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Article

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Optimization of thermal processing of canned mussels

M.R. Ansorena[1,2] and V.O. Salvadori[2,3]

Abstract

The design and optimization of thermal processing of solid–liquid food mixtures, such as canned mussels, requires the knowledge of the thermal history at the slowest heating point. In general, this point does not coincide with the geometrical center of the can, and the results show that it is located along the axial axis at a height that depends on the brine content. In this study, a mathematical model for the prediction of the temperature at this point was developed using the discrete transfer function approach. Transfer function coefficients were experimentally obtained, and prediction equations fitted to consider other can dimensions and sampling interval. This model was coupled with an optimization routine in order to search for different retort temperature profiles to maximize a quality index. Both constant retort temperature (CRT) and variable retort temperature (VRT; discrete step-wise and exponential) were considered. In the CRT process, the optimal retort temperature was always between 134 °C and 137 °C, and high values of thiamine retention were achieved. A significant improvement in surface quality index was obtained for optimal VRT profiles compared to optimal CRT. The optimization procedure shown in this study produces results that justify its utilization in the industry.

Keywords

Optimization, thermal processing, canned mussels

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INTRODUCTION

Thermal processing is such a mature technology that it is generally perceived as having almost no potential for further development. However, there is still a demand for heat-processed foods with high nutritive value. Hence, this technology will continue evolving toward the optimization of processing conditions, achieving better energy utilization, more efficient production and better product quality (Holdsworth, 2004).

Many thermally processed foods are constituted by solid food particles immersed in a liquid medium. Heat transfer flux differs in both components of the mixture, being mainly conductive in the particles and convective in the immersion solution. The temperature profile at the slowest heating point is required to accurately design the thermal process to estimate the process time.

In pure conductive solid foods, the slowest heating zone, characterized as the point which receives minimum heating, is usually located at the geometrical center of a can. However, in the sterilization of solid–liquid foods, there is experimental evidence (Ghani et al., 1999; Kumar et al., 1990) that this point does not lie at the geometrical center of the can, but is located in a region closer to the can's bottom, due to the effect of natural convection.

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The lack of accurate temperature prediction models for these complex food systems may lead to under-processing of the solids, especially when the particle sizes vary, or to over-processing of the liquid components.

In literature, only a few articles report on this subject. Recently, Ghani and Farid (2006), employ computational fluid dynamics (CFD) to analyze the location of the slowest heating point of pineapple slices canned in a liquid. Experimentally, some authors have studied the heat processing and quality index of different shellfish products: mussels (Casales et al., 1988), shrimps (Mohan et al., 2006; Sreenath et al., 2008) and canned black clams (Bindu et al., 2007).

In consequence, there is a growing interest toward the development of simple mathematical models to predict temperature profiles in such situations. In particular, canned mussels usually contain a large quantity of filling brine, making both convection and conduction heat transfer mechanisms relevant. Besides, mussel's geometry is irregular and its size is variable, leading to considerable errors in the temperature prediction when known methods are applied.

The principal advantage of thermal processing is to eliminate deteriorative microorganisms, producing stable foods at ambient temperature. But heat also induces several deteriorative processes that diminish the sensorial and nutritional qualities of processed foods. An optimization procedure will search for the best process conditions, assuring a safe and high-quality food preserve.

Several works applying different optimization strategies to conductive canned foods have been reported in literature (Almonacid-Merino et al., 1993; Banga et al., 1991, 2003; Chen and Ramaswamy, 2002a, b; Durance et al., 1997; Noronha et al., 1993; Simpson et al., 2008). In these works, authors found that variable retort temperature (VRT) processing not only improves the quality, but also reduces the sterilization process time in comparison to traditional constant retort temperature (CRT) processing. However, as far as we know, there is no available scientific literature dealing with the optimization problem in solid–liquid food systems.

Therefore, the aim of this work is to study the thermal processing of canned mussels, processed in batch retorts, with focus on two aspects:

1. Characterization of the food system by a discrete transfer function that allows the prediction of the coldest point temperature in a simple way.
2. Searching for the retort temperature (constant or variable) that maximizes the retention of a quality index. CRT and VRT schedules will be analyzed.

