Journal of Food Engineering 275 (2020) 109839

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: http://www.elsevier.com/locate/jfoodeng

Assessment and outlook of variable retort temperature profiles for the thermal processing of packaged foods: Plant productivity, product quality, and energy consumption

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ARTICLE INFO

Keywords:
Thermal processing
Variable retort temperature profiles
Packaged foods
Optimization

ABSTRACT

Thermal processing has been used for packaged foods for many years and remains one of the most common and safe processes to preserve foods and extend their shelf life. Advances in thermal processing in the last two decades have helped maintain its relevance in international food trades. In this study, we aimed to gain a better understanding of thermal food processing using variable retort temperature profiles (VRTPs). VRTPs were assessed to optimize processes, either by ensuring high quality level or minimizing the operating process time. Based on the research results, VRTPs could improve quality retention; however, the improvement was not sufficient to be detectable by consumers and to justify implementation of VRTPs at the industrial level. Our general assessment provided a preliminary guide for processors to discover real opportunities for VRTPs, e.g., increased productivity by reducing operating process time and energy consumption.

1. Introduction

Although thermal processing has been used for the preparation of packaged foods for many years, it is still one of the most common and safe processes to preserve foods and extend shelf life. Advances in the last two decades have maintained the relevance of thermal processing in the worldwide food trade. For example, modeling of thermal sterilization through computational fluid dynamics (Ai et al., 2018; Park and Yoon, 2018), heat penetration analysis and modeling (Grauwet and Shpigelman, 2018), process optimization to improve quality retention (Park et al., 2019; Singh et al., 2018; Wang et al., 2019), and real-time optimization of the sterilization process (Vilas and Alonso, 2018) are major topics currently being investigated.

All advances in the thermal processing of packages foods, particularly those related to the introduction of new equipment, packaging materials, and formats, can be reanalyzed, reviewed, and rethought in order to improve quality and reduce the operating process time and energy consumption for thermally sterilized products. Most optimization studies were developed in past decades (Chen and Ramaswamy, 2002a, 2002b, 2002c; Abakarov et al., 2009; Balsa-Canto et al., 2002a, 2002b; Banga et al., 2003; Erdogdu and Balaban, 2001; Erdogdu and Balaban, 2002; Erdogdu and Balaban, 2003a, 2003b) and aimed to maximize quality retention without major consideration for reducing the operating process time and energy consumption or its implications in the production capacity/productivity of the process plant (Simpson et al., 2007). An interesting alternative to maximize quality is the use of variable retort temperature profiles (VRTPs). This process mode is based on temperature control of the retort, allowing generation of positive and negative temperature ramps. Furthermore, although many theoretical studies have been performed, VRTP processes have not managed to gain ground in the industry mainly because improvements in quality retention are not substantial using these processes (Saguy and Karel, 1979). Only a few studies have shown that the advantages of VRTPs can be realized when the objective function is to minimize the operating

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https://doi.org/10.1016/j.jfoodeng.2019.109839
Received 14 August 2019; Received in revised form 22 November 2019; Accepted 22 November 2019
Available online 29 November 2019
0260-8774/

process time and reduce energy consumption while maintaining quality as a constraint (Almonacid-Merino et al., 1993).

Research studies on energy consumption are unusually scarce. Seminal studies by Barreiro et al. (1984) and Bhowmik et al. (1985) established detailed methodologies to estimate the total energy consumption of the process. In addition, Simpson et al. (2006) developed a procedure that allows us to quantify not only the total energy consumption of the process but also the transient energy consumption during the process. One of the main advantages of the estimation of transient energy consumption is that it allows optimum design of the retort schedule to avoid a high peak in the energy consumption of the whole plant operation.

The aim of this study was to assess the implementation of thermal processing of packaged foods through VRTP processes. VRTP processes were analyzed in terms of guaranteeing product safety (a required F_r) and optimizing the process, either by ensuring an adequate quality level to minimize the operation process time and resulting reduction in energy consumption or by maximizing the quality and controlling both the operating process time and energy consumption.

2. Description and identification of the problem

The search for an optimal process performed under VRTPs will have two different foci: 1) minimizing the operating process time **(P_t)**, which would have the advantages of reducing energy consumption while maintaining high product quality; and 2) maximizing the quality and controlling both the operating process time and energy consumption.

