolution:

$$F(s) = \frac{R(s)}{P(s)} \text{ and } F(z) = \frac{R(z)}{P(z)} \tag{1}$$

By its definition, z-transform is a polynomial in z^{-n}, and in most situations its calculus is simpler than continuous Laplace transform:

$$Z[p(t)] = L[p^*(t)] = P(z) = \sum_{n=0}^{\infty} p(n\Delta)z^{-n} \tag{2}$$

where $p(t)$ is the continuous perturbation and $p^*(t)$ is the same perturbation, sampled with sampling interval Δ.

Therefore, when discrete variables are selected, the response of the studied system $R(z)$, to any perturbation $P(z)$, can be predicted knowing the coefficients f_n of transfer function $F(z)$ as:

$$R(z) = F(z)\,P(z) \tag{3}$$

In thermal processing of foods, the perturbation signal is the external medium temperature $T_{\text{ext}}(t)$ and the response is the temperature, T, of a characteristic point, i.e., the coldest point that coincides with the geometrical center for homogeneous foods, symmetric boundary conditions and conductive heat transfer mechanism (Salvadori et al., 1994).

The coefficients of z-transform $P(z)$ and $R(z)$, $p(n\Delta)$ and $r(n\Delta)$ respectively, are evaluated from the dimensionless temperatures at sampling times $n\Delta$:

$$\begin{aligned} P(z) &= \sum_{n=0}^{\infty} p(n\Delta)z^{-n} \text{ where } p(n\Delta) = \frac{(T_{ext}(n\Delta) - T_i)}{(T_{ext}(0) - T_i)} \\ R(z) &= \sum_{n=0}^{\infty} r(n\Delta)z^{-n} \text{ where } r(n\Delta) = \frac{(T(n\Delta) - T_i)}{(T_{ext}(0) - T_i)} \end{aligned} \tag{4}$$

where T_i is the initial temperature, uniform in the whole system.

So, the temperature in the thermal center T_c is calculated at specific sampling intervals Δ, according to Equation (5):

$$T_c(n\Delta) = T_i + (T_{\text{ext}}(0) - T_i)\,r(n\Delta) \tag{5}$$

where:

$$\begin{aligned} r(n\Delta) &= p(0)f_{n+1} + p(\Delta)f_n + \cdots\cdots + p((n-1)\Delta)f_2 \\ &\quad + p(n\Delta)f_1 = \sum_{i=0}^{n} p(i\Delta)f_{n+1-i} \end{aligned} \tag{6}$$

As a summary: knowing the coefficients f_n and $p(n\Delta)$, 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, at each interval $n\Delta$. Therefore, Equation (6) allows, in an easy and simple way, the prediction of the thermal evolution for different perturbation signals.

In particular, in thermal processing of foods, the temperature of the thermal center T_c is directly related to the prediction of the process time t_p, defined as the necessary time to achieve a target value F_0:

$$F = \int_0^{t_p} 10^{(T_c(t) - T_{\text{ref}})/z_m}\,\mathrm{d}t \geq F_0 \tag{7}$$

where T_{ref} is a reference temperature and z_m is the temperature difference required for a ten-fold change in the decimal reduction time, both depending on the target microorganism.

Calculation of the Thermal Response to a Pattern Signal

To evaluate the coefficients of the function $F(z)$ for each can size it is necessary to solve the transient energy balance, given by Equation (8) in cylindrical coordinates:

$$\rho Cp\frac{\partial T}{\partial t} = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \Phi^2} + \frac{\partial^2 T}{\partial z^2}\right] \tag{8}$$

where ρ is the density (kg/m^3), Cp the heat capacity (J/(kg· °C)) and k the thermal conductivity (W/(m· °C)).

Assuming uniform initial temperature T_{i} and a step as the pattern perturbation signal (constant T_{ext}), the initial and boundary conditions were:

$$T(r, z, 0) = T_i \tag{9}$$

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

$$T(D/2, z, t) = T_{\text{ext}} \tag{11}$$

$$T(r, \pm H/2, t) = T_{\text{ext}} \tag{12}$$

In the cases under study the heat transfer coefficient is high enough to consider prescript temperature boundary condition. It is also assumed that the heat transfer mechanism inside the product is conductive and that the food has constant physical properties.

