Development of a Novel Methodology To Validate Optimal Sterilization Conditions for Maximizing the Texture Quality of White Beans in Glass Jars

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Optimal thermal processes were designed for white beans in glass jars heated in a still and end-over-end rotary pilot water cascading retort. For this purpose, isothermal kinetics of thermal softening of white beans were studied in detail using a tenderometer and a texturometer. The fractional conversion model was applied in both cases to model the texture degradation. The Arrhenius equation described well the temperature dependence of the reaction rate constant. With regard to the heat transfer, heat penetration parameters (f_h and j_h) were experimentally determined from 100 containers under static as well as rotational (end-over-end) conditions at 4, 7, 10, and 15 rpm. Theoretical optimal temperatures, maximizing volume average quality retention, were calculated using a computer program valid for conduction heating foods. Experimental verification of the calculated results was conducted. Considering the finite surface heat transfer coefficient, theoretical and experimental optimal temperatures were of the same order of magnitude, around 130 °C, while for an infinite surface heat transfer coefficient the calculated optimum temperature was much lower than the experimental value. The type of reaction kinetic model, fractional conversion or first-order models, does not significantly affect optimal sterilization temperatures. Although some differences were found, the developed theoretical approach was successfully applied to convective and mixed heating mode products. The use of the correct surface heat transfer coefficient is crucial to design optimal processing conditions.

Introduction

Food sterilization remains one of the most important preservation techniques, providing *long shelf life* and *very easy transport* and *preparation products*. Its primary objective is to kill the pathogenic and spoilage microorganisms and its spores by applying heat to achieve commercial sterility. The application of heat also causes significant quality losses. Although relevant research work has been carried out, there is still a lack of information about the quantification of the effects of heating that is needed to reduce the impact of the thermal processes (Lund, 1975; Villota and Hawkes, 1987; Ávila and Silva, 1999). Optimization of thermal processes must be done in terms of maximization of quality attributes (Teixeira et al., 1969) because this relates directly to consumer's preference and therefore market value (Silva, 1993).

Considering sterilization of prepackaged foods, it is possible to calculate suitable processing conditions leading to maximum product quality retention (Teixeira et al., 1969). Several investigations on theoretical calculations of these conditions, for conduction heating foods, exist (Noronha, 1996; Silva et al., 1993; Ávila and Silva, 1999). For convective and mixed mode heating only Van Loey et al. (1994a) presented a theoretical study to calculate processing conditions maximizing the final texture of white beans in brine. On the other hand, only a quite limited number of authors (Teixeira et al., 1975; Nasri et al., 1993; Silva et al., 1994; Van Loey et al., 1994a) attempted to experimentally validate the simulated results. Experimental validation of calculated optimal conditions for maximizing quality is very important to *meet consumer requirements*. A desirable approach to this problem requires work in different fields such as kinetic modeling, sensory analysis by trained taste panels, and heat distribution and heat penetration studies. However, there are no research studies available which consider all these important steps together toward optimization.

Mathematical models for thermal degradation of different quality parameters are indispensable to quantify the effects of heating on the product. A review on kinetic data for quality thermal degradation indicators is given by Lund (1975), Villota and Hawkes (1987), Hallstrom et al. (1988), Holdsworth (1990), and Silva and Ignatiadis (1995).

One of the most important sensory quality attributes of a food is *color*, because it measures the first impact of the product on the consumer's perception. Also the effect of heat on the *texture* of various products is particularly important. However, kinetic data are lacking for these indicators. In addition, modeling real food products rather than model systems where degradation kinetics

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may be different from first-order kinetics is not often found. Therefore, extensive information is needed to obtain as much consistent, reliable, and comparable data as possible (Villota and Hawkes, 1987).

Experimental validation of heat transfer models to ensure that every container produced achieves the target lethality is indispensable before any validation of calculated optimal conditions is attempted. Process establishment requires identification of the *worst case* conditions by performance of both heat distribution and heat penetration studies. Heat distribution studies are carried out to study the uniformity in lethality throughout the retort in order to identify the location of the lowest lethality (coldest zone) (Ramaswamy et al., 1991; Smout et al., 1998). Temperature measurements are also taken inside containers to determine at which point the lowest lethality occurs. Heat penetration data then measured both at the coldest zone of the retort and at the coldest point of the container are essential to determine the heating and cooling characteristics necessary for both the design and the evaluation of heat treatments (Pflug, 1975). Different *retort processes*, as still and rotary procedures or different heating media, or the use of different *packaging materials* or *shapes* gives different heat penetration profiles into the product. Also the use of *particulate foods* instead of homogeneous solid products strongly affects the heat penetration behavior. This means that if new conditions are introduced into an established process, retesting of the whole process is required to guarantee product safety and quality (May and Fletcher, 1995).