Therefore, the first step was to define variables to cover "all" potential product processes carried out in the "canning" industry. The selected variables for this broad search were packaging format (shape and size), heat transfer properties of the food, and parameters that define the quality factors. Lethality criteria were established considering *Clostridium botulinum* spores as the target microorganism by applying an F_0 value of 6 min ($T_{reference}$ = 121.1 °C and z-value = 10 °C) for the whole search (Holdsworth and Simpson, 2016).

2.1. Estimating quality

For the scope of this study, we assumed that quality factors could be characterized with first-order kinetics (Holdsworth and Simpson, 2016; Simpson et al., 2019). In addition, the temperature dependence of the quality factors was assumed to be a function of z and D values. As described by Simpson et al. (2019), the estimate of quality on the surface has two clear advantages; the surface is the most damaged portion of the food, and given that the retort temperature is recorded, the impact on the food surface can be easily estimated assuming that the surface temperature of the food is equal to or similar to the retort temperature. Given the extremely high local heat transfer coefficient (vapor condensation) (Kern, 2017) and the negligible resistance of most packaging material, the food surface temperature is approximately equal to the retort temperature at any time during the thermal process, not only for constant retort temperature profiles (CRTPs) but also for VRTPs.

According to Holdsworth and Simpson (2016), z-values depend on the product and the product quality attributes. Then, a wide range of z-values can be obtained, approximately between 18 °C and 130 °C, although a range from 20 °C to 60 °C is more reasonable because virtually all quality factors fall in this range. For example, in studies of vitamin degradation, z-values for vitamin B1 and thiamin can vary from 22 °C for carrots to 41.7 °C for salmon, and those of folic acid can vary from 18.3 °C for pea purée to 91.2 °C for spinach.

As indicated by Teixeira et al. (1975), changes in D values will not change optimal processes using a CRTP (optimum processing temperature), and its impact is only minor in terms of quality retention. The aforementioned statement could be extrapolated to VRTP processes; then, different D values could generate the same optimum VRTPs. Accordingly, it is possible to use a unique D value and vary the z-value to cover all potential quality factors and their impact on product quality.

2.2. Operating process time and quality maximization

A parameter that simultaneously characterizes the thermal properties of food and format (shape and size) is the f_h parameter (Holdsworth and Simpson, 2016). As the heat penetration rate increases, f_h becomes lower. As detailed by Stumbo (1973), for solid and semisolid foods, f_h can range from 20 to 230 min. Thus, in order to include all current formats (shapes and sizes) and new formats of cans, glass jars, retortable pouches, pillow pouches, gusset pouches, and trays, f_h values ranging from 20 to 220 min were analyzed (Simpson et al., 2019). For example, cherry tomato pulp (thermal diffusivity of 1.46 × 10^{-7} m^2/s) packaged in a can with a size of 202 × 108 has a f_h value of 30 min; a mixture of meat, tomatoes, and potatoes (thermal diffusivity of 1.57 × 10^{-7} m^2/s) packaged in a can with a size of 300 × 405 has a f_h value of 56 min; and processed ham (thermal diffusivity of 0.94 × 10^{-7} m^2/s) packaged in a can with a size of 307 × 403 has a f_h value of 122 min (Holdsworth and Simpson, 2016).

The operating conditions for CRTP and VRTP processes were set with a fixed come-up time (CUT) of 10 min, retort processing temperatures (TRTs) ranging from 110 °C to 130 °C, and a fixed cooling temperature of 25 °C. Furthermore, the initial product temperature and final ending temperature of the product were set at 45 °C and 60 °C, respectively. In addition, the criterion for the reduction of the operating process time was limited to achieving a high-quality product and a feasible/low energy consumption process. In contrast, the selected quality attributes are related to the labile compounds, which have z-values in the range of 20 °C–60 °C and a fixed $D_{121.1^\circ C}$ value of 250 min (Feliciotti and Esselen, 1957), where D is the property that defines the lability of the quality attribute and the z-value is its temperature dependence. The product quality, defined as the percentage retention, was calculated using the following equation:

$$\%\_Surface\_Retention = 100e^{-\frac{\ln 10}{D_r}\int_0^t 10^{\frac{T_S - T_r}{z}}dt} \quad (1)$$

For example, vitamin retention, color retention, texture retention, and antioxidants were defined as inputs for analysis of VRTP processes obtained from a CRTP process with maximum quality for each product. For each standard CRTP process, the optimum conditions were obtained to maximize quality retention. The optimal VRTP process was defined in such a way as to minimize the operating process time while maintaining high quality (optimum retention for CRTP process) and a feasible (reproducible) time-temperature profile (Almonacid-Merino et al., 1993). In addition, VRTPs were defined in terms of maximum quality retention while controlling operating process time and energy consumption.