MATERIALS AND METHODS

Discrete transfer function

The transfer function of a system represents a biunivocal relationship between an input signal $p(t)$, or perturbation, and the system's evolution $r(t)$ (Ansorena et al., 2010):

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

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, generally the coldest point, also named as the thermal center or critical point (CP).

In order to determine the transfer function of a system, its response to a pattern perturbation is measured and the quotient presented in Equation (1) is calculated. 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 $n\Delta$.

Equation (1) was solved using the *stmcb* function included in the signal processing toolbox of MATLAB 7.0 (MATLAB 7.0 R14, 2004). This function computes the transfer function coefficients by means of an iterative Steiglitz–McBride procedure. More details on this subject can be found in Ansorena et al. (2010).

The dependence of coefficients f_n on the sampling interval and on the container dimensions (diameter and height) was analyzed. In this sense, a wide variety of empirical, non-linear regression models were tested (exponential, logarithmic, polynomial, etc) in order to find the equations that give the best fit. All equations (detailed in 'Results and Discussion' section) were adjusted with non-linear least squares routines using the function *lsqcurvefit*, coded in MATLAB 7.0.

Once the coefficients f_n of transfer function $F(z)$ are determined, the response of the system $R(z)$ to any perturbation $P(z)$ can be evaluated; and also the temperature in the thermal center T_{ce} at specific sampling intervals Δ, according to Equation (2):

$$T_{\text{ce}}(n\Delta) = T_0 + (T_{\text{ext}}(0) - T_0)r(n\Delta) \tag{2}$$

where

$$\begin{aligned} r(n\Delta) &= p(0)f_{n+1} + p(\Delta)f_n + \cdots + p((n-1)\Delta)f_2 + p(n\Delta)f_1 \\ &= \sum_{i=0}^{n} p(i\Delta)f_{n+1-i} \end{aligned} \tag{3}$$

Therefore, Equation (2) allows, in an easy and simple way, the prediction of the thermal evolution for different perturbation signals.

Experimental thermal response to a pattern signal

In order to determine the transfer function of canned mussels, the samples were subjected to a step perturbation moving them from one well-stirred water bath to another (M 911 Coleparmer, Germany).

Lacquered cylindrical tinplate cans were filled with devalved mussels and brine. Mean weight of the mussels was 3 ± 0.3 g. Twelve different can sizes, commonly used in the canning industry and detailed in Table 1, were used to carry out the heat penetration tests.

As the position of the CP was not known, a first series of experiments were performed to determine its location. Several cans, filled with different brine contents (%w/w) were used, always taking into account the net weight of each can size (Table 1).

Two or three Cu–constantan thermocouples were placed through holes punctured in the can wall in the axial direction. Each sensor was carefully inserted into the center of a mussel (previous to can sealing) and connected to the acquisition system INSTRU DaqPRO 5300-IN12530. According to the manufacturer, the accuracy and the resolution of thermocouples were ±0.5 and 0.1 °C, respectively. An additional thermocouple was used to measure the brine temperature.

After the temperature equilibration of the samples in the first thermostatic bath (at 25 °C) to insure uniform initial food temperature, samples were transferred to a bath at 90 °C. Three experimental runs were completed with each canned size.

A second series of experiments were performed using the whole set of cans detailed in Table 1, measuring the thermal response of the location previously determined as the CP.

Table 1. Can dimensions (diameter *D* and height *H*)

		Can dimensions (m)	
Samples	Content (g)	*D*	*H*
S_1	115	0.050	0.072
S_2	150	0.073	0.040
S_3	170	0.073	0.057
S_4	180	0.087	0.044
S_5	200	0.056	0.072
S_6	300	0.087	0.068
S_7	320	0.073	0.095
S_8	320	0.062	0.072
S_9	325	0.065	0.076
S_{10}	325	0.070	0.072
S_{11}	330	0.087	0.072
S_{12}	380	0.073	0.113

Optimization theory – problem statement

Thermal processing of a canned food not only inactivates microorganisms, but also produces undesirable effects such as nutrient or specific quality factor degradation. Hence, there is a typical optimization problem to solve: achieve the safety target of thermal processing with minimum detrimental impact on the product quality (Avila and Silva, 1999; Jung and Fryer, 1999).