On the other hand, the reduction of excessive safety margins used in industry and consequent reduction of quality loss and costs are only possible with a complete statistical study on heat penetration parameters and lethality variability (May, 1997). Despite the numerous publications on thermal process evaluation there has been relatively little information reported on the magnitude of the uncertainties and errors involved in thermal process determination (Robertson and Miller, 1984). The application of a statistical procedure to quantify the level of uncertainty associated with the heating parameters can identify the *worst case* condition (Pflug, 1975). The statistical approach determined by Pflug (1975) is to obtain representative f_h and j_h values that are greater than P percent of all f_h and j_h values for a given system by constructing one-sided confidence intervals. However, this procedure does not represent worst case values if the sample size is large. Hence, a new statistical approach is needed. From this point, the thermal process is designed, and the next step is optimizing the process for retention of quality parameters.

Therefore, the main objective of this work was to design a new methodology to validate experimentally optimal conditions, for maximizing final volume average retention of particulate in-pack food products considering still and end-over-end rotary processes in a water cascading retort. The goal was to make progress in modeling, characterizing heat transfer into the products, and combine this with relevant quality kinetic data.

Materials and Methods

1. White Beans: Product Characteristics. Dried white beans with origin in Michigan were purchased from a canning company and stored dry at 15 °C. Before processing, the white beans were soaked in distilled and demineralized water at 15 °C for at least 16 h. Analysis of the soaked behavior of the white beans proved that after 16 h the beans had reached their maximal moisture content. The mean sizes of white dry beans were 8.86 ± 0.5 mm length, 5.30 ± 0.510 mm width, and 5.98 ± 0.37 mm thickness. It was also determined that in 100 g of white dry beans there exist 516 ± 0.5 beans. The density of the beans was evaluated, and its value was 1315 ± 0.6 kg/m^3.

2. Kinetics of Thermal Softening of White Beans. Cans of 71 mm diameter and 27 mm height were filled with 50 g of soaked white beans and filled to the top with demineralized water. Cans were relatively small to minimize internal temperature gradients. Thermocouples were placed at the geometric center of six cans containing beans and connected to a data acquisition system to check the existence of a come up time. The experiment was performed in an oil bath of 30 L (Grant Instruments (Cambridge) Limited, HB30) with temperature control. An average come up time of 20 min was observed. All time intervals, with the exception of time = 0 min, for all experimental data points, were corrected by subtracting 58% of the come up time (Ball and Olson, 1957).

Five isothermal experiments were performed at 100, 105, 110, 115, and 120 °C in the oil bath referred to above. The cans were immersed into the oil bath after the oil had reached the specified temperature. At prespecified time intervals, the samples were cooled in an ice−water mixture immediately after withdrawal from the oil bath.

After the samples were cooled, the hardness of 100 g of heat-treated white beans was measured by use of an industrial Tenderometer unit (FMC, model 4011). A Texture Analyzer TA.XT2 (Stable Micro System) was also used to measure hardness. A flat-ended cylindrical probe of 25 mm diameter of stainless steel was used for compression of the white beans at a speed of 3.3 mm/s. This procedure was performed bean by bean at a total of 10 beans per sample.

To determine the detection limit of the tenderometer, a sample of white beans was thermally processed for 4 h in the oil bath at 110 °C. One hundred g of this sample was measured in the tenderometer unit, giving a value of 20.2×10^3 kg/m^2. Also 100 g of the same sample was pureed and then measured in the tenderometer, giving a value of 0 kg/m^2. This procedure proved that with very soft whole samples a residual value could still be measured by the equipment and that the value obtained did not correspond to the detection limit of the unit. In relation to the texturometer this study was not done, because there was no doubt that the values measured were very far from the detection limit of the equipment.

Statistical analysis of the data was performed using the software STATA program version 3.0 (STATA, 1990). Both two-step and one-step nonlinear regressions (Arabshahi and Lund, 1985) were performed, and a regression analysis of the residuals was also carried out (Box et al., 1978).

3. Heat Penetration Studies. Heat penetration studies were carried out in a Pilot Barriquand Steriflow retort which is a Steriflow simulator, microflow type 911R no. 877 of Barriquand (France). Glass jars (capacity of 370 mL) with 84 mm height, 75 mm diameter, and a thickness of 2.6 mm were hand filled with the white beans. Each jar contained 240 ± 0.1 g of soaked beans. Jars were filled with distilled and demineralized water, leaving a 10 mm headspace.