2.3. Defining a model processing plant as a quantitative example

According to the advice of Saura Consulting (2019), a model processing plant was defined to quantitatively investigate and analyze the potential advantages of using VRTPs over the standard CRTPs. The processing plant had three retorts, each with three carts that operated for 7400 h/year (H) and processed three low-acid products with f_h values of 74, 57, and 34 min (called products 1, 2, and 3, respectively) (Saura Consulting, 2019). The kinetic factors for quality evaluation (degradation) were the $D_{121.1^\circ C}$ and z-values of 250 min and 25 °C, respectively, when the packaging dimensions were 300 × 509, 300 × 407, and 211 × 414 inches for products 1, 2, and 3, respectively. According to Saura Consulting (2019), each retort could be loaded with approximately 2590 units of product 1, 3450 units of product 2, and 4110 units of product 3. In addition, 40% of the annual operating process time (H) was assigned to the processing of product 1, and 30% of the operating process time was assigned to products 2 and 3. Furthermore,

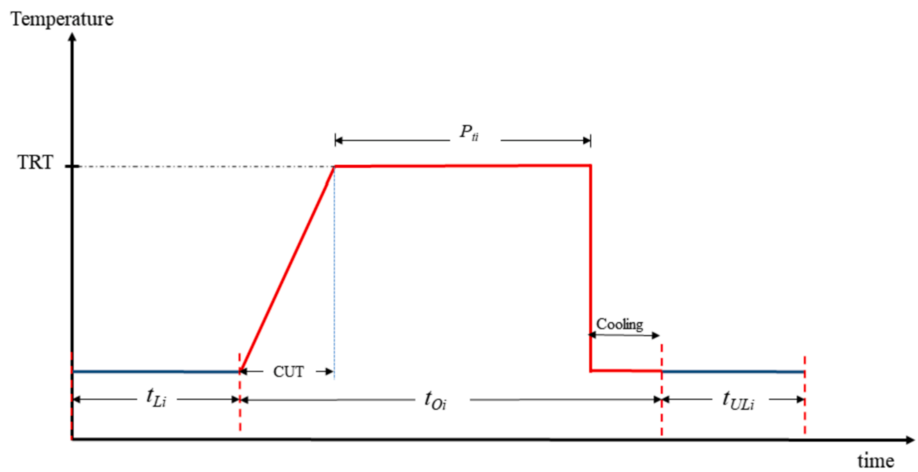

Fig. 1. Schematic representation of a sterilization process depicting different times for the whole batch operation.

the processing operation mode for VRTP or CRTP consisted of two profiles (programs), i.e., one for the temperature set point and one for the pressure set point.

3. Methodology

3.1. Scope of research

To investigate the potential advantages of VRTPs over CRTPs, we performed three tasks: 1) maximize product quality; 2) increase the production capacity of the processing plant and reduce the energy consumption; and 3) perform a quantitative analysis of a model industrial cannery. In addition, we consolidated our opinions and general recommendations on how to investigate different opportunities for VRTPs in real canneries.

3.2. Mathematical formulation: CRTP and VRTP processes

The following mathematical formulation for processes performed under CRTPs or VRTPs was generated based on a description of an optimal control problem. The objective of the control was to minimize the total processing time of the canned products, subject to maintaining the minimum preset values for surface quality retention and lethality for the product. Operational constraints were included to ensure the feasibility of the process (Hildenbrand, 1980). The dynamics of the system were modeled by the conduction heat transfer equation, where the temperatures inside the packages were considered state variables and the retort temperature was considered the control signal. The mathematical formulation was detailed by Simpson et al. (2019). With this reformulation, the obtained discrete model was a nonlinear programming (NLP) problem that could be solved using commercial interior point-based NLP solvers. In this work, a numerical solution for our model was obtained using AMPL (Fourer et al., 1990) as the mathematical programming language with KNITRO (Nocedal, 2006) as the nonlinear solver (with default settings). Because some of the constraints of the VRTP process model were nonconvex, the NLP solver could only find local optimal solutions. To improve the performance of these solvers as global optimization tools, some modeling recommendations were incorporated into our discrete formulation (Vanderbei, 2000).

