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Computer Simulation of Thermal Processing for Food

Rudi Radrigán Ewoldt

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1. Introduction

This chapter presents some mathematical tools that will allow a computer to make decisions in various thermal processes such as thermal conduction and diffusion applied to the preparation of processed foods and their study in the particular case of Canning.

The purpose of this chapter is to introduce the reader to the use and determination of heat transfer properties allowing a real approximation to the phenomenon under study.

Foods are complex systems that exhibit anisotropic behavior, which hinders real modeling of the phenomena that occurs within them or their interaction with the environment.

After several years of study of thermal phenomena in foods, we have identified some routes and mathematical algorithms, which are modeled on personal computers with Intel architecture. We have also corroborated the results of these models with real data of canning, pasteurizing, cooking and freezing experiments, showing less than 3% deviation between theoretical and real value.

Example Case:

A computer-aided engineering model is described. This model is capable of simulating the thermal sterilization of canned foods. The use of the model to find optimum processing conditions, physical properties and container geometry is reported.

This example describes the use of thermal properties in the development of computer models that simulate conduction heat transfer in canned foods. These models can be used to mix physical and thermal properties of the material under study for the prediction of the product temperature and processing time, considering different geometries from the metallic containers for foods and conditions of operation in pressure and temperature of the steam. The results obtained in the simulations are compared with the real processes of

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canning in the pilot plant. A second advantage is that the retort's temperature need not to be held constant, but can vary in any prescribed manner throughout the process and the model will predict the correct product temperature history at the can's center. The use of these models has become invaluable for simulating the process conditions in sterilizer system. Another important application of these models is the rapid evaluation of an unscheduled process deviation, such as when an unexpected drop in retort temperature occurs during the process. The model can quickly predict the product center temperature history in response to such a deviation, and calculate the delivered sterilizing value (Fo) comparison with the target value specified for the product. Specific objectives of this chapter are to briefly describe how the model was developed and to use it in process optimization and on-line computer control applications.

2. Principles of thermal processing

Generally, thermal processing is not meant to destroy all microoganisms in a packaged product. Such a process would result in low product quality due to the long heating required. Instead, the pathogenic microorganisms in a hermetically sealed container are destroyed an enviroment is created inside the package which does not support the growth of spoilage type microoganisms. In order to determine the extent of heat treatment, several factors must be known [1], (1) type ab heat resistance of the target microorganisms or enzime present in the food; (2) pH of the food; (3)heating conditions; (4) thermo-physical properties of the food and the container shape and size; and (5) storage conditions following the process.

Foods have different microoganisms and/or enzimes that the thermal process is designed to destroy. In orden to determine the type of microoganims on which the process should be based several factors must be considered. With reference to thermal processing, the most important distinction in pH classication is the dividing line between acid and low acid food. Most laboratories deading with thermal processing devote special attention to *Clostridium botulinum* which is a highly heat resistance, rod-shaped, spore-forming, anaerobic pathogen that produce botulism toxin. It has been generally accepted than C.botulinum does not grow and produce toxins below a pH of 4.6. Hence, pH as 4.5 is taken the dividing line between the low acid and acid foods. There are other microorganisms, for example *Bacillus thermoacidurans*, *B. stearotermophilus*, and *C.thermosaccolyticum*, which are more heat resistance than *C.butulinum*. These are generally thermophilic in nature (50-55ºC), and hence are not of much concern if the processed cans are stored at temperatures below 30ºC.

The phrase "minimal thermal process" was introduced by tha US Food and Drugs Administrations in 1977 and defined as "the application of heat to food, either before or after sealing in a hermetically sealed container, for a period of time and at temperature acientifically determined to be adequate to ensure the destruction of microorganims of public health concern"[2].

The C.butulinum is a microorganims of public health low-acid foods and due to this high-heat resistance, temperatures of 115-125ºC are commonly employed for processing these foods.With reference to the acid and medium-acid foods, the process is usuallly based on the heat-resistant spoilage-type vegetative bacteria or enzyme which are easily destroyed even at temperatures below 100ºC. The thermal processes for such foods are therfore normally carried out in boiling water.

3. Thermal resistance of microoganimsms

The thermal resistance of microorganisms (vegetative cells or spores) is dependent upon a number of factors: 1) the growth characteristics of the microorganisms, 2) the nature of the food in which the microorganisms are heated, and 3) the kind of food in which the heated microorganisms are allowed to grow. Because of the variability of any biological entity, thermobacteriology is a highly complex science, and variations in any of these factors can affect the heat resistance of microorganisms.

3.1. Thermal death time (TDT) tests

The amount of heat required to destroy microorganisms in a product can be determined through thermal death time (TDT) tests. TDT tests are conducted by thermobacteriologists in a laboratory. Very few food processing establishments have the facilities to conduct TDT tests on-site.

The instruments and equipment used for TDT tests include TDT retorts, tubes, and/or cans; three-neck flask, oil baths, sealed plastic pouches, and/or capillary tubes. The equipment and instrumentation used will depend on the type of product being tested – whether it is low-acid, acidified, thick puree, solid or a liquid. TDT tests involve heating a known amount of microorganisms in a buffer solution or food at several temperatures and for several time intervals at each temperature. The results from the TDT tests are used to calculate D- and z-values. These values are used to define the heat resistance of the microorganisms of concern.

3.2. Determination of D- and z-values

In conducting TDT tests, the thermal characteristics (D- and z-values) of the microorganisms will be determined. The D-value is defined as the time at a particular temperature required to reduce a known number of microorganisms by 90% or to result in a 1-log reduction. This is also termed the decimal reduction time because exposure for this length of time decreases the population by 90%, thus shifting the decimal point in the number of microorganisms remaining one place to the left. For example, if you had 100,000 spores and if exposing them to a temperature of 240°F for 3 minutes reduced the count to 10,000 spores, the $D_{240°F}$ would be 3 minutes.

The D-value decreases as the temperature increases, since it takes less time to destroy the microorganisms at the higher temperature. By determining the D- values at various temperatures, a z-value can be determined from the slope of the line that results from plotting the log of D-values versus temperature (Figure 1a). The z-value, indicative of the change in the death rate based on temperature, is the number of degrees between a 10-fold changes (1 log cycle) in an organism's resistance (Figure 1b). As an example, suppose that z = 18°F and $D_{232°F}$ = 3 minutes. The $D_{250°F}$ would be 0.3 minutes. (Because 232°F + 18°F = 250°F and 3 minutes / 10 = 0.3 minutes.) Both D- and z-values are indirectly used to establish processing conditions.

