CRITICAL EVALUATION OF RESTRICTIONS USED TO OPTIMIZE STERILIZATION PROCESSING CONDITIONS

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A computer program, using a finite differences method, was developed to model the heat sterilization for cylindrical packaged conduction heating foods. This program was introduced into an optimization routine to calculate optimum processing conditions, maximizing the surface or the volume average quality, using different restrictions.
Depending on the pack dimensions and the heating rate of the product the least-lethality point is at the geometric center or along the radius or the vertical axis. Therefore, sterility values specified at the center and at the least-lethality point were used as sterility criteria for calculating optimum conditions. The effect of an integrated sterility value constraint on optimal temperature was also investigated.
Depending on the product thermal properties, processing conditions and target lethality the optimum temperature calculated using the sterility value at the center as restriction can overestimate the correct value by as much as 4°C.

INTRODUCTION

Container heat sterilization of conduction heating foods is based on the application of suitable time-temperature profiles to obtain commercially sterile products (Richardson *et.al.*, 1988). An integrated sterility value or a sterility value at a single point are normally used as constraints (Stumbo, 1973). Silva *et. al.* (1993) stressed that the sterility value at the least-lethality point assures a minimum sterility in all points of the food, therefore this is the most adequate criterion.

The geometric center is usually considered the least-lethality point for a cylindrical package (Ball & Olson, 1957). This assumption is correct if only the heating phase is included in the calculation of the sterility value. Teixeira *et. al.* (1969a) were the first to discuss the localization of this point. They concluded that the least-lethality point is not always at the center and that the correct position depends on the container geometry and processing conditions. If the cooling phase is also taken into consideration for the sterility value calculation, the least-lethality point appears along the radius or the vertical axis, depending on the half-height to radius ratio (Flambert & Deltour, 1972). The Flambert & Deltour (1972) research assumed no surface resistance to heat transfer. Recently Silva & Korczak (1994) presented a similar study for the existence of surface resistance to heat transfer. They concluded that the processing temperature, target sterility and the kinetic parameters for the microorganisms do not significantly affect the location of the least-lethality point. However, the package dimensions and the heating rate of the product (this variable also takes into consideration the surface heat transfer coefficient) have a great influence on the least-lethality point position.

Several research works on the theoretical calculation of optimal sterilization temperatures have been presented in the literature (Teixeira *et. al.*, 1969b, 1975; Thijssen *et.al.*, 1978; Saguy & Karel, 1979; Ohlsson, 1980a,b; Thijssen and Kochen, 1980; Nadkarni & Hatton, 1985; Banga *et.al.*, 1991). Silva *et. al.* (1993) concluded, from a review on this research field, that the two optimization restrictions most commonly used are a target integrated sterility value, as defined by Stumbo (1973), or a sterility value specified at the geometric center of the cylindrical container. As it was explained above, neither of these two constraints is the most adequate. A target sterility value specified at the least-lethality

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point is the most correct criterion, however there is no research work on the calculation of optimal sterilization temperatures using it.

Therefore the purpose of this research is a critical evaluation of the restrictions normally used to optimize sterilization processing conditions. Optimal temperatures maximizing the surface or the volume average quality retention will be calculated using the three different criteria. The differences between optimal temperatures will be studied as a function of food properties, processing conditions and target lethality.

THEORETICAL CONSIDERATIONS

To optimize a sterilization process it is necessary to identify the design variables and requirements and define the objective function (Norback, 1980).

The design variable is the variable that can be controlled and is usually the heating medium temperature profile.