3.3. Quantifying the impact on plant production capacity and energy consumption

One of the expected advantages of food processing under VRTP is reduction of the operating process time and energy consumption. Therefore, a methodology was developed to quantify the impact of the reduction in operating process time on the production capacity/productivity of the plant and the reduction in energy consumption. In addition, if the current production level of the processing plant was maintained, we could determine how many hours of operating process time were eliminated because of implementation of VRTPs instead of standard CRTPs.

The following expression represented the batch number of product i ($i = 1,2,3, \ldots p$) per year (BN_i) as a function of the available plant hours per product i (H_i) and the batch process time, i (t_B). In addition, the total available production hours of the plant per year were designated as H.

$$BN_i = \frac{H_i}{t_{B_i}} \tag{2}$$

where: $\sum_{i=1}^{p} H_i = H$; $t_{Bi} = t_{Li} + t_{Oi} + t_{ULi}$ and $t_{Oi} = CUT + pt + Cooling$ (see Fig. 1). Then:

$$BN_i = \frac{H_i}{(t_{L_i} + t_{O_i} + t_{UL_i})} \tag{3}$$

where H_i, t_{Li}, and t_{ULi} are constant. Then, BN_i is only dependent on t_{Oi}.

Differentiating BN_i,

$$dBN_i = \frac{-H_i \times dt_{O_i}}{(t_{L_i} + t_{O_i} + t_{UL_i})^2} \tag{4}$$

$i = 1,2,3, \ldots, p$ and $dt_{Oi} < 0$

$$100 \times \frac{dBN_i}{BN_i} = \frac{-100 \times dt_{O_i}}{(t_{L_i} + t_{O_i} + t_{UL_i})} \tag{5}$$

where Eq. (4) represents the change in the number of batches of product i as a function of a reduction in the operating process time of product i ($-dt_{Oi}$). In the same way, Eq. (5) represents the change in the number of batches as a percentage. Furthermore, the released retort-time (RTRT) per year due to the reduction in the operating process time per product i was:

$$RTRT_i = -BN_i \times dt_{Oi} \tag{6}$$

Additionally, because the number of processed packaged foods of product i was directly related to the number of batches of product i per year, the change in the number of processed packages of product i could be determined easily using Eq. (4) ($n_i \times dBN_i$), where n_i is the number of packages of product i processed per batch.

An indirect measure of energy savings per batch is the reduction in the operator process time (P_t). According to Barreiro et al. (1984), Bhowmik et al. (1985), and Simpson et al. (2006), energy consumption during the holding time or P_t represents approximately 30% or more of

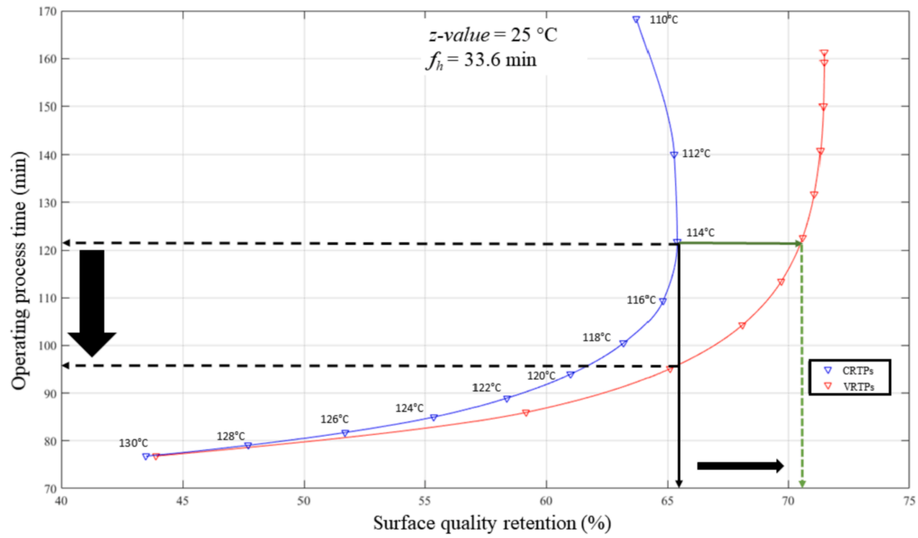

Fig. 2. Comparison of CRTPs and VRTPs for a specific product ($z = 25$ °C and $f_h = 33.6$ min).