Preliminary heat penetration tests were conducted to determine the least lethality point in the container. The temperature was measured at different locations (1, 1.5, 2, 2.5, and 3 cm from the bottom) along the central axis of several glass jars. For each position, three thermo-

Table 1. Processing Conditions for Heat Penetration Experiments

medium	time (min)	temp (°C)	pressure (bar)
1. steam	0	35	0.5
2. steam	2	40	0.5
3. steam	*a*	40	0.5
4. steam	8	121	2
5. steam	20	121	2
6. water	5	90	1.6
7. water	7	35	0.5
8. forced cooling	30		

[a] Until all temperatures acquired are equal within 0.2 °C.

couples were used. The heating parameters (f_h, j_h, and j_{hb}) were determined, and the F values were calculated using the general method (Hayakawa, 1977, 1978). Results were analyzed using the analysis of variance (ANOVA) at a 5% level to check if there were significant differences in the calculated F values. For the static mode significant differences at a 5% level were found, but the coldest point was found to be located 15 mm from the bottom of the container. The same procedure was performed for 4, 7, 10, and 15 rpm. As no significant differences were found among the F values and f_h values the same position from the bottom (15 mm) as in the static mode was selected.

Static and rotating processes were conducted to check the influence on the sterilization value and heating rate. One hundred containers were processed for each condition to determine the variability in the heating characteristics of the product. All the processes were preceded by a phase to equilibrate the product temperature at 40 °C. The processing temperature was 121 °C. The program schedule of the retort followed is shown in Table 1.

The temperature histories in the pilot retort were monitored at 15 s intervals and registered using the Ellab CMC-92 data acquisition system (Ellab, Denmark). A multiplexer box (UMX6-88) was connected to a personal computer and installed with two temperature probe boxes (TR9216). Output was reported with an accuracy of ±0.1 °C. For the rotary processes, a slipring contact (Ecklund) was used together with a connecting plate to switch the Ellab connection on the thermocouple to an Omega connection on the slipring contact. The temperature histories were also monitored at 15 s intervals and registered using a Mess+System Technik GmbH (MDP 82 series) data acquisition system.

Temperatures of the product and retort were monitored using thermocouples of copper−constantan (type T) from Ellab (Denmark). The temperature of the processing medium was monitored using thermocouple probes SSR-60020-G700-SF and SSA-12080-6700-TS for liquids and air. For measuring inside the products, thermocouple probes, needle-type with round tip, SSA-12080-G700-SF, were used. Space bars were used to measure at the desired position in the product for the coldest spot determinations. For the rotary processes, self-made copper−constantan (type T) thermocouples (Omega thermocouple wire, TT-T-24-1000FT) were used to record ambient temperature. The calibration of the thermocouples was carried out by mutually comparing the thermocouples in use in the pilot Barriquand Steriflow retort in water cascading at 121 °C. Once the heating medium has stabilized, readings were taken every 15 s over a period of 20 min.

Heat penetration parameters were calculated from the experimental data using a Pascal computer program already developed in the laboratory. The adjusted f_h and j_h values were estimated using the semiempirical approach, the apparent position numerical solution (APNS) method (Noronha et al., 1995). This method is able to calculate empirical heat penetration parameters (adj.f_h and adj.j_h), using the classical approach (Ball, 1923) as initial guess, that are not influenced by the duration of the retort come up time. The means (μ) and standard deviations (σ) of the heat penetration parameters were calculated, and the test of normality, the Sapiro−Wilk statistic test (W), was applied for the null hypothesis that the input data values are a random sample from a normal distribution. When "$Pr < W$" is smaller than 0.05, the null hypothesis will be rejected at a 95% confidence level. On the basis of the variability of the heat penetration parameters, a statistical approach to assess the worst case f_h and j_h values was formulated. As the worst case corresponds to the major value of f_h found, the procedure was formulated looking for the distribution of maximum values (Murteira, 1990). The distribution was developed as follows:

$$\text{adj.}f_h = Z$$

$$Z = \max(X_i)$$

$$G(Z) = P(Z \le z)$$

$$G(Z) = P(\max(X_i \le z))$$

$$G(Z) = P(X_1 \le z \cap X_2 \le z \cap \ldots \cap X_n \le z) = P(X_1 \le z)\, P(X_2 \le z)\, \ldots\, P(X_n \le z)$$

$$G(Z) = [P(X \le z)]^n$$

Therefore, the distribution function is

$$G(Z) = [F(Z)]^n \tag{1}$$

A critical adjusted f_h value (q) was calculated for a confidence level of $1 - \delta$

$$P(Z \le q) = 1 - \delta \Leftrightarrow G(q) = 1 - \delta \Leftrightarrow [F(q)]^n = 1 - \delta \Leftrightarrow F(q) = (1 - \delta)^{1/n}$$

$$P(f_h \le q) = (1 - \delta)^{1/n}$$

$$P(U \le (q - \mu)/\sigma) = (1 - \delta)^{1/n} \tag{2}$$

where X_i is the random variable in the study, $G(Z)$ the distribution function of the maximum value of adj.f_h, $F(Z)$ the distribution function of the random variables, and U the normal standard value.