Even though this balance has an analytical solution, its implementation becomes tedious when the evolution of temperature in time for a 3D geometry solid has to be calculated. Otherwise, the use of commercial finite elements software permits the evaluation of the response of multidimensional systems to different operative conditions in a simple and efficient way. The latter solution was implemented in this work, using COMSOL Multiphysics (COMSOL AB) for a large number of cans of different dimensions, in order to cover all sizes of commercial packaging. Diameters ranged between 0.040 m and 0.090 m, and heights ranged from 0.030 m to 0.113 m were used in the numerical simulations. Because the geometry of the simulation domain is a regular one (finite cylinder), a standard mesh was created, originating between 8000 and 10 000 tetrahedron elements depending on the dimensions of the can.

The physical properties of tuna were adopted (assuming homogeneous composition), obtained from bibliography (Holdsworth, 1997): $\rho = 1003$ kg/m^3, $Cp = 3470$ J/(kg· °C) and $k = 0.463$ W/(m· °C). Every numerical simulation considered uniform T_{i}, equal to 25 °C, and constant T_{ext}, equal to 110 °C.

The software predicts the temperature profiles in every node of the discretized domain.

Estimation of *F*(*z*) Coefficients

A polynomial $R(z)$ was generated from the temperature data of the thermal center, sampled at constant Δ

interval and expressed as dimensionless temperature according to Equation (4). $P(z)$ is a polynomial of ones, because the external temperature is constant.

The polynomial quotient indicated in Equation (1) was solved with the *stmcb* function corresponding to the signal processing toolbox of MATLAB (MATLAB 7.0 R14, 2004). This function computes a linear model using Steiglitz–McBride iteration.

It is important to bear in mind that although calculation of the response is simple, the transfer function can be evaluated only at constant sampling interval. The sampling theorem (Luyben, 1973), states that the sampling interval Δ must be smaller than half of the smallest time constant of the system to ensure accurate results. When the dynamics of the studied system is unknown the sampling interval should be experimentally determined. In general it can be stated that it should be considerably smaller than the period in which a macroscopic evolution of the system can be observed.

According to its definition, $F(z)$ is an infinite series. But in the calculus of a new response $R(z)$ only a discrete number of coefficients of the transfer function (N) is used. So, the precision of the method is also affected by N. A practical criterion is that N must ensure that:

$$\sum_{n=1}^{N} f_n \geq 0.99 \tag{13}$$

The dependence of coefficients f_n on the sampling interval and on the container dimensions (diameter and height) was analyzed. All equations (detailed in the results and discussion section) were adjusted with nonlinear least squares routines using the function *lsqcurvefit*, coded in MATLAB 7.0.

Experimental Validation

With the aim of studying the system behavior more deeply and testing the numerical simulations and the transfer function results, several experimental runs were performed. The cans were those frequently used in the anning industry and are detailed in Table 1. Steel cans were filled with tuna fish.

The heat penetration tests were performed in a vertical discontinuous pilot-plant retort, with internal vapor generation and an internal capacity of 0.06 m^3. The final retort temperature was manually regulated. Therefore the temperature T_{ext} evolves from its initial value $T_{ext}(0)$ (equal to T_i) to its final value. Different initial and final temperatures were tested.

The evolution of the temperature in the geometrical center of each can and the retort temperature was registered, using T-thermocouples connected to an acquisition system INSTRU DaqPRO 5300 - IN12530.

RESULTS AND DISCUSSION

Some of the experiences mentioned in the 'Experimental validation' section were simulated in COMSOL Multiphysics to check the capability of the software to reproduce the behavior of the studied system and also the accuracy of the adopted physical properties values. Figure 1 shows the experimental and numerical thermal evolution of the center of a can (sample S7 of Table 1). High correlation was found for all tested runs (results not shown in this article), which confirms the accuracy of the finite element software.

Also, to demonstrate the capability of z-transfer functions to predict temperatures in the entire domain, additional experimental and predicted results for different radial positions inside a can are reported in Figure 2.

In order to obtain the transfer function coefficients by the methodology detailed in the previous section, numerous simulations (considering a total of 60 different can sizes) were carried out.

Figures 3a and 3b show coefficients f_n corresponding to cylindrical containers of different dimensions, calculated with a sampling interval Δ of 2 min.