The mathematical formulation of such problem is:

$$\max_{T_{\mathrm{ret}}(t)} \frac{C_{\mathrm{sup}}(t_{\mathrm{p}})}{C_0} \tag{4}$$

where t_{p} is the process time, defined as the necessary time to achieve a target value F_0. The calculus of the process time originates a constraint associated to the process lethality:

$$F_{\mathrm{process}}(t_{\mathrm{p}}) = \int_0^{t_{\mathrm{p}}} 10^{(T_{\mathrm{ce}}(t)-T_{\mathrm{ref}})/z_{\mathrm{m}}} \mathrm{d}t \geq F_0 \tag{5}$$

For low-acid products, such as canned seafood, the *Clostridium botulinum* is held as the target microorganism, i.e., $D = 0.21$ min and $z_{\mathrm{m}} = 10$ °C (Holdsworth, 2004). Shellfish are sensible to thermal processing and consequently it is typical to adopt low values of F_0 (3 min), so as not to affect the sensory quality of the product (Holdsworth, 2004).

Although the optimization problem should include, in its general version, the resolution of the energy balance in the whole system (solid food particles immersed in liquid medium), the lethality constraint, Equation (5), only involves the evolution of the thermal center temperature, which is predicted by means of Equation (2).

Assuming prescript temperature, the surface retention of the quality parameter is evaluated by:

$$\frac{C_{\mathrm{sup}}}{C_0} = \exp\left(-\frac{\ln 10}{D^*_{\mathrm{ref}}} \int_0^t 10^{\frac{(T_{\mathrm{ret}}(t)-T^*_{\mathrm{ref}})}{z^*}} \mathrm{d}t\right) \tag{6}$$

where T^*_{ref}, D^*_{ref} and z^* are the kinetic parameters of the selected quality index.

CRT versus VRT processes. The benefits of VRT over CRT thermal processing have been reported by several authors, mainly in conductive systems (Almonacid-Merino et al., 1993; Banga et al., 2003; Chen and Ramaswamy, 2002a, b; Durance et al., 1997; Noronha et al., 1993, 1996; Simpson et al., 2008).

Accordingly, it was necessary to analyze the behavior of the food system under study, considering both CRT and VRT procedures.

At first, the optimization problem was solved considering CRT profiles; thus, $T_{\mathrm{ret}}(t)$ adopted a constant value in Equation (6). CRT profiles are defined as profiles consisting of a holding time at constant heating temperature, followed by a cooling period at a constant temperature. A zero retort come-up time is assumed. The process time (t_{p}) is defined as the sum of holding and cooling times. The optimization of the optimum CRT profiles reduces in this case to the optimization of a single value, the temperature of the heating medium during the holding phase. An additional constraint in the final temperature at the thermal center of the product at the end of the process time is imposed (Durance et al., 1997; Noronha et al., 1993, 1996).

The optimization routine searches, from all the combinations of T_{ret} and t_{p} that verify both constraints, the one which gives the maximum surface quality retention.

The control variable for this optimization technique was the retort temperature and the limits of this variable were set according to standard values found in industrial practice (Durance et al., 1997).

Subsequently, different VRT profiles were considered in order to look for an improvement in the surface quality index. Several types of functions, such as sine, exponential, ramps and steps, can be used. The sine and exponential functions involve only two parameters, while others more parameters depending on the experimental arrangement. Moreover, ramps and step functions include abrupt temperature changes that are difficult to reproduce in a commercial retort.

In this study, two different VRT profiles were tested:

Discrete step-wise function. The discrete step-wise function was described as N equally long time intervals, each at a different CRT (Simpson et al., 2008). The number of time intervals was a pre-established independent variable. During the cooling phase, the retort temperature remained constant and equal to the cooling water temperature.