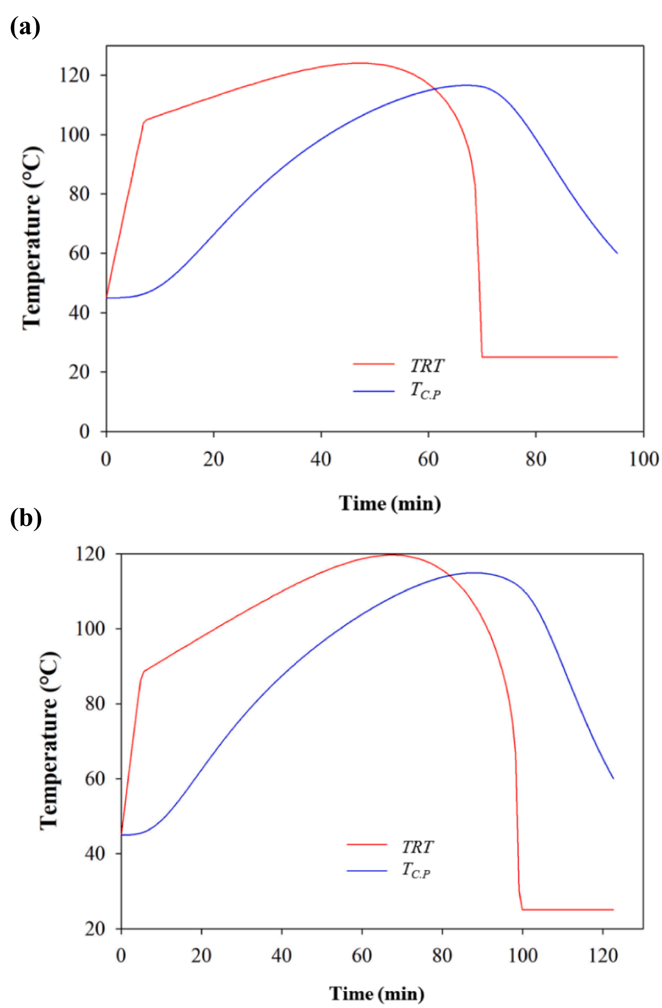

Fig. 3. VRTPs for (a) reduction of the operating time and b) maximizing quality retention.

Table 1
Surface quality retention obtained for different z-values and f_h values processed under CRTPs and VRTPs.

Surface quality retention (%)																				
z (°C)	f_h(min)																			
	20		34		57		74		94		115		138		162		189		218	
	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT	CRT	VRT
20	77	81	71	76	63	69	59	64	53	60	49	55	44	50	40	46	36	41	32	37
25	74	78	65	71	55	61	50	57	45	51	40	46	35	41	31	36	27	32	23	28
30	72	76	62	67	51	56	44	51	39	46	34	40	29	35	25	30	21	26	18	22
40	71	74	60	64	46	51	38	43	32	37	26	32	22	27	18	22	14	19	12	15
50	71	73	59	62	44	48	36	40	29	33	23	27	19	22	15	18	11	15	9	11
60	71	72	59	61	43	47	35	38	28	31	22	25	17	20	13	15	10	12	8	9

the energy consumed per batch, where the bleeder alone accounts for more than 25% of the energy consumed in the whole batch operation and the flow rate of the saturated steam through the bleeder depends on the pressure difference between the retort and the environment. Therefore, the consumed mass of steam in a given process depends directly on the operating pressure of the retort (to a corresponding TRT) and the operator process time (P_t).

The energy consumption during the processing time (processing temperature was obtained into the retort) could be roughly estimated by calculating the energy consumed by the bleeder. By carrying out a thermodynamic analysis of the bleeder and considering isentropic steam flow in the bleeder that obeys the ideal gas law, the following equation could be obtained:

$$\dot{m} = \frac{P_s \times A_b}{\sqrt{\frac{R \times T_{vs}}{\gamma}}} \left(\frac{P_{amb}}{P_s}\right) \sqrt{\left(\frac{2}{\gamma - 1}\right)\left(1 - \left(\frac{P_{amb}}{P_s}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right)} \tag{7}$$

The maximum velocity of an ideal gas in the throat of a simple converging nozzle is identical to the speed of sound under the throat conditions. The critical pressure is P_c (Balzhizer et al., 1972):

$$Pc = P_{amb} \times \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \tag{8}$$

Then, Eq. (7) will be valid for P_s in the following range:

$$\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \leq \frac{P_{amb}}{P_s} < 1 \tag{9}$$