4. Optimization of Sterilization Conditions. A Pascal computer program previously developed was used to predict optimal sterilization conditions for white beans in glass jars. The program used a finite-difference numerical method with noncapacitance surface nodes to describe the heat transfer by conduction into a cylindrical container (Silva, 1993). This program required information about the thermal degradation kinetics for the quality attribute under consideration, characterization of the heat transfer into the product and the surface heat transfer coefficient. For a finite cylinder heating by conduction the heating rate parameter can be expressed in terms of the thermal diffusivity (α) as

$$f_h = \frac{0.0383}{\alpha(\beta_1^{\,2}/H^2 + \beta_2^{\,2}/l^2)} \tag{3}$$

where β_1 is the first positive root of the equation $\beta\tan(\beta)$

$= Bi$, β_2 the first positive root of the equation $\beta J_1(\beta) - B_i J_0(\beta) = 0$, $J_0(x)$ the Bessel function of the first kind of order zero, $J_1(x)$ the Bessel function of the first kind of first order, H the half-height of the cylinder (m), and l the radius (m) (Carslaw and Jaeger, 1959).

Two values for the surface heat transfer coefficient were considered: an infinite surface heat transfer coefficient used as a simplification and an estimated value using empirical equations (Geankoplis, 1983) including resistance of the container wall, and external and internal natural convection at the surface. The overall heat transfer coefficient was estimated as 408 W/(m^2 K), the major value that can occur during the process.

For a given retort temperature and sterilization value, this computer program can also calculate the overall retention of the quality parameter. However, some simplifying assumptions are made: the food product is homogeneous and isotropic, the initial temperature is uniform, and the time−temperature profile consists of a come up time with a linear increase of temperature from the initial to constant holding temperature. An extrapolation of kinetic data for softening of white beans was also done for temperatures larger than 120 °C.

For first-order quality degradation kinetics, eqs 4 and 5 were used to predict the optimal temperature considering volume average quality retention ($(T_{opt})^{av}$)

$$\begin{aligned}(T_{opt})^{av} = {} & 113.8 + z(0.343 + 0.389V/(Al)) + \\ & \log(F_t/f_h)(10.85 - 0.725V/(Al) - 0.032z) + \\ & 1/D^2_{121.15°C}[F_t^{\,2}(-1.52 + 5.22V/(Al)) + f_h^{\,3/2}(-3.03 + \\ & 0.015z^2 + F_t(1.05 - 3.86V/(Al) + z^2(-0.0044 + \\ & 0.017V/(Al))))] - 9.1/Bi + 1.94z/Bi \end{aligned} \quad (4)$$

$$\begin{aligned}(T_{opt})^{av} = {} & 113.8 + z(0.343 + 0.389V/(Al)) + \\ & \log(F_t/f_h)(10.85 - 0.725V/(Al)) - 0.032z) + \\ & 1/D^2_{121.15°C}[F_t^{\,2}(-1.52 + 5.22V/(Al)) + f_h^{\,3/2}(-3.03 + \\ & 0.015z^2 + F_t(1.05 - 3.86V/(Al) + z^2(-0.0044 + \\ & 0.017V/(Al))))] \end{aligned} \quad (5)$$

valid for finite and infinite surface heat transfer coefficients, respectively (Silva et al., 1992; Hendrickx et al., 1993; Silva, 1993). V is volume (m^3), A is surface area (m^2), l is radius (m), F_t is the target sterility (F_0) value (min), z is z value (°C), $D_{121.15°C}$ is the D value (min) for the quality factor at a reference temperature of 121.15 °C, f_h is the heating rate (min), and Bi is the Biot number.

Validation experiments were performed in the pilot retort at holding temperatures of 105, 110, 115, 120, 125, 130, and 135 °C for sterility values of 3 and 5 min. The F_0 value of 3 min is the minimum value used in sterilization processes, and the F_0 value of 5 min is used normally by industry to process beans. This procedure was possible with the use of the Ellab program together with the Ball method to predict the time to start cooling the product to reach the desired F_0 value. Three thermocouples were placed inside the product at the coldest point to on-line calculate the F_0 values using the general method. Objective measurements were carried out in the processed white beans with the tenderometer unit.

Results and Discussion

1. Thermal Degradation Kinetics of the Texture of White Beans. The thermal degradation kinetics of white bean texture was evaluated using two different systems, a tenderometer and a texturometer. Both methods lead to the conclusion that the softening kinetics of beans follows the fractional conversion model (Levenspiel, 1972):

$$\frac{C - C_f}{C_0 - C_f} = \exp(-kt) \quad (6)$$

where C is the measured hardness value, C_0 is the initial C, C_f is the final equilibrium value of C, t is the heating time, and k is the reaction rate constant.

Rizvi and Tong (1997) pointed to this model as a more accurate and reliable technique for reanalyzing texture degradation kinetics instead of the two simultaneous first-order reactions at two different rates (Huang and Bourne, 1983; Heil and McCarthy, 1989; Van Loey et al., 1994b).