In order to analyze the relationship between $F(z)$ and Δ, coefficients f_n were calculated with other sampling intervals, Δ values of 0.5 and 4 min, respectively (results not shown in this work). The observed tendency of the coefficients f_n with n is similar to that shown in Figure 3 for $\Delta = 2$ min. Nevertheless, using $\Delta = 0.5$ min always gives a high number (around 160) of too small value coefficients. Besides, successive coefficient values are very similar, which bothers in the later stage of adjustment of the relationship between f_n and D and H. On the contrary, a value of $\Delta = 4$ min could mask the macroscopic response of the system, since the higher coefficients are lost, and thus the sum of Equation (13) is less than 0.99.

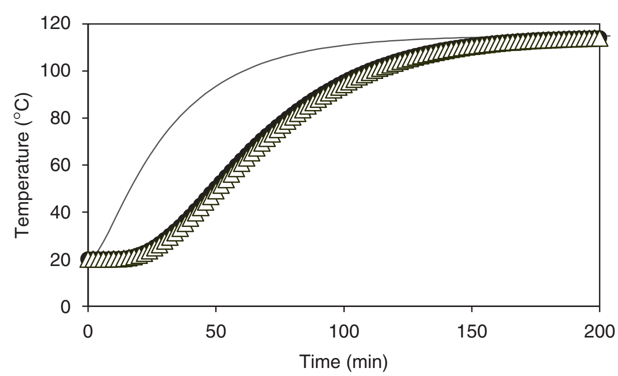

Figure 1. Experimental and numerical evolution of center temperature of sample S7 under variable external temperature: (—) retort, (•) experimental, (△) numerical.

Table 1. Dimensions (diameter *D* and height *H*) of tuna fish steel containers used for experimental validation.

Samples	Content (g)	Can dimension: D × H (mm)
S1	115	50 × 72
S2	180	87 × 44
S3	300	87 × 68
S4	330	87 × 72
S5	170	73 × 57
S6	320	73 × 95
S7	380	73 × 113

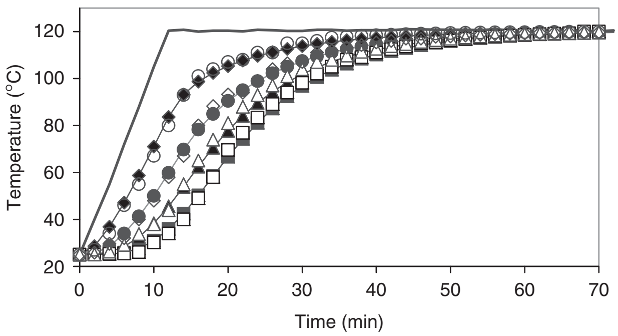

Figure 2. Experimental and predicted thermal history at different radial positions inside canned tuna fish (sample S1): (–) retort, (■) $r = 0$ (predicted), (▲) $r = 0.01$ m (predicted), (•) $r = 0.015$ (predicted), (◆) $r = 0.02$ (predicted), (□) $r = 0$ (predicted), (△) $r = 0.01$ m (experimental), (◇) $r = 0.015$ m (experimental), (○) $r = 0.02$ m (experimental).

From previous experimental studies (Ansorena et al., 2005) and based on the theoretical principles of heat transfer in conductive systems with constant properties, two regression models describing the influence of the sampling interval Δ on the coefficients f_n were tested (Equations (14) and (15)):

$$f_n = a(n\Delta)^d \exp(-b(n\Delta - c)) \quad (14)$$

$$f_n = a(n\Delta)^d \exp(-b(n\Delta)) \quad (15)$$

Because of the size of the systems under study, the empirical parameter c in Equation (14), which is equivalent to a delay, did always present almost null values. Then, the fitting was performed with Equation (15), obtaining high correlation for all tested container dimensions ($r^2 > 0.98$ in all cases).

Later, the dependence of the three empirical parameters a, b and d on the size of the containers was analyzed with the aim of finding general prediction equations of the transfer function coefficients for any can size.