Exponential VRT profiles. The exponential retort temperature profile during processing was divided into two stages: (1) the vent time, intended to insure a pure steam environment in the retort during which the temperature increased linearly from the initial temperature to 108 °C (Durance et al., 1997), (2) the VRT stage in which the retort temperature was varied according to an exponential profile; and (3) cooling stage, during which the retort temperature decreased from the maximum retort temperature to the cooling water temperature. Exponential functions are described mathematically as:

$$f(t) = A \cdot (1 - e^{-kt}) \tag{7}$$

The control variables for the optimization technique were, for the VRT step function, the process temperatures at equally long time intervals throughout the heating process time, and for the VRT exponential profile, the parameters A and k from Equation (7), for both, the heating and the cooling phases.

When considering the possibilities of reducing the degradation of surface quality index, while maintaining the process time using VRT procedures, and in order to compare with the CRT approach, an additional restriction to the system formed by Equations (4), (5) and (6) is imposed:

$$t_{\mathrm{p}} = t_{\mathrm{p}}^{*} \tag{8}$$

where t_{p}^{*} is the process time under CRT processing conditions, to achieve the maximum surface quality retention.

Computer simulation and process optimization. The optimization problem was solved by means of a program coded in MATLAB, using the *fmincon* function included in the optimization toolbox (MATLAB 7.0 R14, 2004).

For each tested value of the control variable vector, this program calculates the thermal history of the CP for mussels in brine using the transfer function methodology previously detailed. These thermal histories were coupled to another MATLAB function that calculates the surface quality deterioration using kinetic data for thiamine ($D^* = 96$ min and $z^* = 46.7$ °C; Holdsworth, 2004). Thiamine is a characteristic indicator of seafood quality (Bindu et al., 2007; Durance et al., 2007; Mohan et al., 2006; Simpson et al., 2004) and although its retention has no direct physical significance, these kinetic parameters are similar to those associated with the foodstuff surface, e.g., browning reactions and loss of luminosity (Sendín et al., 2010).

The optimization routine, involving a random search technique, also includes a penalty function to handle constraints (Venkataraman, 2002). Use of this kind of penalty function will lead the constraints to be satisfied when the random search is implemented.

RESULTS AND DISCUSSION

Slowest heating zone

Determining the location of the slowest heating point is fundamental to adequately design a thermal process. In solid–liquid food systems such as mussels in brine, this position was unknown *a priori*.

It is known that in homogeneous solid foods, where heat transfer is mainly conductive, the CP coincides with the geometrical center of the can. Previous studies

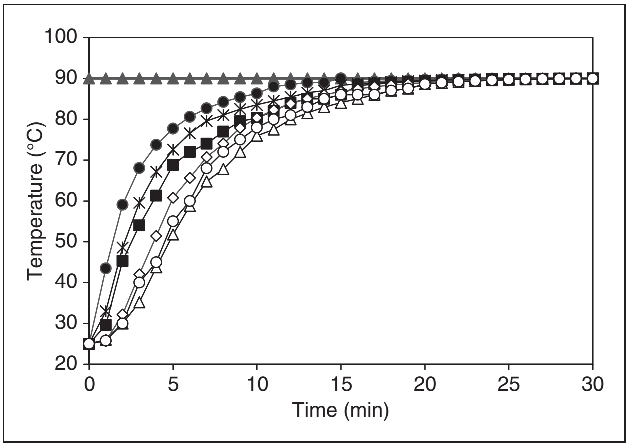

Figure 1. Experimental thermal histories of different positions along the axial axis of container S_{12} measured from the bottom of the can. (▲), External; (●), liquid medium; (⁎), 0.50*H*; (■), 0.35*H*; (◇), 0.25*H*; (○), 0.05*H*; (△), 0.125*H* (CP).

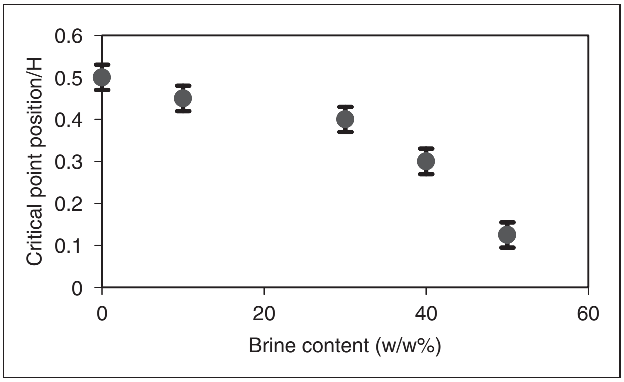

Figure 2. CP location as a function of brine content (%w/w) in sample S_{12}.