The major requirement, or restriction, for optimizing heat sterilization processes is the target lethality needed to obtain a safe product (Holdsworth, 1985). In general there are two approaches to assess the impact of a process: i) a sterility value at the geometric center (F_C) or ii) an integrated sterility value (F_S) representing the volume average survival of microorganisms (Stumbo, 1973):

$$F_c = \int_0^{t_p} 10^{(T_c - T_{refm}) / z_m}\, dt \qquad (1)$$

$$(M / M_o)_c = 10^{- F_c / D_{refm}} \qquad (2)$$

or

$$ASM = \frac{1}{V_T} \int_0^{V_T} 10^{(- F(V) / D_{refm})}\, dV \qquad (3)$$

$$F_S = D_{refm} \log(ASM) \qquad (4)$$

The target microorganism is usually *Clostridium botulinum*, because it is one of the most lethal and more thermal resistant. The mean kinetic parameters for its inactivation are a z-value of 10°C and a $D_{121.1°C}$ value of 0.21 min (Pflug & Odlaug, 1978).
Another criterion, which is a target sterility value at the least-lethality position (F_L), has been proposed by Silva & Korczak (1994):

$$F_L = \int_0^{t_p} 10^{(T_L - T_{refm}) / z_m}\, dt \qquad (5)$$

$$(M / M_o)_L = 10^{- F_L / D_{refm}} \qquad (6)$$

A target sterility value at the least-lethality point assures a minimum sterility in all points of the food (Silva *et. al.*, 1993).

The most common objective function used to optimize sterilization processing conditions is the maximization of the final quality retention. Depending on the quality factor under consideration, the optimization can be done in terms of maximizing surface or volume average quality. The first concept is of interest when optimizing appearance and aroma, while the second one is a more suitable indicator for taste, consistency or nutrient retention (Ohlsson, 1980a). The correct mathematical expression of these two objective functions was critically evaluated by (Silva *et. al.*, 1992):

$$C_i = \int_0^{t_p} 10^{(T_i - T_{refq})/z_q}\, dt \tag{7}$$

$$(N / N_o)_{surf} = 10^{-C_{surf} / D_{refq}} \tag{8}$$

or

$$(N / N_o)_{ave} = \frac{1}{V_T} \int_0^{V_T} 10^{\left[-\frac{1}{D_{refq}} \int_0^{t_p} 10^{(T - T_{refq})/z_q}\, dt\right]} dV \tag{9}$$

MATERIALS AND METHODS

A computer program similar to the one presented by Silva *et.al.* (1994) was developed to calculate the processing time, corresponding to a given sterilization temperature, for conduction heating products packaged in cylindrical containers. Three different types of restrictions (Equations 1, 3 and 5), as described in the theoretical considerations, were used. The cooling phase was taken into consideration in the lethality calculation. An explicit finite differences numerical method with non-capacitance surface nodes (Chau & Snyder, 1988) was used to describe the heat transfer into the food.

The model assumptions were: i) first order inactivation kinetics and expressed as a decimal reduction time D_{ref} and a z - value, ii) heat transfer into the food was by pure conduction, iii) the food product was homogeneous and isotropic, iv) initial temperature of the food (T_o) was uniform, v) the heating medium time-temperature profile was a step function, with zero come-up-time, followed by instantaneous constant cooling temperature and vi) a constant and uniform surface overall heat transfer coefficient. This overall coefficient accounted for the packaging material (e.g. plastic) and heating medium thermal resistance.

To calculate optimal temperatures, the computer program was integrated in an optimization routine, using Davis, Swann and Campey method (Saguy, 1983), for minimum surface cook value or maximum volume average quality retention. Optimum holding temperature, T_h, was calculated to within 0.01°C.

RESULTS AND DISCUSSION

Study of the least-lethality location

The least-lethality point position for a conduction heating product packaged in a finite cylinder container was studied as a function of different variables such as package dimensions, heating rate, surface heat transfer coefficient, heating medium temperature, target lethality and kinetic parameters for the microorganisms thermal inactivation kinetics (Silva & Korczak, 1994). The heating medium temperature, target lethality and kinetic parameters for the microorganisms thermal inactivation have no relevant effect on the least-lethality point location. The most important variables to determine this position are the package dimensions and the heating rate of the product (which takes into consideration the overall surface heat transfer coefficient).