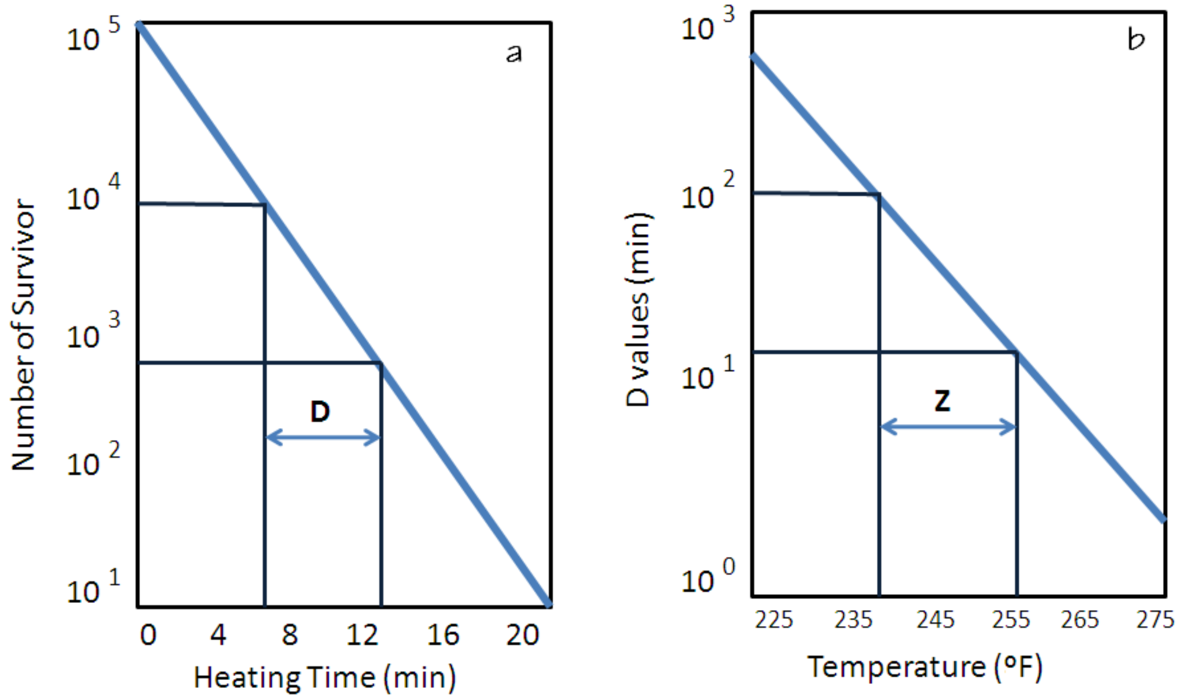

Figure 1. (A) Typical survivor curve. (B) A typical thermal resistance curve.

In other words the D value represents a heating time that causes 90% destruction of the existing microbial population. Graphically, this represents the time between which the survival curve passes through one logarithmic cycle (figure 1). Mathematically

$$D = (t_2 - t_1)/[log(a) - log(b)] \tag{1}$$

Where a and b represent the survivor counts following heating for t_1 and t_2 min, respectively.

Using regression techniques, z value can be obtained as the negative reciprocal slope of the thermal resistance curve (regression of log D values vs. temperature). Mathematically

$$Z = (T_2 - T_1)/[log(D_1) - log(D_2)] \tag{2}$$

Where D_1 and D_2 are D values at T_1 and T_2 respectively. The D values at any give temperature can be obtained from a modified formulation of the above equation using a reference D value (D_0 at a reference temperature, T_0 usually 250ºF for thermal sterilization).

$$D = D_o 10^{(T_o - T)/z} \tag{3}$$

Equations 3 also can be written with reference to TDT values and z values can be obtained from:

$$Z = (T_2 - T_1)/[log(TDT_1) - log(TDT_2)] \quad (4)$$

Where TDT_1 and TDT_2 are TDT values at T_1 and T_2 respectively.

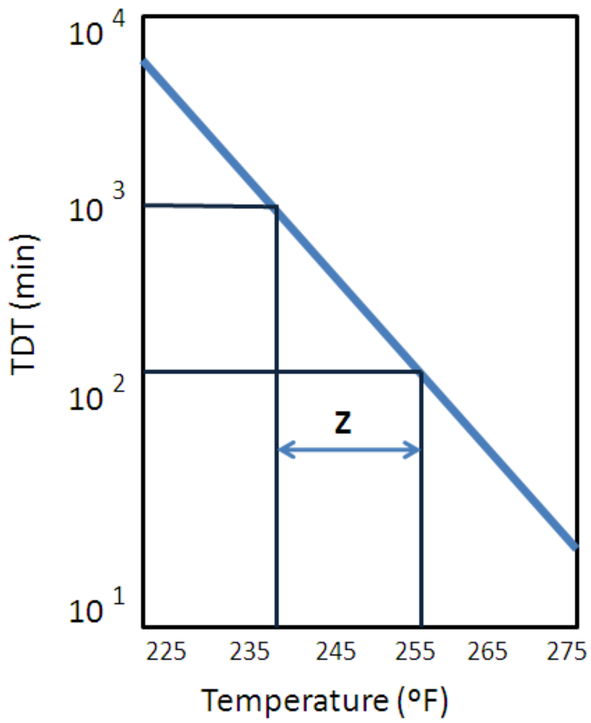

Figure 2. A typical TDT curve

Graphically, as with the D value approach, the z values can be obtained as the negative reciprocal slope of log TDT vs. temperature curve (Figure 2). When using this approach, it is advisable to plot the longest survivor time and shortest destruction time (on logarithmic scale) vs. temperature (linear scale). The regression line could be necessary to make sure that the TDT curve is above all survivor data point. The TDT curve should be parallel to the general trend of the survival and destruction points.

3.3. Lethality concept

Lethality (F value) is a measure of the treatment or sterilization processes. In order to compare the relative sterilization capacities of heat processes, a unit of lethality needs to be established. For convenience, this is defined as an equivalent heating of 1 min at a reference temperature, which is usually 250ºF (121.1ºC) for sterilization processes. Thus, the F value would represent a certain multiple or fraction of D values depending on the type of microorganisms; therefore, a relationship like Equation 4 also holds with reference to F value.

$$F_o = F10^{(T-T_o)/z} \quad (5)$$

The F_o in this case will be the F value at the reference temperature (T_o).A reference TDT curve is defines as curve parallel to the real TDT or thermal resistance curve.