developed in foods heated by free convection reported that the position of the slowest heating zone was located between 10% and 15% of the height from the bottom of the can (Ghani et al., 1999). Varma and Kannan (2006) studied the behavior of natural convective heating in conical and cylindrical containers. They found that the slowest heating zone is initially near the geometrical center, and then it moved axially downward, finally the thermal center settles near the bottom at around 10% of the height of the total axial distance. At the moment, only one work has studied the position of the CP in solid–liquid food mixtures (Ghani and Farid, 2006). The authors simulated the heat processing of pineapple slices in cylindrical cans by CFD and found, for this system, that the CP stays at about 30–35% of the height from the bottom.

Therefore, according to the procedure detailed under ‘Materials and Methods’ section, the dependence of the location of the CP on the solid–liquid food mixture studied in this article is experimentally investigated, focusing on the effect of the brine content (%w/w) in its position.

Figure 1 shows the thermal histories measured on different axial positions of the S_{12} container (distance measured from the bottom), filled with a brine content of 50% (w/w) when it is subjected to a step-like change in the surrounding temperature. Only sample S_{12}’s response is illustrated for simplicity, though all experimental runs presented a similar behavior.

The same procedure was repeated for different brine contents (a total of four experimental runs for each content), and the location of the CP was determined. Figure 2, shows, for container S_{12}, the displacement of the CP location as a function of brine content (%w/w). Similar results were obtained for the complete set of cans detailed in Table 1.

Preliminary tests using glass flasks showed that the convective currents of the filling brine did not move the mussels which, since their density is greater than the density of brine, formed a static bed on the bottom of the cans. Moreover, it must be considered that cans were placed in a static retort, so there was no rotation of the cans. This bed would restrain the free flow of convective currents and this restriction would increase with bed depth. Therefore, the importance of the conductive heat transfer mechanism would increase toward the bottom of the containers. Conductive heating is much slower than convective heating for these products. Also, the warmer fluid moves to the top of the cans and the cooler fluid to the bottom, affecting the temperature surrounding the particles within the can.

The above considerations would explain the displacement of the CP to lower positions as we increased the solid food content of the solid–liquid mixture.

Transfer function

According to the Argentinean food legislation (*Código Alimentario Argentino*), the maximum brine content of this type of food products (canned mussels) is 50% (w/w). Besides, a check was performed using a large number of canned mussels in brine of the most typical trade marks found in local markets, and the average brine content was about 50% (w/w). In consequence, this brine content was adopted for the determination of the transfer function.

Brine content in the container was set to 50%, which means that the CP will be located along the axial axis at a distance of 0.125*H* from the bottom of the can (Figure 2).

In order to obtain the transfer function coefficients by the methodology detailed ‘Discrete transfer function' section, numerous heat penetration tests (using the complete set of cans detailed in Table 1) were carried out.

Figure 3 shows the experimental coefficients f_n corresponding to cylindrical containers of different dimensions ($H = 72$ mm and differing D values), calculated with a sampling interval Δ of 1 min. In previous studies performed on canned tuna (Ansorena et al., 2010), a sampling interval Δ of 2 min was used, but as the thermal response of this kind of systems (solid–liquid food mixtures) is faster than conductive systems, a lower sampling interval is needed.

However, the influence of sampling interval on $F(z)$ was investigated, calculating the coefficient's f_n with Δ equal to 0.5 and 2 min, respectively (results not shown in this study). Although the transfer function coefficients follow the expected behavior, using $\Delta = 0.5$ min always gives a high number of coefficients whose values are too small. On the contrary, a value of $\Delta = 2$ min could mask the macroscopic response of the system, since the higher coefficients are lost, and thus their sum is less than 0.99 (Ansorena et al., 2010).