Figures 1 and 2 show the fractional conversion model adjusted to the experimental points, respectively, for the tenderometer and texturometer measurements. Kinetic parameters were calculated using the nonlinear regression method applied to all data (Arabshahi and Lund, 1985). The Arrhenius equation was used to describe the temperature dependence of the reaction rate constant:

$$k = k_{ref} \exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (7)$$

where T is the absolute temperature, T_{ref} is the reference absolute temperature, k_{ref} is the reaction rate constant at the reference temperature, E_a is the activation energy, and R is the universal gas constant.

Activation energies and rate constants estimated at the reference temperature and corresponding 95% confidence intervals are reported in Table 2. Comparing parameters from the fractional conversion model obtained from the tenderometer and the texturometer data, one can conclude that rate constants at 110 °C are very similar, but the activation energies obtained with the tenderometer and texturometer data were 120 and 70 kJ/mol, respectively. Also residuals were checked, and from Figures 3 and 4 it can be observed that no systematic tendencies (residuals were randomly distributed around zero) were observed for the texture of white beans measured with the tenderometer and texturometer, respectively.

In Table 2 the kinetic parameters for both measurements are also presented for a first-order model: $C = C_0 \exp(-kt)$. The experimental data were reanalyzed not taking into consideration the points in the final equilibrium phase. The objective was only to use a simplifying model for further comparison in the optimization procedure, as it was experimentally proved that the fractional conversion is the model that correctly describes the degradation of the texture of white beans.

The objective of measuring the texture of white beans with both sets of equipment was to confirm the kinetic model and to compare the results. The tenderometer unit measures the strength applied to smash a certain amount of sample, giving an average value, while with the texturometer it was only possible to measure bean by bean and calculate the average of the strength applied at the end. For the harder beans it was very difficult to measure with the texturometer, because this unit only compresses the beans while the tenderometer is able to cut the sample. These two different techniques of measurement explain the difference in the results obtained in the kinetic parameters.

2. Heat Penetration Studies. The heat penetration curves presented a log-linear behavior. However, a large

Table 2. Kinetic Parameters for Thermal Softening of White Beans Estimated Using the One-Step Nonlinear Regression Method for the Tenderometer and Texturometer Units

unit	model	E_a (kJ/mol)	k_{ref} (min^{-1})	T_{ref} (°C)	C_0	C_f	R^2
tenderometer	fc	120 ± 8	$0.066 \pm 4E{-}3$	110	301.2	26.0 ± 4.5	0.995
	1st	115 ± 11	$0.055 \pm 4E{-}3$	110	301.2		0.996
texturometer	fc	70 ± 12	$0.081 \pm 6E{-}3$	112.5	15.2	1.03 ± 0.38	0.994
	1st	65 ± 16	$0.071 \pm 5E{-}3$	112.5	15.2		0.995

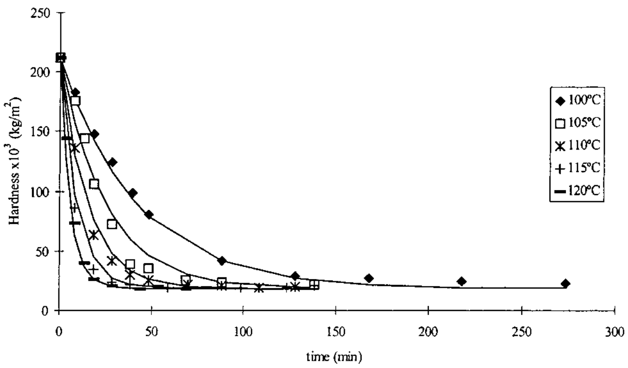

Figure 1. Thermal degradation kinetics of the texture of white beans evaluated using a tenderometer unit.

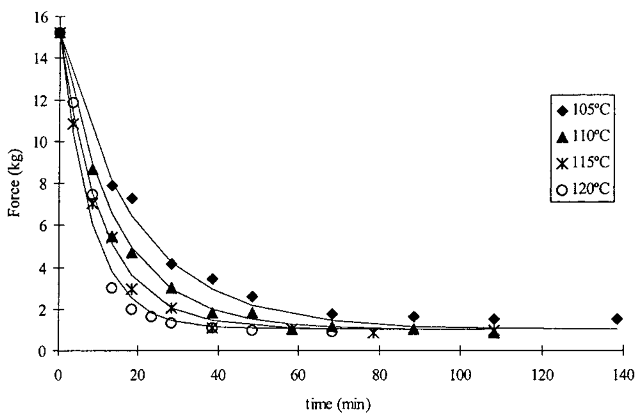

Figure 2. Thermal degradation kinetics of the texture of white beans evaluated using a texturometer unit.