4. pH of the food

Almost every food, with the exception of white eggs and soda crackers, has a pH value of less than 7. Foods can be broadly categorized on the basis of their pH as high acid, acid, medium acid or low acid. Examples of each category include:

high acid (3.7) : apples, lemons, raspberries
acid (3.7 to 4.6) : oranges, olives, tomatoes (some)
medium acid (4.6 to 5.3) : bread, cheese, carrots
low acid (over 5.3) : meat, fish, most vegetables

Most micro-organisms grow best in pH range of 6.5 to 7.5. Yeasts and moulds are capable of growing over a much broader pH range than bacteria. Few pathogens will grow below pH 4.0, such as this valuable information helps in determination of food stability with respect to microbial spoilage.[3]

5. Heating conditions

The heat transfer rate of a solid to a fluid can be expressed by Newton's Law of cooling:

$$Q = hA_s\Delta T \tag{6}$$

Where Q is the heat flow rate (J/s), A_s is the surface area (m^2), ΔT is the temperature gradient (ºC) and the proportional constant h is the heat transfer coefficient or surface heat conductance (W/m^2K). The surface heat conductance depends on the thermophysical properties of fluid and solid (density, specific heat, thermal conductivity), characteristics of the solid (shape, dimensions, surface temperature, surface roughness, outgoing fluxes), and the characteristics of fluid flow (velocity, turbulence intensity) and the systems (heat transfer equipment) [4]. Although heat transfer coefficient is not a property of food materials, but it is an important parameters for designing and controlling food processing equipment where fluids (air, nitrogen, steam, water, or oil), are used as heating, cooling, frying, freezing or cooking media.

The following data are normally obtained from the heat penetration curves and heating condition for calculation purpose (Figure 3).

Autoclaves or retorts do not reach the specified operating temperature immediately after the steam is turned on, but require a measurable heating time until they reach operating temperature. The time measure from steam -on until the unit reaches the specified operating temperature is called the "come-up period"; the objective of the heat penetration test is to obtain data for the product-container system that can be used to design a sterilization process.

In processes where water is used as the heating medium, if come-up time [CUT], is long and the size of the container is small, meaningful fh and j values for the product-container unit cannot always be contained. To have the results of a heat penetration test yield meaningful fh and jch values, the CUT should preferably be less than 0.5fh.

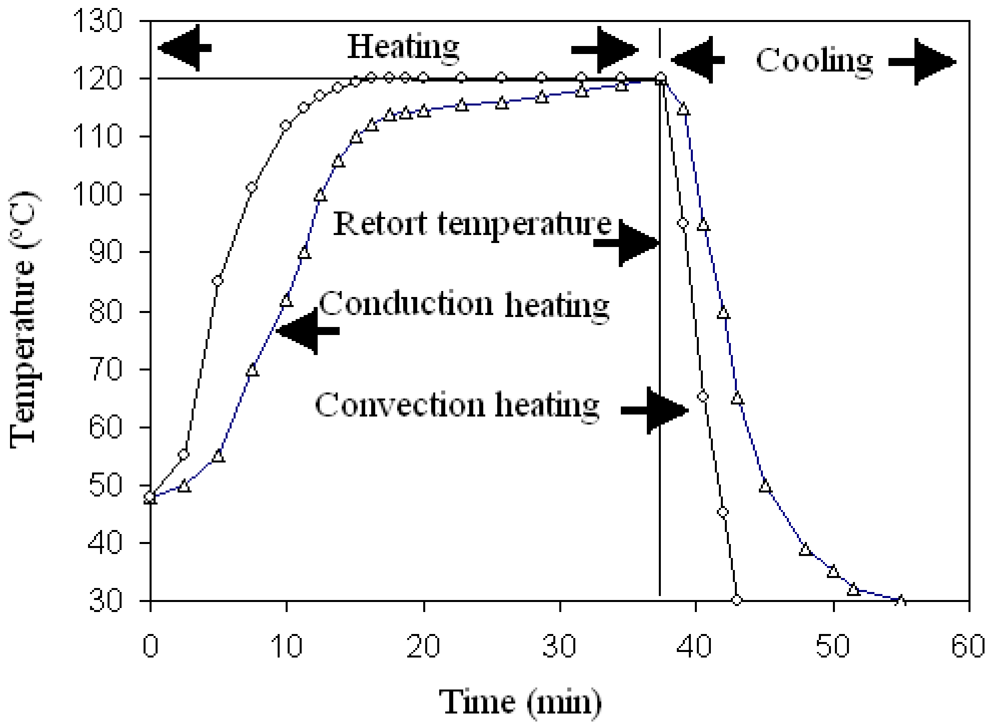

Figure 3. Heat penetration profiles of conduction and convection heating foods.