As the tendency of f_n with coefficient number n is similar to that observed for conductive systems (Ansorena et al., 2010), the following equation is proposed to describe the influence of the sampling interval, $n\Delta$:

$$f_n = a\,(n\Delta)^d \exp(-b(n\Delta)) \tag{9}$$

High correlation was obtained for all tested container dimensions ($r^2 > 0.93$ in all cases). The dependence of the three empirical parameters a, b, and d on the size of the containers was analyzed; the empirical equations that give the best fit are (Ansorena and Salvadori, 2009):

$$a = 2.529^{-22} D^{-13} H^{-4.4} \quad r^2 = 0.959 \tag{10}$$

$$b = 232.876 \cdot \exp(-104.3032 \cdot D + 8.958 \cdot H)\, r^2 = 0.8957 \tag{11}$$

$$d = 0.01 \cdot D^{-1.65}\left[\left(\frac{D}{H}\right)^2 - 4.6184 \cdot \left(\frac{D}{H}\right) + 5.1891\right] r^2 = 0.8472 \tag{12}$$

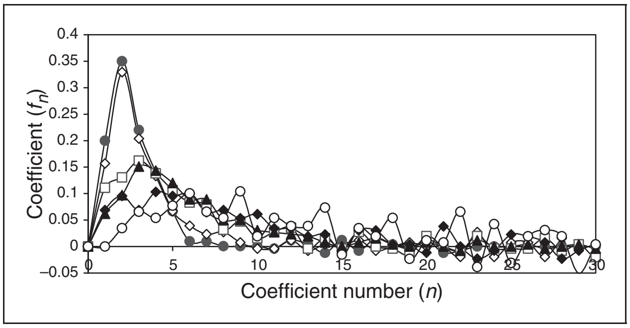

Figure 3. Experimental coefficients (f_n) of transfer functions for calculating the CP in cylindrical containers ($H = 72$ mm and different D values) for mussels in brine. (◆), $D = 0.07$; (●), $D = 0.050$; (◇), $D = 0.056$; (□), $D = 0.062$, (▲), $D = 0.065$; and (○), $D = 0.087$.

The capability of z transfer functions to predict the thermal response of the CP in these complex systems under external variable perturbation was tested for the complete set of cans of Table 1, very good agreement ($r^2 > 0.90$ in all cases) was found between experimental and predicted data (Ansorena and Salvadori, 2009).

Thermal process optimization

CRT process optimization. There are currently no examples of heat process optimization studies for solid–liquid mixtures in literature. In the case of CRT thermal processing, the optimization problem was solved, as described in 'Optimization theory – problem statement' section, considering different can sizes. Diameters ranged between 0.050 and 0.090 m, and heights from 0.040 to 0.113 m. The limits of the control variable are 110 °C $\leq T_{\text{ret}} \leq$ 140 °C. The initial temperature of the product was set as 20 °C and the temperature of the cooling medium considered to be 35 °C. The cooling phase was extended until the temperature at the thermal center of the can reached 90 °C (Durance et al., 1997). Table 2 shows the results for the complete set of cans evaluated.

As it was mentioned in 'Transfer function' section, the results shown in this study correspond to a brine content of 50% (w/w). Under these conditions, on the basis of our own experience and considering that the retort is static, it is assumed that all solid particles (mussels) descend to form a bed at the bottom of the can, and the upper zone is occupied only by brine. In consequence, the lower half of the can is in direct contact with mussels.

From these results, we can conclude that, in spite of the wide range in the limit of the control variable, the optimal CRT is always between 134 °C and 137 °C, for the complete set of cans analyzed. In agreement, Chen and Ramaswamy (2002a) also found that the can size do not affect the optimum retort temperature. As can be seen from values in Table 2, the optimum temperature is perceptibly higher than the values reported by other researchers in conductive foods (Chen and Ramaswamy, 2002a; Simpson et al., 2008). This can be the result of considering a low F_0 value, originated in the high sensitivity to heat deterioration of this type of product.

In addition, the optimum thiamine retention can reach values as high as 90% for the smallest cans, which justifies the implementation of an optimization routine. In particular, for the commercial can sizes employed in this study, the maximum surface thiamine retention, 90.01%, correspond to sample S_1 (the smallest one), with a retort temperature of 137.22 °C and a process time of 2.38 min, while the lowest value of surface retention (31.98%) is obtained for the biggest can size (S_{12}), processed at an optimum T_{ret} of 134.27 °C and a total process time of 18 min.