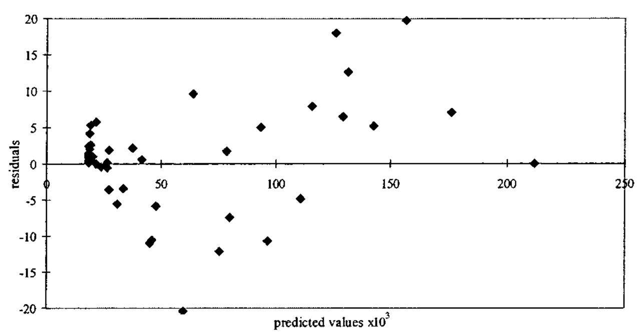

Figure 3. Residuals of the softening of white beans measured with the tenderometer as a function of the predicted values.

variability was observed during cooling, which means that there was a large variability within the product.

Mean f_h values and process values for white beans were plotted (Figure 5) as a function of rotational speed. As expected, increasing rotational speed resulted in faster heat penetration (lower f_h value). Several authors came to similar conclusions (Berry and Bradshaw, 1982; Berry and Kohnhorst, 1985; Van Loey et al., 1994a). However, this influence becomes smaller as the rotational speed increases over 10 rpm, because more broken beans and consequently leakage of starch appeared. Van Loey et al. (1994a), also using white beans, obtained similar conclu-

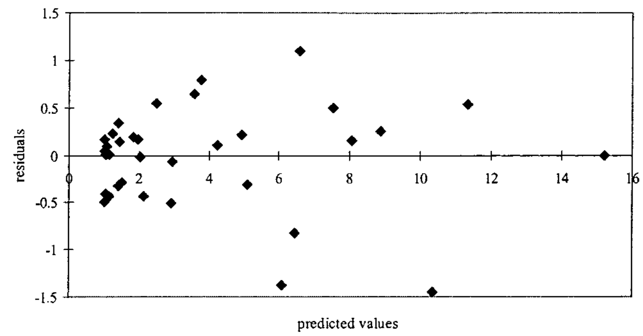

Figure 4. Residuals of the softening of white beans measured with the texturometer as a function of the predicted values.

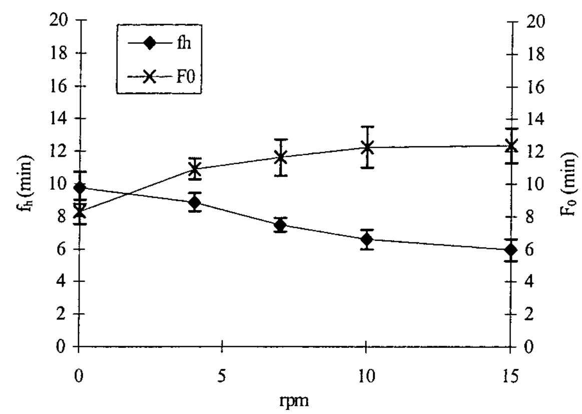

Figure 5. Mean f_h values and sterility process values (F_0) for white beans as a function of rotational speed.

sions, but larger differences were found in the case reported. As at over 10 rpm the process does not have any effect on the f_h and F values, it was decided to choose the static and 10 rpm modes of operation of the retort to proceed to the optimization experiments.

On the basis of the variability of the heat penetration parameters, a statistical approach to assess the worst case f_h and j_h values was formulated. The adjusted values of f_h and j_h calculated with the APNS approach were used. The means (μ), standard deviations (σ), and results of the test of normality of the heat penetration parameters are summarized in Table 3. The critical adjusted f_h and j_h values were calculated for a confidence level of 95% (Table 3). Although the adj.j_h value does not follow a normal distribution, the critical value was calculated using the same method as it does not significantly affect the results. At this step the worst case condition is identified to ensure the safety of the product.

3. Optimal Sterilization Conditions To Maximize Quality Retention. With the parameters presented in Table 3 it was possible to predict the holding times for the thermal process of white beans for a certain F_0 value and for the desired temperature. For this purpose, the Ball method was used, and the results are presented in Table 4. Experimentally this prediction was just followed at low temperatures of 105, 110, and 115 °C, because the method of Ball is based on the linear behavior of the heating curves and does not describe the curvilinear

Table 3. Means (μ), Standard Deviations (σ), Sapiro–Wilk Statistic ($Pr < W$) of the Experimentally Determined Heat Penetration Parameters, and Worst Case adj.f_h and adj.j_h Values Calculated for Process Design

	param	normality	μ	σ	worst case
0 rpm ($N = 115$)	adj.f_h	0.088	9.06	0.75	11.6 min
	adj.j_h	0.001			1.36
10 rpm ($N = 103$)	adj.f_h	0.24	6.51	0.69	8.8 min
	adj.j_h	0.0001			1.58