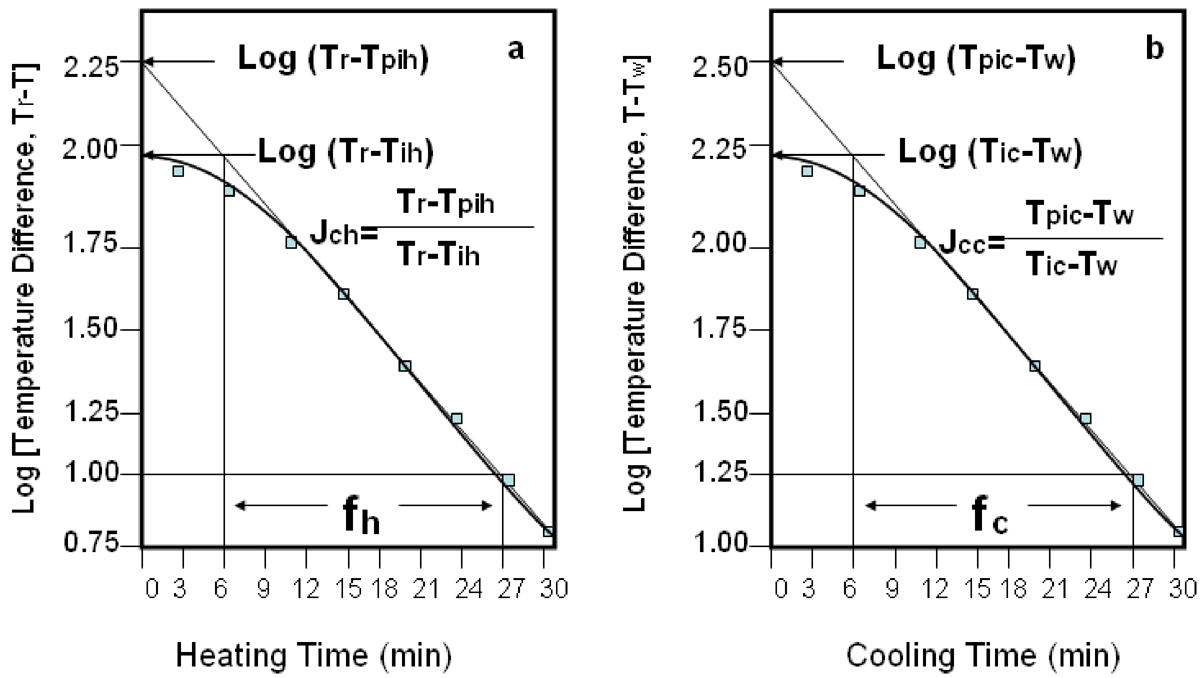

Figure 4. Heating curve and heating parameters (a), cooling curve and cooling parameters (b).

The true j value of a product container unit for ideal condition at time zero, the retort is turned on and is immediately at the operating temperature. For example the autoclave reaches the operating temperature of 121ºC after 5 min and remains at this temperature throughout the remainder of the process. The CUT correction indicates that 2 min of the 5-minutes CUT can be considered time as heating-medium temperature. The net result is the replacement of the first 5 min, the CUT in this example, with 0.42 x tc, which means neglecting the first 0.58 x tc. Therefore, in this example, the corrected zero is 2 min before the time when the retort reached the operating temperature and at 3 min after turning on the stream.

6. Thermo-physical properties of the food

Thermophysical properties, a well-known group of thermal and related properties, aere necessary for the design and prediction of heat transfer operation during handling,processing, canning, and distribution of foods. In this chapter, the most important properties associated with the transfer of heat in foods are defined. Measurement techniques, available empirical equations, and mathematical models used for prediction of density, porosity, specific heat, thermal conductivity, and thermal diffusivity are presented and condensed in tables, figures, and graphs.

6.1. Microestructure

The micro structure in foods are essential for heat flux, how figure 5 show, when seeing the different microstructures we can see some centers that absorb and soon they generate heat, changing the heat flow to inside the food

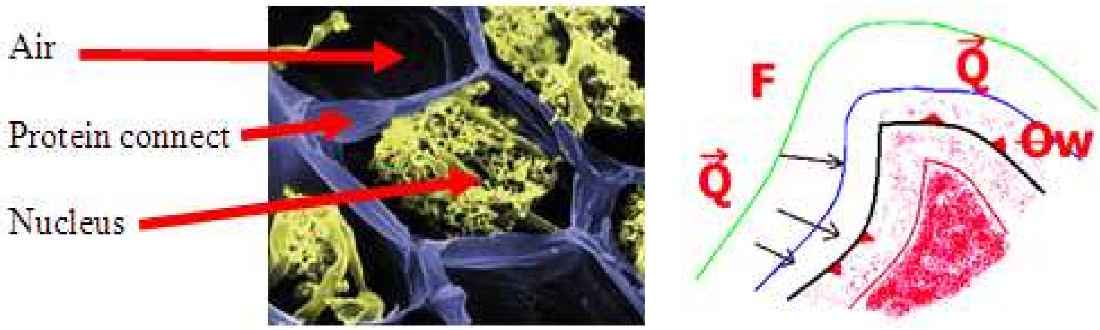

Figure 5. Vortex of Koch Function

The velocity of heat flux depends on the chaotic distribution of the center, with or without complicity of flow and thermal properties which complicity or not the flow and thermal properties affecting directly inside the food. [5]

Real products are rarely of a regular geometry, have thermal properties which vary with temperature and have different heat resistances along the boundary. For example, in retorts, when condensing steam is used as the heating method, condensation may adversely affect the uniformity of heat transfer to the product surface; heat transfer to a dry surface will be very high, but the presence of a film of liquid will reduce the heat transfer rate [6]

Non-isotropic aspects of conductive cooking have been addressed, for example, by Pan *et al.* [7] in the modeling of the cooking of frozen hamburgers. Their approach, which involved unequal cooking to both the major external surfaces of the patty, considered the enthalpy changes associated with the melting of ice and fat as well as resulting mass transfer effects.

In the numerical data analysis to the heat equation incorporated the function of Koch, for the model heat transfer with equation:

$$Cm\frac{T_m^{i+1}-T_m^i}{\Delta t}=\sum_n \frac{T_n^i-T_m^i}{R_{mn}^{cond}}+\sum_n \frac{T_n^i-T_m^i}{R_{mn}^{Rad}}+Q_v^{'''}\Delta V_m \tag{7}$$

When:

$$R_{mn}^{Rad}=\frac{1}{A_n\Gamma_{mn}\sigma\left(T_n^2+T_m^2\right)\left(T_nT_m\right)} \tag{8}$$

Iterative equation:

$$T_m^{i+1}=\left(1-\frac{\Delta t}{Cm}\sum_n \frac{1}{R_{mn}}\right)T_m^i+\frac{\Delta t}{Cm}\sum_n \frac{T_n^i}{R_{mn}} \tag{9}$$

Valid for all coordinates as:

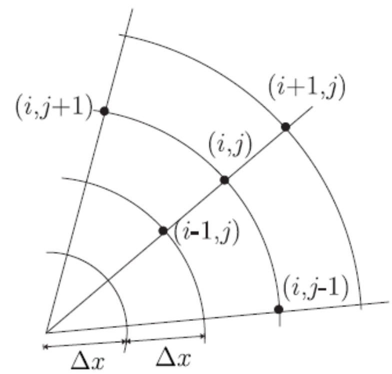

Figure 6. Generated, 160 x 51 iterative spaces nodes in two dimensions (X,Y)

The result of the iterative generates thermograms (8211 nodes per layer), this represents the distribution of heat inside of the cans. [8]

7. Example case

7.1. Introduction

This case describes the use of thermal properties in the development of computer models that simulate conduction heat transfer in canned foods. These models can be used to mixture physical and thermal properties of the material to predict the product temperature and processes time, considering different geometries from the metallic containers for foods and conditions of operation in pressure and temperature of the steam; the results obtained in the simulations compare with the real processes of the canning in the pilot plant. A second advantage is that the retort temperature need not to be held constant, but can vary in any prescribed manner throughout the process and the model will predict the correct product temperature history at the can center. Use of these models has become invaluable for simulating the process conditions experience in sterilizer system, in which cans pass from the can wall. Another important application of these models is the rapid evaluation of an unscheduled process deviation, such as when an unexpected drop in retort temperature occurs during the process. The model can quickly predict the product center temperature history in response to such a deviation, and calculate the delivered sterilizing value (Fo) comparison with the target value specified for the product. Specific objectives of this chapter are to briefly describe how the model was developed and use in process optimization and on-line computer control applications.