In this sense a wide variety of nonlinear regression models were tested (exponential, logarithmic, polynomial, etc.). A first analysis of the results provided by the adjustment of Equation (15) to the numerous series of transfer function coefficients indicates a very low variation of the d parameter with can diameter and height. Consequently a constant value of this parameter, equal to 2.5, was adopted, and a and b parameters were recalculated, observing that these two parameters strongly depend on the diameter D (m) and height H (m) of the cans. The following equations give the best fit:

$$a = 2.8575^{-17} \cdot D^{-6.7032} \cdot H^{-4.4884} \quad r^2 = 0.9937 \quad (16)$$

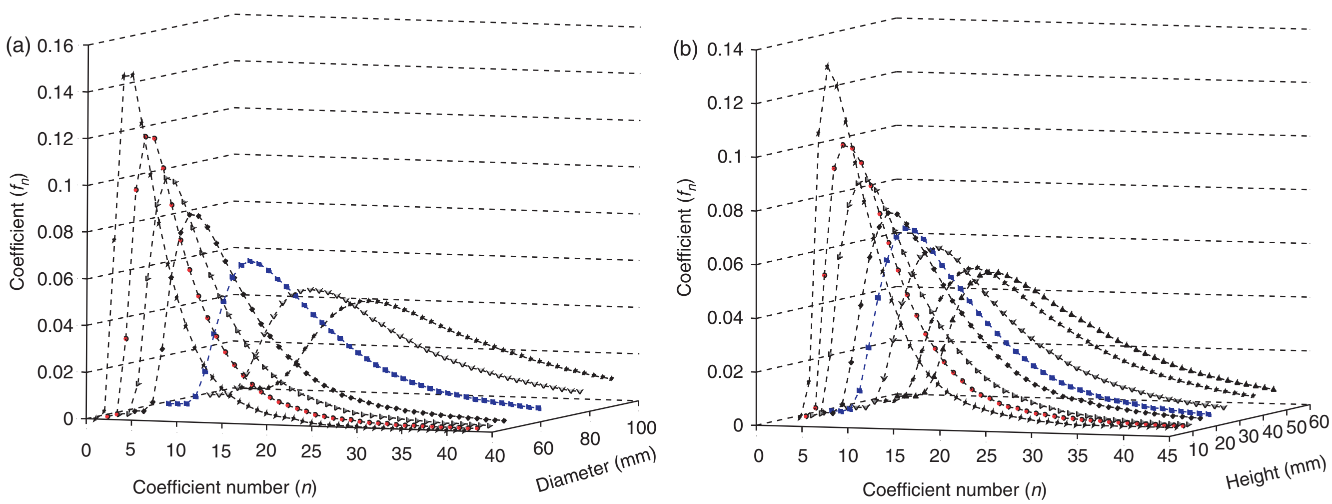

Figure 3. Coefficients (f_n) of transfer functions for tuna fish in cylindrical containers: (a) $H = 72$ mm and different D-values; (b) $D = 73$ mm and different H-values.