Table 4. Holding Times (htime) Predicted Using the Ball Method for the Worst Case f_h and j_h Values and Comparison with Experimental Times Obtained in the Retort

	0 rpm, $F_0 = 3$ min		0 rpm, $F_0 = 5$ min		10 rpm, $F_0 = 3$ min	
T (°C)	Ball htime	exptl htime	Ball htime	exptl htime	Ball htime	exptl htime
105	134.3	156.8	215.9	235.5	130.3	133.3
110	50.9	60.5	76.7	84.9	46.8	47.6
115	24.6	27.2	32.9	34.8	20.5	19.8
120	15.1	13.4	18.5	17.7	11.6	7.9
125	10.7	7.6	12.5	9.5	7.7	4.3
130	8.1	3.7	9.3	6.1	5.5	1.5
135	6.4	1.5	7.2	2.1	4.0	0

portion at the beginning of the heating and cooling curves. Comparing the values predicted with the experimental values, holding times had to be extended or shortened in order to obtain the target F values (Table 4).

Since softening in white beans was less resistant to thermal degradation measured with the tenderometer than with the texturometer, the hardness with the tenderometer was optimized. Calculated results are presented in Table 5, considering the fractional conversion model and the first-order model. Also optimal temperatures were calculated using a first-order model ($z = 29$ °C, $D_{121.1} = 56$ min) obtained from a sensory panel evaluation (Van Loey et al., 1994b). It was observed that optimal temperatures predicted with the two different models, fractional conversion and first-order (objective and sensory measurements), are of the same order of magnitude. Table 5 presents optimal temperatures considering the existence or not of surface resistance to heat transfer at the surface. Experimental results can be observed in Figures 6–8. Retention profiles, calculated and experimental, deviate especially for finite surface heat transfer coefficient and in the case studies with an F_0 value of 3 min. This can be explained by the assumptions made in the optimization procedure. The computer program assumed heat transfer by conduction for solid homogeneous products, and the white beans are a particulate food that heats by convection and conduction (mixed heating mode). On the other hand, kinetic data obtained under isothermal conditions for softening of white beans were extrapolated for temperatures larger than 120 °C. The calculated optimal temperature only matches the experimental value obtained (130 °C) if a finite surface heat transfer coefficient is used. For an infinite surface heat transfer coefficient the optimum temperature calculated was around 123 °C.

A very important conclusion is that the type of reaction kinetic model, fractional conversion or first-order model, does not significantly affect optimal sterilization temperatures, while the use of a simplifying surface heat transfer coefficient implies optimal temperatures completely deviating from the experimentally observed values.

Table 5. Calculated Optimal Sterilization Temperatures for Maximizing the Volume Average Quality Retention of White Beans

model	F_t (min)	rotatn (rpm)	$(T_{opt})^{av}$, eq 4	$(T_{opt})^{av}$, program h_{fin}	$(T_{opt})^{av}$, eq 5	$(T_{opt})^{av}$, program h_{inf}
fc	3	0		131.7		123.8
	5	0		135.9		127.5
	3	10		136.6		124.6
1st	3	0	129.4	130.6	121.1	123.2
	5	0	131.8	133.7	123.5	125.8
	3	10	132.8	134.2	121.8	123.7
1st (sensory anal.)	3	0	132.3	132.3	122.1	123.7
Van Loey et al.	5	0	134.5	134.6	124.3	125.7
(1994b)	3	10	136.6	137.8	123.2	124.5

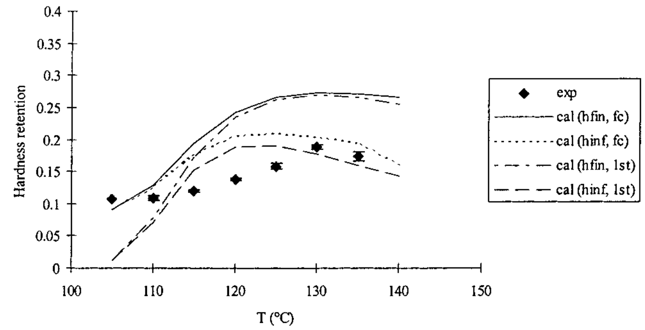

Figure 6. Experimental hardness retention and predicted average values for a target F_0 value of 3 min and static mode. Calculated profiles for first-order and fractional conversion models for finite and infinite surface heat transfer coefficients.