7.2. Method of model development

An attempt was made to define all the physical aspects of the mathematical models developed by Ball [9], using numerical methods, the trapezoidal rule of Patashnik [10]. The disadvantage that raises these traditional methods combined is the absence of the physical properties of foods, all the preceding models to considered a heat coefficient global and deals with it like a solid or block metal, the disadvantage appears when the selected system of heat transference is by conduction or convection.

The foods do not have a linear or logical behavior but an anisotropic behavior and it is a big obstacle, therefore it is little probable to design a system that models the real phenomena of heat transference in no stationary system. The simulation model considers the following aspects:

a. Generation of data composed of format of tins, temperatures of operation and steam, physical properties of the product and liquid of cover.
b. Calculation of physical values of the canning, and verifies the conditions heat transference to the interior of the package.
c. It generates point to point the increase of heat in the cold point and the time necessary to arrive at the temperature of operation
d. It determines the increase of time in optimum conditions of sterilization.

The model consists of four main programs and an information administrator, which work sequentially according to the directives of the user, to include better the process describes next to the sequences and postulates [11].

7.3. Transitory thermal response

The supposition is that it is hoped that the temperature gradients within the system are insignificant when the internal resistance to the heat transfer is small compared with the external resistance, that is to say the heat conduction by its length divided by the thermal conductivity, this relation gives origin to the adimensional Number (Biot);this number represents the relation between the form (plate and infinite cylinder) and the transitory answer, a value of Biot<0.1, it guarantees that the temperature in center does not differ more from a 5%.

For the model the number of Biot equal to 1000 guarantees that the thermal center temperature is different to the surface temperature of the product, and it should be find two functions, one for a plate and other for a cylinder, when uniting these infinite bodies generates a body finite. as shows figure to it 7. The resulting function is the sum of figures 8 and 9.

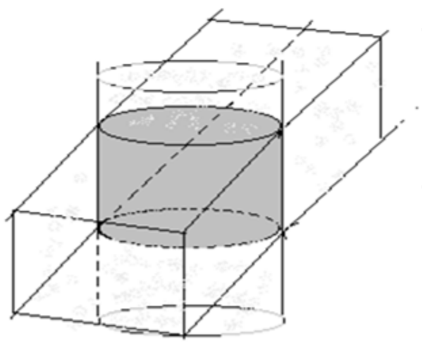

Figure 7. Finite cylinder

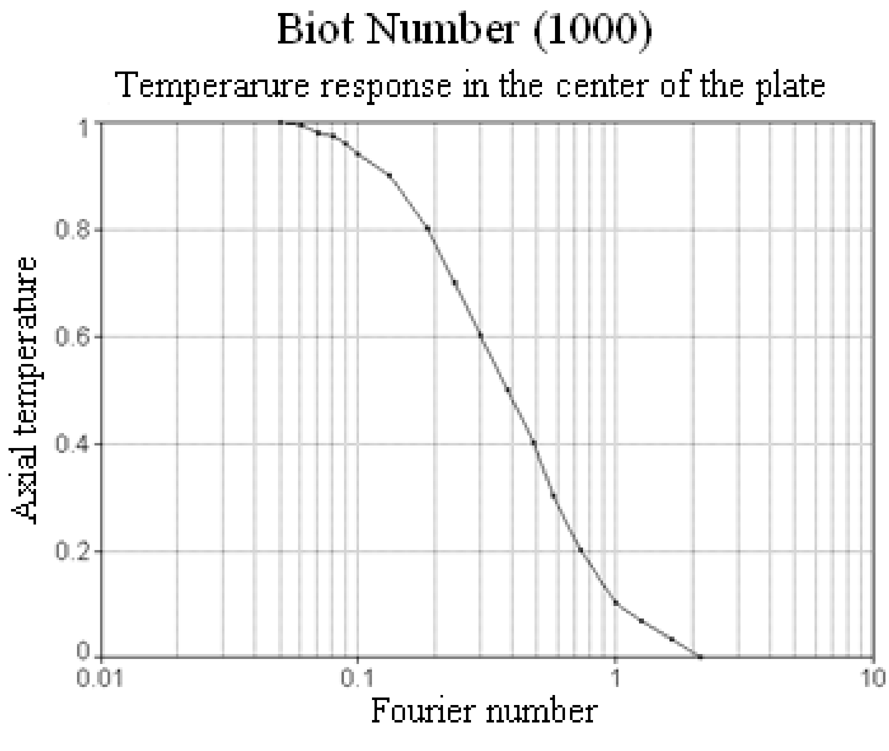

Figure 8. Biot number for infinite plate

Of these figures two dependent equations of Fourier are generated:

Plate:

$$Y = a + b(lnx) + c(lnx)^2 + d(lnx)^3 + e(lnx)^4 +$$
$$+f(lnx)^5 + g(lnx)^6 + h(lnx)^7 + i(lnx)^8 + j(lnx)^9 \quad (10)$$