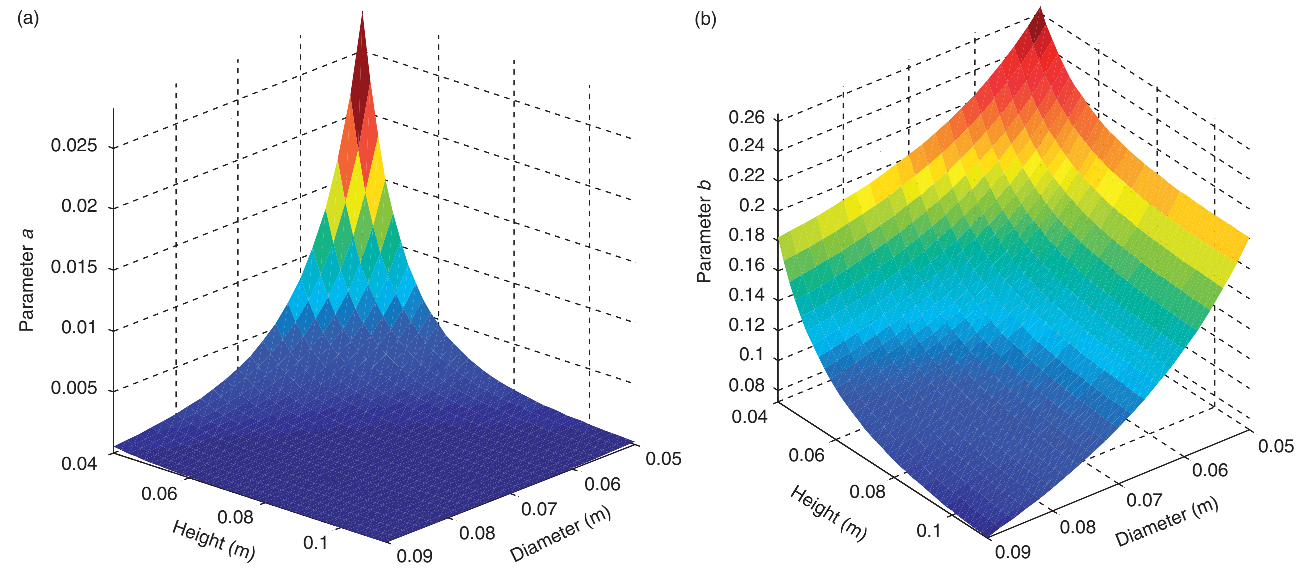

Figure 4. 3D surface plot of empirical parameters *a* and *b* from Equation (15) vs diameter and height of containers: (a) empirical parameter *a*; (b) empirical parameter *b*.

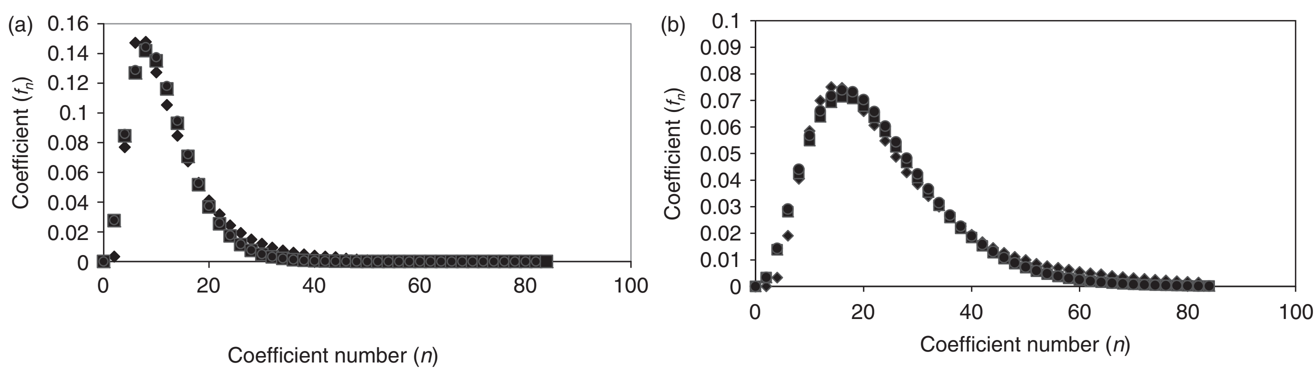

Figure 5. Simulated and predicted transfer function coefficients f_n: (a) 40 × 72 mm container; (b) 73 × 50 mm container. (♦) Simulated, (■) Equation (15), (•) Equations (16) and (17).

$$b = 4.3398^{-4} \cdot D^{-1.8337} \cdot \lfloor (D/H)^2 - 0.9376 \cdot (D/H) + 2.1223 \rfloor \; r^2 = 0.9990 \tag{17}$$

Figures 4a and 4b show the 3D surface plot of parameters a and b against diameter and height of containers in order to visualize the effect of each variable on the regression parameters. It can be seen that a values increase considerably for smaller D and H values. Instead, the variation of the b values with container size is much softer.

In order to validate the proposed regression equations, the numerical f_n were compared with the predicted ones (Equations (15)–(17)), very good agreement was achieved ($r^2 > 0.95$ in all cases). Figures 5a and 5b display the results for two particular samples (40 × 72 mm and 73 × 50 mm, respectively). Similar results were obtained with the complete set of cans detailed in Table 1.

The capability of z-transfer function to predict the thermal response of a can (sample S5 of Table 1) under external variable perturbation was tested. Predicted f_n (Equations (15)–(17)) were used for the calculus of the thermal response. Figure 6 shows the experimental and predicted center temperatures, with a typical retort come-up and with initial and external temperatures different from those used in the calculus of z-transfer function. The agreement between experimental and predicted results confirms that the transfer function of a system is unique and independent from T_i and T_{ext}.