Table 2. Optimization results for CRT process

Sample	Optimum temperature (°C)	Optimum process time (min)	Optimum thiamine retention (%)
S_1	137.22	2.38	90.01
S_2	137.08	6.20	76.70
S_3	135.94	12.92	58.84
S_4	136.31	11.02	56.23
S_5	137.22	3.08	87.71
S_6	135.11	17.38	45.22
S_7	134.39	17.12	36.89
S_8	136.08	7.99	72.00
S_9	135.98	9.30	68.32
S_{10}	135.92	12.56	59.75
S_{11}	135.68	16.20	41.72
S_{12}	134.27	18.00	31.98

VRT process optimization. As a second optimization step, two VRT profiles were investigated, in order to see if any further improvement in surface thiamine retention could be obtained.

The total process time was set equal to the optimum CRT process time, and retort temperatures were set within the upper and lower limits used previously (110–140 °C).

The search technique was first applied by describing the VRT profile as a discrete step-wise function. The number of time intervals was an independent variable and was set in 3, 6 and 9 time intervals. In this case, the control variables are the CRTs at each time interval (N_i). The limits of the control variable are $110\ ^\circ\text{C} \leq N_i \leq 140\ ^\circ\text{C}$. The lethality constraint in this optimization problem is set by Equation (5).

Table 3. VRT optimization results

VRT profile	Number of steps	Control variables	Process time (min)	Thiamine surface retention (%)	Improvement on optimum CRT process (%)	F_{process} (min)
Step	3	$N_1 = 135.78$ °C $N_2 = 138.48$ °C $N_3 = 35.00$ °C	18	35.809	11.875	2.9998
	6	$N_1 = 122.17$ °C $N_2 = 131.21$ °C $N_3 = 139.26$ °C $N_4 = 139.26$ °C $N_5 = 139.26$ °C $N_6 = 35.00$ °C	18	38.233	19.375	2.9995
	9	$N_1 = 122.29$ °C $N_2 = 129.67$ °C $N_3 = 135.24$ °C $N_4 = 137.75$ °C $N_5 = 138.42$ °C $N_6 = 138.42$ °C $N_7 = 138.42$ °C $N_8 = 35.00$ °C $N_9 = 35.00$ °C	18	44.207	38.146	3.0002
Exponential		$A_h = 33.55$ $k_h = 0.31$ $A_c = 110$ $k_c = 0.95$	18	54.076	68.987	3.0007

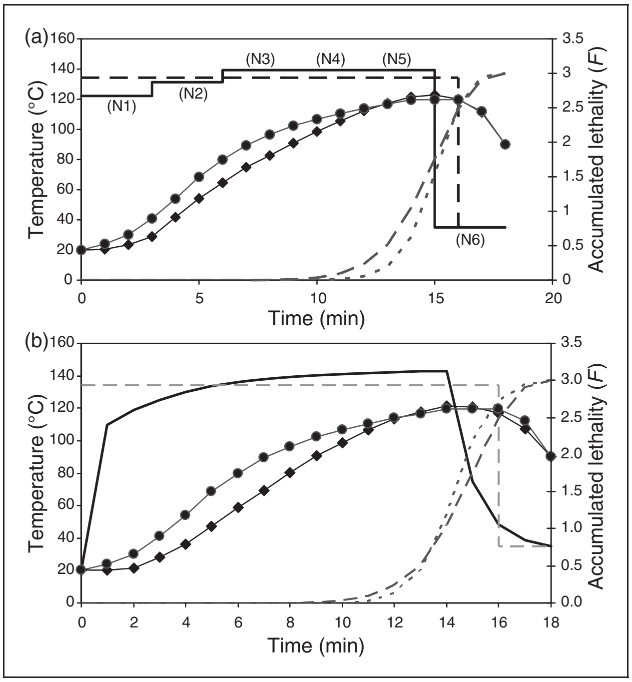

Figure 4. Optimum CRT and VRT profiles, center temperatures and accumulated lethalities for sample S_{12}. (a) Six-step VRT profile and (b) exponential VRT profile. (__), retort (VRT); (◆), CP (VRT); (– –), retort (CRT); (●), CP (CRT); (–––), *F*-value (VRT); and (– –), *F*-value (CRT).