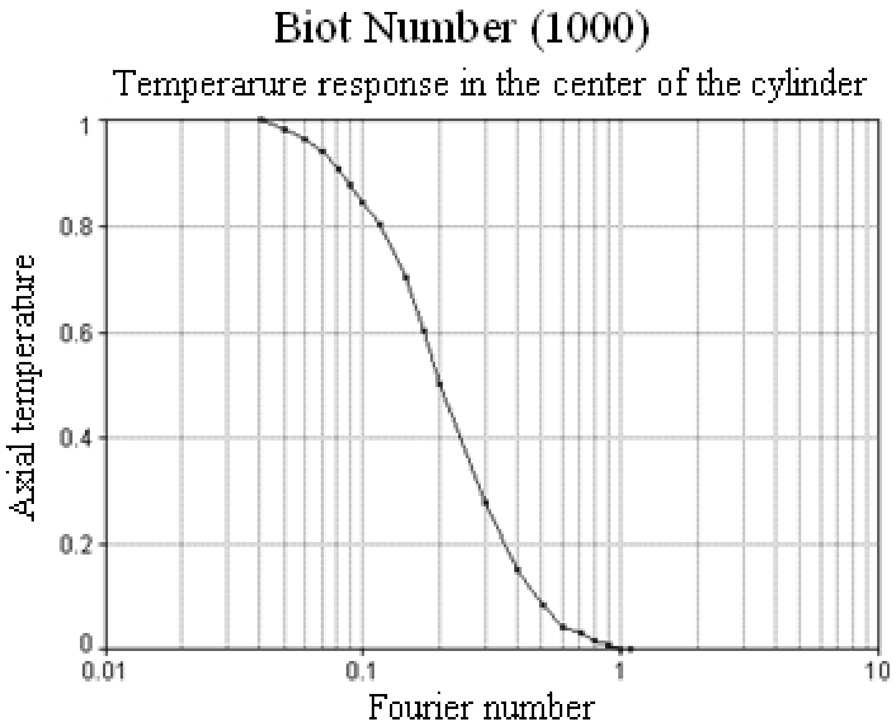

Figure 9. Biot number for Infinite Cylinder

Where:

a= 0.10168949 **b**= -0.21732379 **c**= 0.3032664 **d**= -0.10976533 **e**= -0.36311129
f= -0.052222376 **g**= 0.21755337 **h**= 0.16261937 **i**= 0.04545908 **j**= 0.0045689637

With r^2= 0.999859613

Cylinder:

$$y^{-1} = a + bx + cx^2 + dx^3 + ex^4 + fx^5 \quad (11)$$

Where:

a= 0.89545265 **b**= 3.193429 **c**= -26.00579 **d**= 272.66439 **e**= -553.74231 **f**=540.91268

With r^2= 0.9998774042

7.3.1. Solution of heat transference in multidimensional no stationary state.

The temperature distribution T (x, and, t) of an infinite body that submerges in a solution where St is defines as:

$$\vartheta = \frac{T - Te}{To - Te} \quad (12)$$

Adimensional temperature with boundary conditions $-L_1 \le x \le L_1$, y, $-L_2 \le x \le L_2$

$$\frac{\partial\vartheta}{\partial t}=\alpha\left(\frac{\partial^2\vartheta}{\partial x^2}+\frac{\partial^2\vartheta}{\partial y^2}\right)\ \mathrm{t}=0: \qquad \vartheta=1:\ \mathrm{x}=0\ :\frac{\partial\vartheta}{\partial x}=0\ :\ \mathrm{y}=0\ :\frac{\partial\vartheta}{\partial y}=0:$$
$$\mathrm{x}=\mathrm{L}_1:-k\frac{\partial\vartheta}{\partial x}=h1\vartheta:\ \mathrm{y}=\mathrm{L}_2:-k\frac{\partial\vartheta}{\partial y}=h2\vartheta \tag{13}$$

Using mathematical method

$$\vartheta(t,x,y)=\mathrm{T}(t)X(x)Y(y),$$
$$\vartheta1=\frac{T1-Te}{To-Te} \qquad \vartheta2=\frac{T2-Te}{To-Te}$$
$$\frac{\partial\vartheta1}{\partial t}=\alpha\left(\frac{\partial^2\vartheta}{\partial x^2}\right) \qquad \frac{\partial\vartheta2}{\partial t}=\alpha\left(\frac{\partial^2\vartheta}{\partial y^2}\right)$$
$$\mathrm{t}=0: \quad \mathrm{J1}=1 \qquad \mathrm{t}=0: \quad \mathrm{J2}=1 \tag{14}$$
$$\mathrm{x}=0\ :\frac{\partial\vartheta1}{\partial x}=0 \qquad \mathrm{y}=0\ :\frac{\partial\vartheta2}{\partial y}=0$$
$$\mathrm{x}=\mathrm{L}_1:-k\frac{\partial\vartheta1}{\partial x}=h1\vartheta1 \qquad \mathrm{y}=\mathrm{L}_2:-k\frac{\partial\vartheta2}{\partial y}=h2\vartheta2$$

The product of the solutions satisfies the original problem:

$$\vartheta(t,x,y)=\vartheta1(t,x)\vartheta2(t,y)$$

As it is a finite cylinder and it is the result of the union of an infinite cylinder and an infinite slab, the previous equation stays expressed as:

$$\vartheta=P(t,x)C(r,t)$$
$$x=L1:-k\frac{\partial\vartheta}{\partial x}=\vartheta2\left(-k\frac{\partial\vartheta1}{\partial x}\right)=\vartheta2\left(hc1\vartheta1\right)=hc1\vartheta \tag{15}$$
$$y=L2:-k\frac{\partial\vartheta}{\partial y}=\vartheta1\left(-k\frac{\partial\vartheta2}{\partial x}\right)=\vartheta1\left(hc2\vartheta2\right)=hc2\vartheta$$

Where:

h_c= convective coefficient
y= radio

As we can see the law of Fourier is implicit in the previous equations and for that reason we will only denote the use of the physical parameters in the use of these:

$$F_o\ =\frac{\alpha t}{L_2}\ o\ F_o=\frac{t}{t\ _c} \tag{16}$$

And

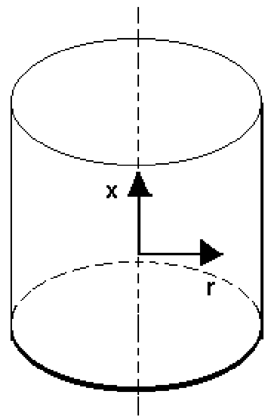

Figure 10. Finite Cylinder

$$\alpha = \frac{K}{(Cp * \rho)} \tag{17}$$

Where $\mathbf{t_c = L^2/\alpha}$

α = thermal diffusivity
K= thermal conductivity
Cp= Specific heat
ρ = density appears.