If P_s is larger than P_c, substituting Eq. (8) into Eq. (7), the expression for the mass flow is as follows:

$$\dot{m} = \frac{P_s \times A_b}{\sqrt{\frac{R \times T_{vs}}{\gamma}}} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2 \times (\gamma - 1)}}; \quad \text{for} \quad \frac{P_{amb}}{P_s} < \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \tag{10}$$

Therefore, the energy released by the bleeder in CRTP and VRTP processes during P_t is as follows (Eqs. (11) and (12), respectively):

$$E_B = \dot{m} \times H_{vs} \times P_t \tag{11}$$

$$E_B^* = \int_0^{P_t^*} \dot{m}(t) \times H_{vs}(t) dt \tag{12}$$

where 0 corresponds to the time right after CUT.

Therefore, the estimated reduction in energy consumption (%) due to the implementation of the VRTP process instead of the CRTP process was estimated by the following expression:

$$\Delta E = 100 \times f_e \times \frac{\left(\dot{m} \times H_{vs} \times P_t - \int_0^{P_t^*} \dot{m}(t) \times H_{vs}(t) dt\right)}{\dot{m} \times H_{vs} \times P_t} \tag{13}$$

where the factor f_e was assumed to be 0.25 (Simpson et al., 2006).

As a first approximate calculation in a real processing plant for the change in the number of batches per year, the released hours of retort per year and the percentage reduction in energy consumption could be estimated using Eqs. (4), (6) and (13) with the necessary technical data from the plant (number of retorts, type of retorts, operation hours per year, etc.).

4. Results and discussion

According to Saura Consulting (2019), we have discussed the general and specific results of the model processing plant. Generally, the definitions of the products and retort operating conditions covered practically all expected possibilities in real processing plants for solid and semisolid foods.

As an example, Fig. 2 represents the expected results from the analysis to compare CRTP and VRTP processes for a wide range of z and f_h values. Fig. 2 depicts the results for the operating process time (y-axis) versus quality retention (x-axis) for different CRTP processes (blue line) and the optimum VRTP process (red line) considering a food with f_h = 33.6 min and quality dependence temperature z-value of 25 °C. As shown, our comparison of the optimum CRTP indicated a maximum quality retention of ~66% and an operating process time of ~121 min; in contrast, the optimum VRTP for the same quality retention level was capable of reducing the operating process time to ~96 min (~21% reduction). In addition, if the target was to improve quality retention with the same operating time, the optimum VRTP showed quality retention of ~71%. As discussed in Section 4.1, this improvement was generally not sufficient to be detected by consumers. As depicted in Fig. 3a and b, the optimum VRTP to reduce the operating process time while maintaining the optimum quality retention level of a CRTP and the optimum VRTP to maximize the quality retention level while maintaining the operating process time of the CRTP were easily programmable and manageable in real operations.

4.1. Maximization of product quality

Improvements in surface quality retention when VRTP was used instead of CRTP for different simulations considering quality z-values ranging from 20 °C to 60 °C and f_h values ranging from 20 to 218 min are summarized in Table 1. At first glance, the results showed that as the z-value increased, the improvement in surface quality retention using VRTPs was less significant, independent of the f_h value used. For example, the surface quality retention for a product with a f_h value of 94 min processed under VRTP conditions increased to 7% for a z-value of 20 °C and only 3% for a z-value of 60 min, similar to data reported by Noronha et al. (2007) for simulated VRTPs considering different food geometries. Thus, as food became more sensitive to process temperature, the expectation of improving surface quality retention using VRTP increased. A similar conclusion was obtained by Durance (1997) in a study focused on selection of a VRTP for the processing of canned salmon. In the referenced research, the authors evaluated a VRTP for

Table 2
Operating time obtained for different z-values and f_h values processed under CRTPs and VRTPs.

z (°C)	Operational time (min)																			
	f_h(min)																			
	20		34		57		74		94		115		138		162		189		218	
	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP	CRTP	VRTP
20	86	63	140	104	228	176	273	224	322	274	374	332	430	388	489	447	551	510	618	578
25	75	60	122	95	200	159	273	208	322	260	374	315	430	370	489	432	551	496	618	561
30	67	56	109	90	180	150	244	195	322	244	374	297	430	352	488	415	551	478	618	544
40	60	52	100	83	165	137	206	177	267	223	341	271	394	323	451	379	551	441	617	507
50	52	51	89	80	146	130	194	167	250	208	297	254	346	303	423	357	481	415	541	475
60	44	44	85	78	139	126	184	162	226	200	282	243	331	290	381	339	457	393	517	450

Table 3
Impact of implementing VRTPs on a model processing plant: change in the number of batches per year, released hours per retort per year, and reduction of energy consumption per batch (%).