Figure 7 shows the predicted thermal response, under VRT. The predicted thermal history was validated with results provided by the numerical finite element simulation, because of the difficulty of performing the

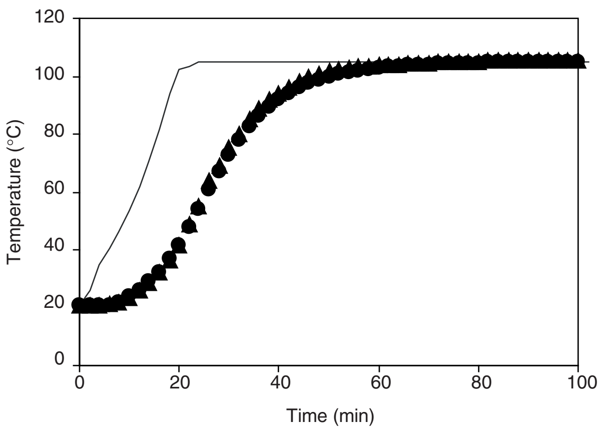

Figure 6. Experimental and predicted evolution of center temperature of sample S5 under variable external temperature ($T_i = 20$ °C and $T_f = 105$ °C): (–) retort, (♦) experimental, (▲) Equations (15)–(17).

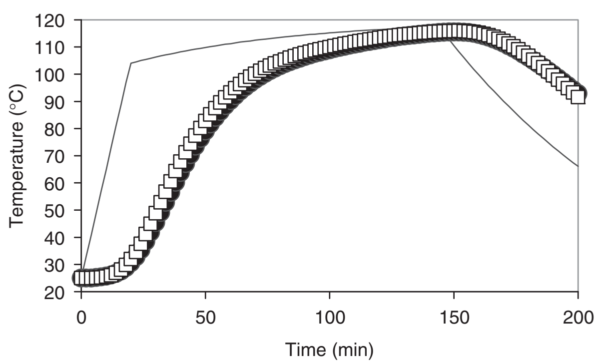

Figure 7. Simulated and predicted response of thermal center temperature of sample S7 under a VRT perturbation: (–) retort, (•) simulated, (□) predicted Equation (15)–(17).

proposed VRT perturbation in our manually controlled retort. Again, the results confirm the accuracy of the presented method. In Figure 8, predicted thermal responses of several cans are shown, indicating that the methodology presented in this work is an efficient way to compare the thermal response of different size containers.

In order to calculate the process time, the thermal response of the coldest point must be related to the evaluation of lethality F (Equation (7)). As an example, two different VRT profiles were tested. The thermal responses were evaluated by the transfer function method and the calculus of the lethality was performed in a spreadsheet, assuming a z-value of 10 °C considering *C. botulinum* spores as the target microorganism (Figures 9a and 9b).

Finally, in order to validate the developed methodology with a different canned seafood (mackerel) from the

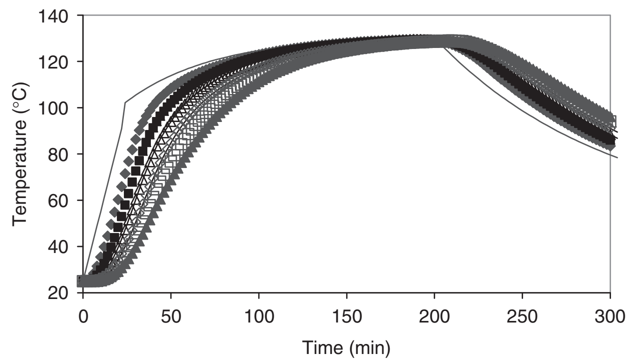

Figure 8. Predicted thermal response of cylindrical containers of $H = 0.07$ m and different D-values under a VRT perturbation: (♦) $D = 0.04$; (■) $D = 0.05$; (△) $D = 0.06$; (◇) $D = 0.07$; (□) $D = 0.08$; (▲) $D = 0.09$; (–) retort.

one used in the numerical simulation, the experimental and predicted center temperatures as well as the experimental and predicted lethality for canned mackerel processed in a batch retort subjected to a dynamic retort temperature were calculated (Figure 10). Again, very good agreement was found between experimental and predicted data.

CONCLUSIONS

In this work z-transfer functions are used to predict the thermal response of conductive systems.

A systematic study was done to obtain the dependence of transfer function coefficients f_n on the sampling interval and the characteristic dimensions of cylindrical containers (diameter and height). In particular, the numerical simulations were performed with canned tuna fish.

Different regression models were applied and on the basis of the results the transfer function coefficients of containers with different dimensions could be predicted.

Once the $F(z)$ is known, it can be used to design both CRT and VRT thermal processing. In VRT case, numerous temperature–time functions can be considered: linear, sinusoidal, exponential, broken heating, different come-up and come-down, etc. According to Equation (3) the response $R(z)$ and the temperature in the coldest point could be calculated, allowing the evaluation of the process time to achieve a desired F_0 value.