7.4. Conduction or convection

One of the controversial subjects in the thermal transmission to the interior of the tin, since this allows us to know the coldest point the interior of the tin, and is there where the microorganisms proliferate and contaminates to the product, in practice it is said that if the product is solid the transference is by conduction and if he is liquid is convection, but What happens to food when liquids materials and solids materials are mixed ?, the usual thing to do is work them like solids, but this is not correct. A model for a porous and semisolid material considers the total factor of porosity of the package like:

$$PF = \frac{(\rho_{solid} - \rho_{average})}{\rho_{solid}} \tag{18}$$

In this way it can be compared the critical volume (V_c) of the product with the corrected volume and if the relation of the absolute value (V_t), when $V_c < 3/4V_T$ then transference is convective and when $V_c \geq 3/4V_T$ then the transference is conductive, this empirical relation allows us to increase the time necessary to assure a suitable commercial sterilization in the cold point.

7.5. Results

The output data of the simulation are graphical and shows the behavior through a temperature curve, which shows the temperature of operation of the retort and the thermal center. Once finalized it calculates the time necessary to equal the temperatures and to incorporate the time of commercial sterilization, as it shows the following figure 12 and table 1:

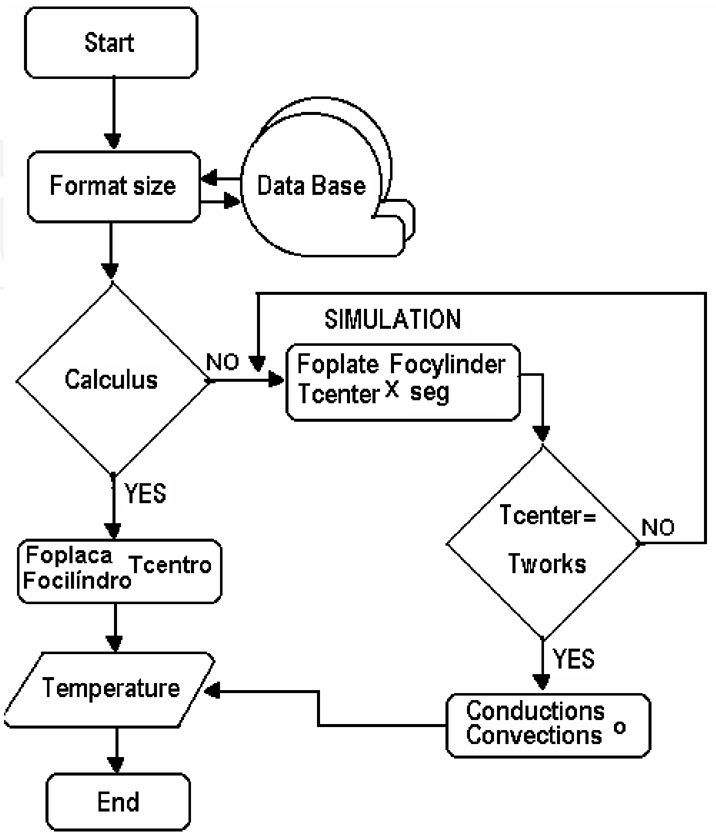

Figure 11. Flow Chart

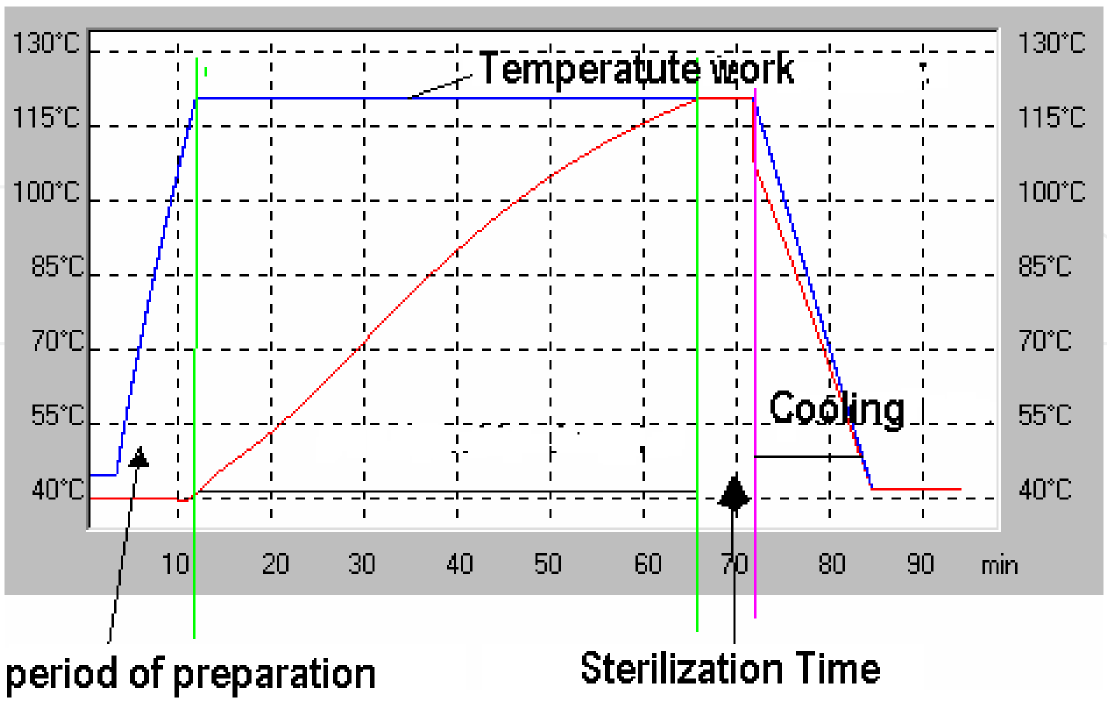

Figure 12. Characteristic line of a process of commercial sterilization

Product	Real Time	Simulation Time	St.Deviation
Pears	25min	24.99min	-0.01
Peach trees	35min	35min	0.00
Seafood's	55 min	55.1min	0.10
Peas with Bacon	56min	56min	0.00