	Product 1	Product 2	Product 3
H (h/year)	2690	2220	2220
t_B (h) for *CRTPs*	4.72 (4.55)[a]	3.5 (3.33)[a]	2.2 (2.03)[a]
t_B (h) for *VRTPs*	3.63 (3.46)[a]	2.82 (2.65)[a]	1.75 (1.58)[a]
BN	570	634	1010
dBN	131	124	206
$100 \times dBN_B/BN$ (%)	23	19.5	20.4
RRT (h)	618	433	455
ΔE (%)	8.9	8.3	9.2

[a] Numbers in parenthesis represent the operating process time (t_{Oi}).

processing of canned salmon through simulation, showing that the thiamine content was improved from 16.8% (for CRTP) to 19.6% when VRTP was applied (i.e., a change of 3% in thiamine retention). Additionally, surface quality changes were more sensitive to temperature changes for small z-values.

Similar results were observed by Bland et al. (2018) in texture measurements of frozen catfish fillets. For example, the chewiness metric showed a value of 68.61 ± 16.86, representing a variability of 20%, and the hardness metric showed a value of 200.34 ± 42.19, representing a variability of 20%. Clearly, considering the wide variability of this type of measurement, a 7% quality improvement could be considered part of the measurement error for canned food quality parameters.

Based on the capacity of sensorial panels, an improvement of 7% is not expected to be detectable. For example, Majumdar et al. (2017) observed such results in a study of the effects of the F_0 value on the textural and sensory characteristics of freshwater prawns that were thermally processed using CRTP and retortable pouches. Their results showed that as the F_0 value increased from 6 to 8, the processing time increased from 53 to 63 min, modifying the hardness from 0.68 to 0.56 kgf (i.e., a reduction of 17%) and the chewiness from 0.28 to 0.11 kgf · mm (i.e., a reduction of 60%). However, when quality was measured by sensory evaluation, the chewiness values did not show significant differences, similar to toughness and fibrosity values, and the overall acceptability was not affected by the processing time. Finally, Trejo-Araya et al. (2009) evaluated the effects of high-pressure processing (HPP) on the sensory perception and quality attributes of carrots compared with raw, sous-vide, and cooked carrots. For HPP and sous-vide, the juiciness was higher for HPP carrots than for sous-vide carrots by instrument analysis, but the difference was not significant for perception of juiciness. These results suggested that the main advantage of VRTP was a significant reduction in processing time and that the maximum quality improvement was only 7%, depending on the z-value. Additionally, this time reduction enabled an increase in productivity and facilitated the production of food with reduced contamination, as previously discussed (Zanoni et al., 2003).

4.2. Operating process time reduction (-dt_O) and percentage reduction of energy consumption (ΔE)

Table 2 shows the operating process time obtained for different z-values and f_h values processed under CRTP and VRTP. For a z-value of 20 °C, the reduction in operating process time (as a percentage) always decreased as f_h increased. In contrast, for a z-value of 60 °C, the reduction in operating process time always increased as f_h increased, except at low z-value and low f_h values (~13% reduction compared with ~25%). Importantly, scientific articles on this specific subject, i.e., processing time reduction, are scarce; practically all published articles have focused on optimizing quality rather than reducing the operating process time, and there are few references to energy consumption and scheduling (Bhowmik et al., 1985; Almonacid-Merino et al., 1993;

Simpson et al., 2003; Simpson and Abakarov, 2013).

4.3. Quantifying the impact of implementing VRTPs on a model processing plant

The calculations for Table 3 were performed using the equations developed in Section 2.4 and the data provided in Section 2.5 to quantitatively measure the impact of reduction of the operating time (definition of a model processing plant). Although the selected products were quite different ($34 \leq f_h \leq 75$, and z-value = 25 °C), the reduction in energy consumption was similar and significant in the order of ~9% (Eq. 14).