Table 1 presents the location of the least-lethality point (see Figure 1) as a function of dimensions and heating rate of the product when the surface heat transfer coefficient is equal to 10 $W/m^2/K$. When the half-height to radius ratio is approximately equal to 0.9 the least-lethality point position is at the center. This happens also when this ratio is very small (smaller than 0.1) or very large (larger than 4.0). When the half-height is smaller than the radius (0.1<H/R<0.9) the least-lethality point is located along the vertical axis. The least-lethality point is located along the radius (0.9<H/R<4.0) when the radius is larger than the half-height. The least-lethality point is closer to the geometric center for slower heating products (larger f_h), which corresponds to products with lower thermal diffusivity and/or larger dimensions.

A similar work, considering infinite surface heat transfer coefficient, was also carried out by Flambert & Deltour (1972). Under experimental conditions with no surface resistance to heat transfer the only variable affecting the position of the least-lethality point is the package dimensions, and the heating rate of the product has no significant effect.

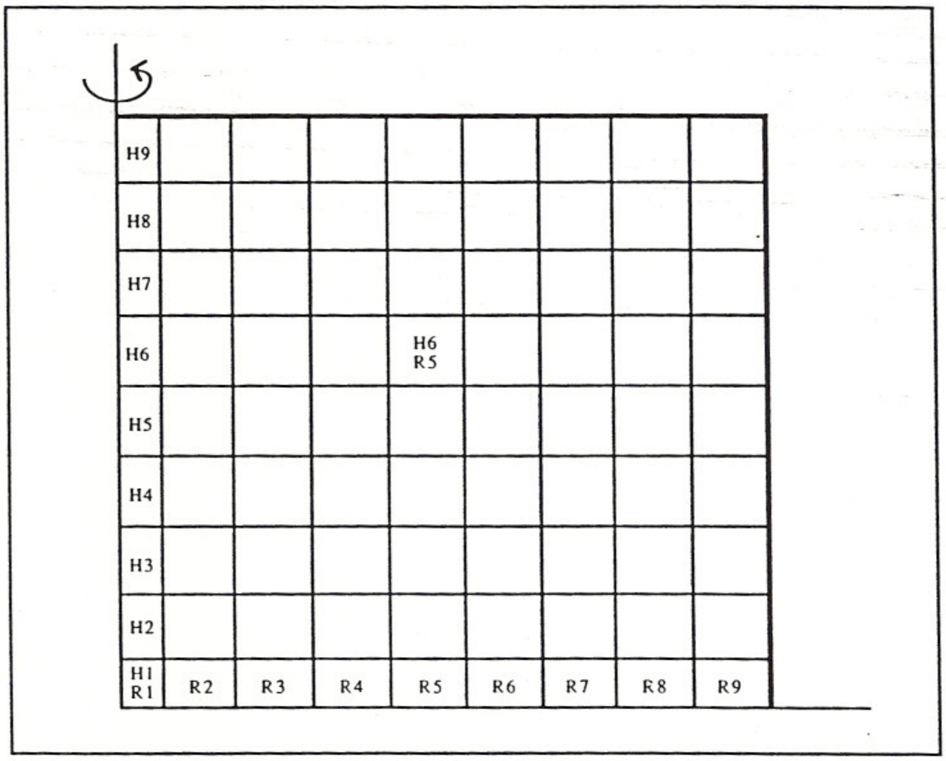

Figure 1: *Geometrical breakdown of a cylindrical container and identification of the volume elements.*

Effect of different restrictions on optimal sterilization temperatures

Optimal sterilization temperatures, maximizing the volume average or the surface quality, using as restriction a target sterility value specified at the geometric center or at the least-lethality point were calculated for 14 case studies (Table 2). Different surface heat transfer coefficients, heating rates of the product, package dimensions, target sterilities and kinetic parameters for the quality attribute were taken into consideration. These cases were based on the case study presented by Teixeira *et.al.* (1969b).