Performance of the thermal process simulation was tested for predicting product temperature in the coldest point and lethality. Cans filled with tuna fish and mackerel were fitted with thermocouples and subjected to deviations of various types. Center temperature profiles and lethality predicted by the model in response to dynamic retort temperatures were compared with those

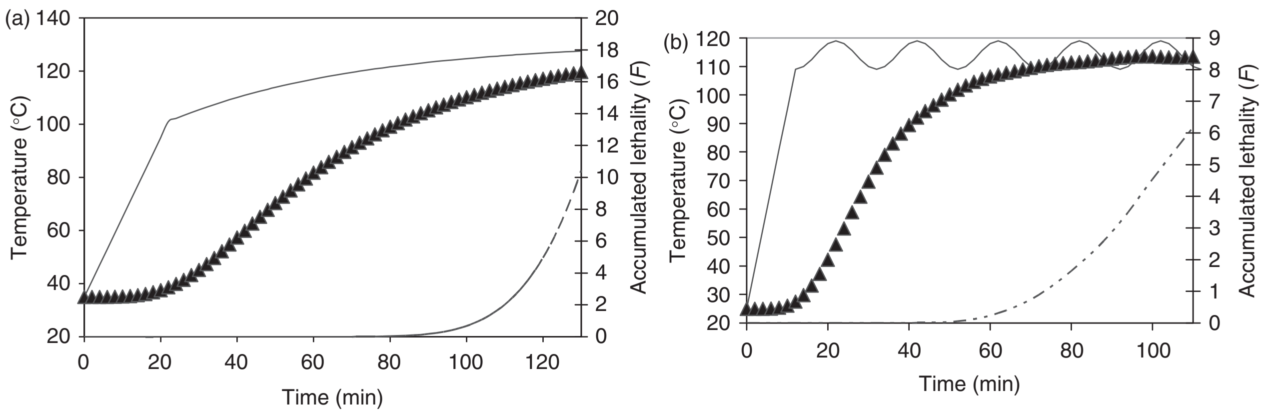

Figure 9. Predicted thermal history and integrated lethality value under variable processing conditions: (a) linear and exponential retort temperature, container of $D=0.08$ m and $H=0.1$ m; (b) linear and sinusoidal retort temperature, container of $D=0.07$ m and $H=0.06$ m. (–) Retort (▲) Equations (15)–(17); (-_-) *F*-value.

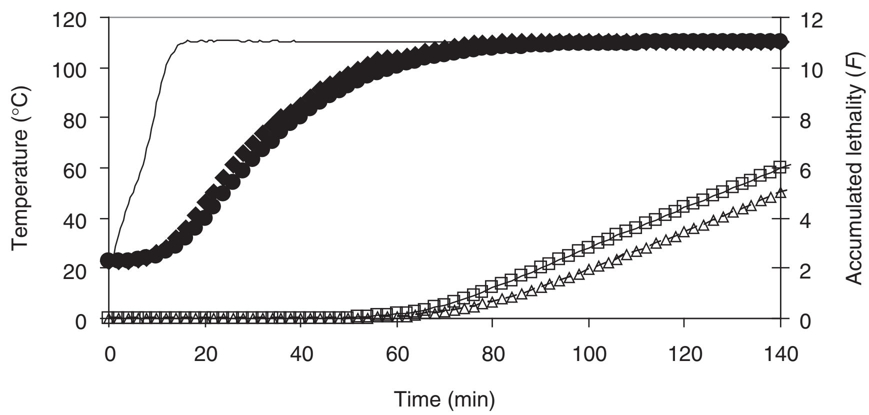

Figure 10. Experimental and predicted response of thermal center temperature and integrated lethality value of canned mackerel (sample S2) under variable processing conditions: (–) retort (■) predicted equations (15)–(17), (△) predicted lethally, (□) experimental lethally.

measured by thermocouples. Excellent agreement was found between predicted and experimental data for both products.

The calculus is very easy, even for operators with no special training, and can be performed with a standard calculator or a spreadsheet. The results clearly indicate that this methodology allows very fast and accurate solutions of heat balances with variable external conditions. Therefore, the methodology developed in this work provides a useful tool to be used in the design of thermal processing and in the implementation of on-line control strategies.

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