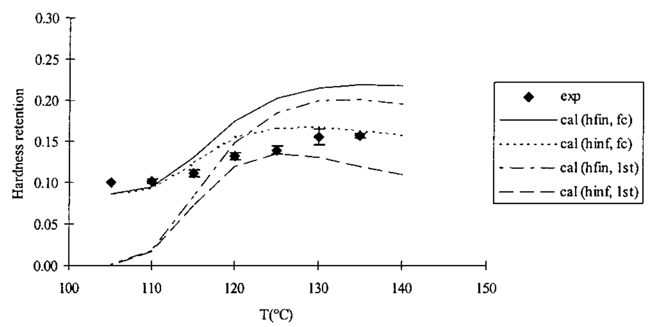

Figure 7. Experimental hardness retention and predicted average values for a target F_0 value of 5 min and static mode. Calculated profiles for first-order and fractional conversion models for finite and infinite surface heat transfer coefficients.

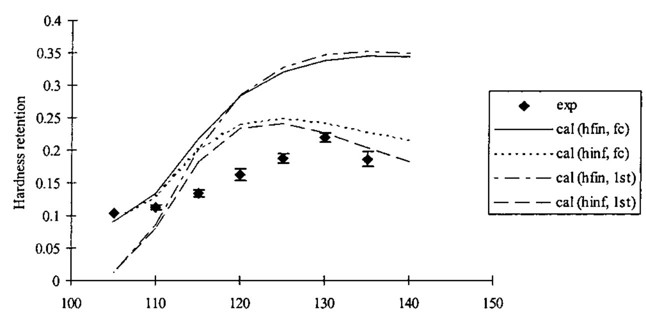

Figure 8. Experimental hardness retention and predicted average values for a target F_0 value of 3 min and 10 rpm. Calculated profiles for first-order and fractional conversion models for finite and infinite surface heat transfer coefficients.

This result had already been discussed by Silva (1997). The author performed a simulation study to predict the effect of reaction type kinetics (zero-order, second-order, and fractional conversion models) on optimal thermal processing conditions and final quality retention. The reaction kinetics did not affect optimal sterilization conditions for maximizing the surface quality. Optimal conditions for maximizing volume average quality retention were affected, depending on the reaction type kinetics, kinetic parameters, and processing conditions.

Conclusions

On the basis of product quality parameters, thermal degradation kinetics, heating rates, process conditions, and the target F_0 value, optimal processes were calculated for white beans prepacked in glass jars. Still and rotating conditions were conducted in a pilot water cascading retort. Optimal processes were successfully designed. Considering the finite surface heat transfer coefficient, predicted and experimental optimal temperatures were of the same order of magnitude. For the infinite surface heat transfer coefficient, completely deviating values were found. Despite the success obtained in validating calculated optimal temperatures, large differences in estimated and experimental quality retention profiles were found. Simplifying assumptions made in the heat transfer model are the main reason for these results. It can be concluded that the theoretical approach was successfully applied to the convective and mixed heating mode products. The use of a simplifying kinetics (first-order models) instead of the fractional conversion model did not affect optimal temperatures, but the use of the correct surface heat transfer coefficient is crucial in calculating optimal processing conditions. However, implementation of novel processes should follow all the important steps referred to as each new design is only valid for the specific product, container, fill weight, and retort heating medium and processing conditions.

Notation

A	surface area (m^2)
adj.f_h	adjusted heating rate (min)
adj.j_h	adjusted lag factor
Bi	Biot number ($=hl/\lambda$) (dimensionless)
C	measured hardness value (kg/m^2)
D	decimal reduction time (time required for the number or concentration of spores, microorganisms, or quality factors to be reduced by a factor of 10 at a given temperature) (min)
E_a	activation energy (kJ/mol)
F	sterility value at the slowest heating zone and at the reference temperature of 121.1 °C (min)
fc	fractional conversion model
f_h	heating rate (min)
$F(Z)$	distribution function of the random variable
$G(Z)$	distribution function of the maximum value
H	half-height of the container (m)
h	surface heat transfer coefficient (W/(m^2 °C))
j_h	lag factor
j_{hb}	corrected lag factor according to Ball
k	reaction rate constant (min^{-1})
l	radius (m)
n	exponent
N	number of experiments
q	critical value
R	universal gas constant (8.314 J/(mol K))
R^2	correlation coefficient
t	heating time (min)
T	temperature (°C)
U	standard normal variable
V	volume (m^3)
X_i	random variable
z	z value (°C)
α	thermal diffusivity (m^2/s)
δ	significance level
λ	thermal conductivity (W/(m K))
μ	mean
σ	standard deviation
1st	first-order model

Superscripts

surf	surface
av	average

Subscripts

0	initial C (kg/m^2), initial product temperature (°C), or sterility value (F_0) (min) at the reference temperature of 121.1 °C
calcd	calculated
exptl	experimental
f	final equilibrium value of C (kg/m^2)
fin	finite
inf	infinite
opt	optimum
ref	reference
t	target

Acknowledgment

I.M.L.B.Á. acknowledges the European Commission for financial support (TMR grant, Contract No. FAIRCT-965078) that allowed this research work to be carried out at the Catholic University of Leuven, Belgium. We also thank Ilse Mampaey for her help in the experimental work.

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