When there is no surface resistance to heat transfer the difference between optimal temperatures, using the two constraints, (Table 2) is negligible. However, when a finite surface heat transfer coefficient exists, the difference ranges from 0.5 to 3.6°C. This difference becomes more significant for case studies with larger z_q values. The difference between the two optimal temperatures, using as restriction a target sterility value at the geometric center or at the least-lethality point, for maximizing surface quality is smaller than the corresponding difference of temperatures for maximizing volume average quality.

Table 1: Location of the least-lethality point, for a finite cylindrical container (see Figure 1), as a function of dimensions and heating rate of the product. The surface heat transfer coefficient is equal to 10 W/m^2/K. The target lethality was an ASM=1x10^{-12}.

f_h (min)	H/R																								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.85	0.9	0.95	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.5	3.0	3.5	4.0
30	H9	H10	H10	H9,H10	H9,H10	H8-H10	H7,H8	H6,H7	H5-R2	H4-R5	R3,R4	R4,R5	R4-R6	R6	R5-R7	R6	R6,R7	R6,R7	R6,R7	R6,R7	R6,R7	R6,R7	R6,R7	R5,R7	R5,R7	R5,R7
70	H5,H6	H7	H8	H8	H7,H8	H7	H7	H5,H6	H4	H2-R3	R3,R4	R4	R5	R5	R5	R5	R5,R6	R5,R6	R5,R6	R5,R6	R5,R6	R5	R5	R5	R4,R5	R4
100	H4	H6	H7	H7	H7	H7	H6	H5,H6	H3-H5	H2-R3	R3	R4	R4,R5	R5	R5	R5	R5	R5	R5	R5	R5	R5	R4,R5	R4	R4	R3,R4
150	H2,H3	H5,H6	H6	H6,H7	H6,H7	H6	H6	H5	H4	H1-R2	R3	R4	R4	R4,R5	R5	R5	R5	R5	R5	R5	R4,R5	R4	R4	R4	R3	R3
250	H1,H2	H4	H5	H6	H6	H6	H6	H5	H4	H1	R3	R3	R4	R4	R4	R4	R4	R4	R4	R4	R4	R4	R3	R3	R2	R1,R2
400	H1	H3	H5	H5	H5	H5	H5	H5	H4	H1	R2,R3	R3	R4	R4	R4	R4	R4	R4	R4	R4	R3	R3	R3	R2	R1,R2	R1
600	H1	H3	H4	H5	H5	H5	H5	H5	H4	H1	R2	R3	R3	R4	R4	R4	R4	R3	R3	R3	R3	R3	R2	R1,R2	R1	R1
900	H1	H2	H3	H4	H5	H5	H5	H4	H4	H1	R2	R3	R3	R3	R3	R3	R3	R3	R3	R3	R2,R3	R2	R2	R1	R1	R1

Table 2: Optimal sterilization temperatures as a function of different variables, for maximizing volume average or surface quality, using as restriction a sterility value at the geometric center or at the least-lethality point.