From a practical point of view, temperature during the heating phase should increase with time. Thus, one more specific constraint was considered:

$$N_{i+3} \geq N_{i+2} \geq N_{i+1} \geq N_i \tag{13}$$

Table 3 details the results obtained for sample S_{12}. Figure 4a shows, for the same can, the optimum CRT and VRT profiles (six steps), as well as its corresponding center temperatures (evaluated by the transfer function methodology) and the accumulated lethalities.

As can be seen from these results, an improvement of up to 38% in the surface thiamine retention was achieved when considering a nine-step profile. It is important to note that the profile, which includes nine steps of equal duration, becomes a six-step profile with a different duration.

When describing the VRT profile as an exponential function, the control variables are the parameters A and k. The limits of the control variables for this VRT profile are $10 \leq A_h \leq 40$ and $0.03 \leq k_h \leq 0.4$ for the heating phase and $50 \leq A_c \leq 150$ and $0.03 \leq k_c \leq 1$ for the exponential cooling stage. Table 3 summarizes, for sample S_{12}, the results obtained from this optimization procedure and Figure 4b shows, for the same can, the optimum CRT and VRT exponential profiles, as well as their corresponding center temperatures and the accumulated lethalities.

The comparison of the optimum CRT and VRT profiles for the same process time for container S_{12} (Table 3) shows that it is possible to get for this particular container size, an improvement in the surface quality retention as high as 68% (from 32% to 54%) using the VRT exponential profile. These results are considerably higher than the improvements in quality retention found by other researchers in pure conductive foods, such as pork pate (Banga et al., 1991), salmon (Durance et al., 1997) and beans (Noronha et al., 1996).

CONCLUSIONS

In this study, *z* transfer functions are used to predict the thermal response of solid food particles (mussels) immersed in a liquid medium (brine).

Experimentally, the location of the slowest heating zone was investigated, focusing on the effect of the brine content (%w/w). This point descends along the axial axis as the solid food content of the solid–liquid mixture increases.

Then, the transfer function of canned mussels was experimentally determined. The relationship between the transfer function coefficients f_n on the sampling interval and characteristic dimensions of the cans (diameter and height) was obtained.

On the basis of these 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 processings. These thermal processes were compared, looking for the optimal operative conditions, assuming surface thiamine retention as the quality factor.

In the CRT process, the optimal retort temperature is always between 134 °C and 137 °C, and high values of thiamine retention can be obtained.

Two VRT profiles were tested: discrete step-wise function and an exponential one. A significant increase of surface thiamine retention was obtained using VRT.

The optimization procedure shown in this study, which implements an approach using MATLAB, produces results that justify its utilization in the industry.

NOMENCLATURE

a = Empirical parameter defined by Equation (10)
A = Limitation range of exponential function
b = Empirical parameter defined by Equation (11)
C = Concentration of a quality index (mg/g)
d = Empirical parameter defined by Equation (12)
D = Can diameter (m)
D^* = Decimal reduction time for quality index (min)

f_n = Transfer function coefficient
F = Accumulated lethality (min)
F_0 = Target lethality (min)
$F(z)$ = Transfer function
H = Can height (m)
k = Rate constant of exponential function
N_i = CRT at each interval of the step-wise function (°C)
$p(n\Delta)$ = Value of the input signal (perturbation) $P(z)$ at time $n\Delta$
$P(z)$ = z-Transform of the perturbation
$r(n\Delta)$ = Value of the response $R(z)$ at time $n\Delta$
R = Can radius (m)
$R(z)$ = z-Transform of the response to $P(z)$
t = Time (min)
T = Temperature (°C)
z = z-Transform variable
z^* = Temperature dependence for quality index (°C)
z_m = Temperature dependence for microorganism (°C)

Greek symbols

Δ = Sampling interval

Subscripts

0 = Initial
c = Cooling
ce = Thermal center
ext = External
h = Heating
p = Process
ref = Reference
ret = Retort
sup = Surface

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