As shown in Table 3, by implementing VRTPs, products 1, 2, and 3 could be processed at 5984 h/year instead of 7400 h/year for CRTP processing, resulting in the release of 1506 h/year of operating process time (~20%) and with an expected reduction in energy consumption of ~9%. This result can have several positive consequences for the processing plant, in addition to an increase in the plant production capacity of products 1, 2, and 3, e.g., the potential incorporation of new products and increased flexibility by redefining the allocation problem due to temporal variations in the availability of raw materials (reformulating the scheduling) (Almonacid-Merino et al., 1993). These results generated from a "real" cannery confirmed the potential advantage of VRTPs compared with CRTP in several cases.

The above results obtained in Sections 4.1, 4.2, and 4.3 demonstrated a clear tendency and suggested that VRTPs should be explored in a real processing plant.

5. Conclusions

Although VRTPs can improve the quality retention of a wide range of products, the improvements were not significant or detectable by consumers and may therefore not be sufficient to change established CRTP processes.

The results provided a preliminary guide for processors to discover real opportunities in the implementation of VRTPs in terms of reducing both the operating process time and energy consumption. These advantages were found in the range of low f_h values and more sensitive quality factors (low z-value). Processors could further explore modification of current product shapes to reduce f_h, decrease the processing time, and provide more opportunities to VRTPs.

In general terms, we concluded that VRTPs could be advantageous in comparison with CRTPs, specifically for increasing the productivity of plants and reducing energy consumption without sacrificing product quality.

Author contribution section

Ricardo Simpson: Supervision, Conceptualization, Writing - Original Draft, Formal analysis, Funding acquisition. Diego Jiménez: Data Curation, Software. Sergio Almonacid: Writing - Review & Editing, Formal analysis. Helena Nuñez: Investigation, Writing - Review & Editing. Marlene Pinto: Investigation, Writing - Review & Editing. Cristian Ramírez: Data Curation, Writing - Review & Editing, Formal analysis, Funding acquisition. Oscar Vega-Castro: Investigation, Writing - Review & Editing. Lida Fuentes: Investigation, Writing - Review & Editing. Alejandro Angulo: Data Curation, Software, Funding acquisition.

Acknowledgments

We are grateful for the financial support provided by CONICYT through FONDECYT project number 1191280 (Cristian Ramírez), project number 1181270 (Ricardo Simpson), and project number 11170229 and the Basal Project FB0008 "Advanced Center for Electrical and Electronic Engineering" (Alejandro Angulo). In addition, we thank Carlos Sanchez from Saura Consulting for his contribution to the processing plant data.

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Glossary

A_b: bleeder area
CRTPs: constant retort temperature profiles
CUT: come-up time (time measured from the beginning of the process until the retort reaches the processing temperature [TRT])
D_r: decimal reduction time at a reference temperature
E_B: energy released by the bleeder during P_t in a CRTP
E^*_B: energy released by the bleeder during P_t in a VRTP
ΔE: percentage reduction in the energy consumption due to the implementation of VRTPs
F_o: lethality for *Clostridium botulinum* spores obtained at 121.1 °C
F_r: required lethality value
f_h: heating rate factors (related to the slope of the semi-log heat penetration curve)
f_e: factor to relate the energy consumed during P_t to the total energy of the process
H: number of operating hours of the plant per year
H_{vs}: enthalpy of saturated steam per unit mass
$\dot{m}$: vapor mass flow rate
BN: number of batches per year
n_i: number of packages of product *i* processed per batch
P_{amb}: ambient pressure
P_c: critical pressure
P_s: saturation pressure of water
P_t: operator process time for a CRTP (time measured from the time when the retort reaches the processing temperature [TRT] until the time when the steam is turned off)
P_t^*: operator process time for VRTPs (time measured from the time when the retort reaches the processing temperature [TRT(t)] until the time when the steam is turned off)
R: ideal gas constant 8.315 (Pa m^3 / kmol °K); (J / kmol K)
RRT: released retort time
T: temperature
$T_{C.P}$: temperature at the coldest point
IT: initial temperature of the food
TRT: retort processing temperature
T_w: cooling temperature
T_r: reference temperature, 121.1 °C
T_S: surface temperature of food
T_{ws}: saturation temperature of water
t: time
t_B: batch process time
t_L: time to load the retort
t_O: operating process time (CUT + P_t + cooling)
t_{UL}: time to unload the retort
VRTPs: variable retort temperature profiles
z-value: slope index of the thermal death time curve

Greek letters and sub-indexes

b: bleeder
γ: ratio of the specific heat at a constant pressure to the specific heat at constant volume (dimensionless)
i: product *i*