Case No.	h (W/m^2/K)	$f_h$$^{(2)}$ (min)	R (m)	H (m)	H/R	Fo (min)	D_{refq} (min)	z_q (°C)	L$^{(1)}$	$T^{ave}_{op,c}$ (°C)	$T^{ave}_{op,L}$ (°C)	$T^{ave}_{op,c}$ - $T^{ave}_{op,L}$ (°C)	$T^{surf}_{op,c}$ (°C)	$T^{surf}_{op,L}$ (°C)	$T^{surf}_{op,c}$ - $T^{surf}_{op,L}$ (°C)
1	∞	60	0.04365	0.05795	1.33	11.34	202.0	33.33	R2	124.90	124.81	0.09	117.57	117.40	0.17
2	∞	50	0.0490	0.3430	0.7	3.0	202.0	16.7	H3	109.35	109.03	0.32	105.82	105.81	0.01
3	∞	100	0.0690	0.0483	0.7	3.0	202.0	16.7	H3	106.45	106.38	0.07	102.86	102.79	0.07
4	∞	200	0.0980	0.0686	0.7	3.0	202.0	16.7	H3	103.63	103.34	0.29	99.93	100.03	-0.10
5	∞	100	0.0690	0.0483	0.7	3.0	202.0	20.0	H3	108.55	108.73	-0.18	104.76	104.69	0.07
6	∞	100	0.0690	0.0483	0.7	3.0	202.0	30.0	H3	114.90	114.60	0.30	108.94	108.79	0.15
7	∞	100	0.0690	0.0483	0.7	3.0	202.0	35.0	H3	118.01	117.14	0.87	110.66	110.51	0.15
8	100	129	0.0840	0.0420	0.5	3.0	202.0	30.0	H3	116.42	115.91	0.51	110.56	110.56	0
9	100	129	0.0840	0.0420	0.5	3.0	202.0	45.0	H3	126.89	126.31	0.58	117.14	116.35	0.79
10	100	129	0.0840	0.0420	0.5	15.0	202.0	45.0	H3	134.39	132.93	1.46	123.52	123.22	0.30
11	10	400	0.0840	0.0420	0.5	3.0	202.0	16.7	H5	114.26	113.00	1.26	108.90	108.26	0.64
12	10	400	0.0840	0.0420	0.5	15.0	202.0	16.7	H5	121.44	120.45	0.99	115.93	115.20	0.73
13	10	400	0.0840	0.0420	0.5	3.0	202.0	20.0	H5	120.88	119.00	1.88	114.26	112.93	1.33
14	10	400	0.0840	0.0420	0.5	3.0	202.0	25.0	H5	131.04	127.41	3.63	121.14	120.07	1.07

(1) least-lethality point position

(2) thermal diffusivity = 1.7 x 10^{-7} m^2/s
thermal conductivity = 0.66 W/m/K

To compare optimal temperatures using as a restriction an integrated sterility value (Equation 3) or a sterility value specified at the least-lethality point, the two criteria values must be equivalent in terms of microorganism lethality. A few case studies were carried out and under these conditions there is not a significant difference between optimal temperatures.

CONCLUSIONS

The most important variables affecting the position of the least-lethality point are the package dimensions, the heating rate of the product and the surface heat transfer coefficient. For $0.1<H/R<0.9$ the least-lethality point is located along the vertical axis, and for $0.9<H/R<4.0$ is located along the radius. When this ratio is smaller than 0.1, larger than 4.0 or equal to 0.9 the least-lethality point is at the geometric center.

A target sterility value specified at the least-lethality point is the most adequate optimization criterion to use. Depending on the product thermal properties, processing conditions and target lethality the optimum sterilization temperature calculated using the sterility value specified at the center as restriction can overestimate the correct value by as much as 4°C.

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NOMENCLATURE

ASM	mass average survival of microorganisms
C	cook value (min)
D	decimal reduction (min)
f_h	heat penetration parameter - slope factor of a heating curve (min)
F	sterility value (min)
Fo	sterility value at reference temperature of 121.1°C and z-value of 10°C (min)
F(V)	sterility value in the volume element dV (min)
h	surface heat transfer coefficient ($W/m^2/K$)
H	half-height of the container (m)
(M/M_o)	survival of microorganisms
(N/N_o)	quality retention
R	radius of the container (m)
t	time (min)
T	temperature (°C)
V	volume (m^3)
z	z-value (°C)

Superscripts

ave	volume average
surf	at the surface

Subscripts

ave	volume average
c	at the geometric center
h	holding
i	at position i
L	at the least-lethality point
m	for microorganisms
o	initial
op	optimal

p	total processing
q	for quality factor
ref	reference temperature
refm	reference for microorganisms
refq	reference for quality factor
S	integrated value
surf	at the surface
T	total