Table 1. Process Simulated by TDT and Real date

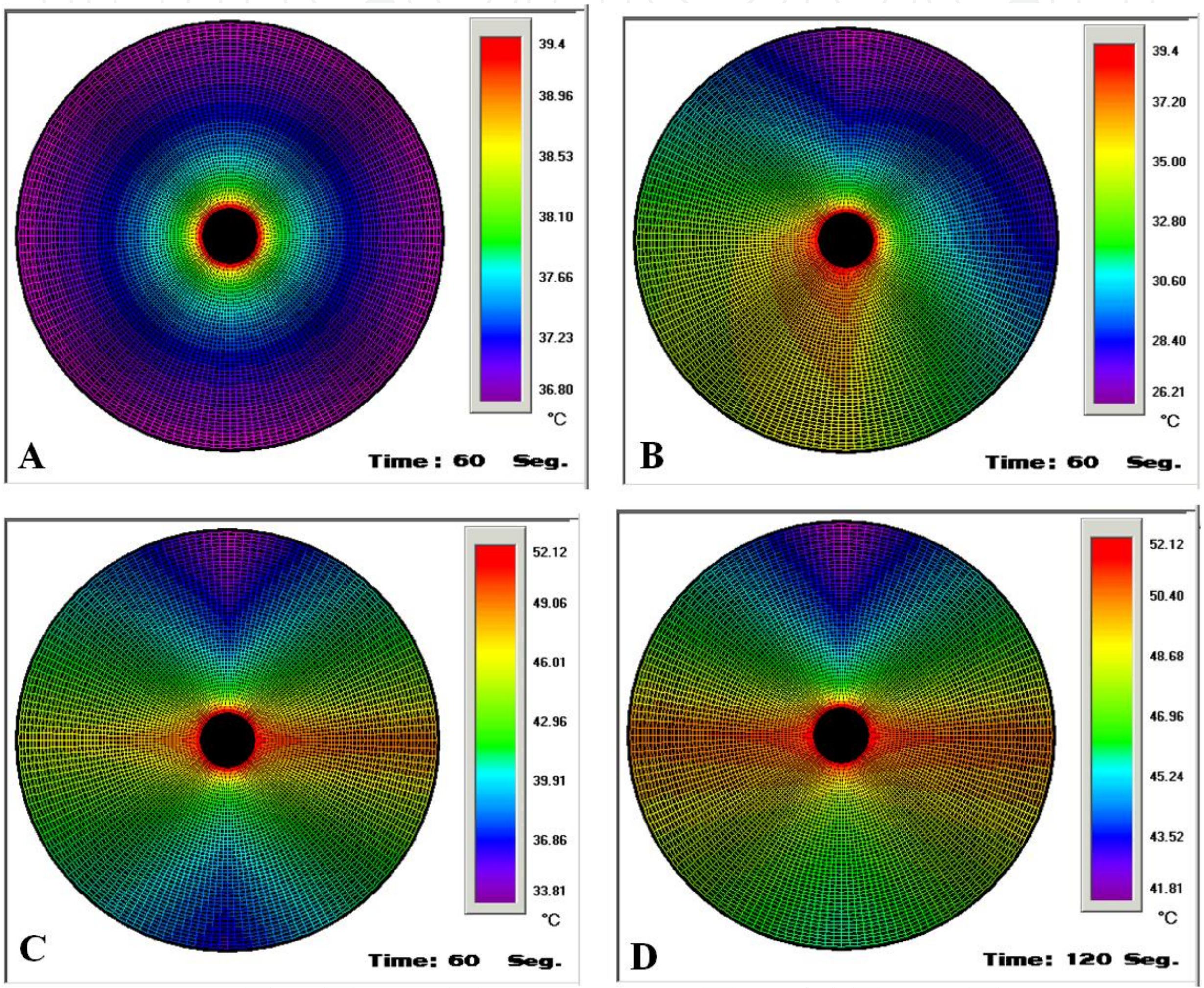

Figure 13. A Theory model, B Real flux heat in apple, C and D Real flux heat in pear

The theory analysis generates heat flux concentric like figure 13 without concerning the material, but when incorporating the Koch equation thermogram changes their form with the fig 13, B, C and D, this must to the distribution of the fiber to the interior of the food

8. Conclusion

As the results showed, the model proposed to the reader is a better approximation than the models of common usage. In practice, usually you overestimate the sterilization time for guarantee a better cleaning of pathogenic organisms and as consequence the loss of nutritional quality of the product. With the new model this is not a problem because of the better approximations in time, usage of physical properties and for the transference heat mechanisms.

In comparison, the data obtained from the simulation tests with real data obtained from experiments in the pilot plant were very close to the real data.

In computational terms, the new model showed a considerable improvement of the simulation average execution time (10 seconds.) This was compared with a normal simulation process that is about 25 minutes to 60 minutes.

An advantage of the new simulation is that from the thermograms shows second by second what is happening with the product during the process. This is not possible with the methods used normally.

As said before the average time of the simulations were low, making it a good choice for decision making in terms of industrial processes as for commercial decisions.

The numerical methods well formulated are a powerful tool for the decision making. In this case, finite differences and the finite volumes were used for the development of the work and the study that is shown in this chapter.

Nomenclature

$0.58l$	Effective beginning of the process; the retort come-up period varies from one process to the other and from one retort; to the other; in process evaluation procedures, about 42% of this come-up period generally considered as time at retort temperature because the product temperature increases even during this period.
α	Thermal diffusivity
A_n	Opacity factor
A_s	Surface area (m^2)
B	Thermal process time; Ball-corrected for come-up period.
Cm	Control node
cp	Specific heat
CUT	Come-up time
D	Represents a heating time that 90% destruction of the existing microbial population
Γ_{mn}	Emissivity angular and radial
ϱ	Density appears
$\varrho_{average}$	Density appears of average
ϱ_{solid}	Density appears of solid
F	Lethality value
f_c	Cooling rate index; the time required for the straight line portion of the cooling curve (Figure 4 b) to pass through one log cycle; also the negative reciprocal slope of the cooling rate curve.

f_h Heating rate index; the time required for the straight line portion of the heating curve,(Figure 4 a) to pass through one log cycle; also the negative reciprocal slope of the heating rate curve.

F_o Initial lethality value

Fo Fourier number

ϑ Temperature distribution

g Difference between the retort temperature and food temperature at time t.

g_c The value of g at the end of heating or beginning of cooling.

h Proportional constant of heat transfer coefficient

hc Convective coefficient

I_c Difference between the cooling water temperature and food temperature at the start of the cooling process.

I_h Difference between the retort temperatures at the start of the heating process

j_{cc} Cooling rate lag factor; a factor which when multiplied by I_C, locate the intersection of the extension of the straight-line portion of semilog cooling curve and the vertical line representing start of the cooling process.

j_{ch} Heating rate lag factor, a factor which, when multiplied by I_h locates the intersection of the extension of the straight-line portion of the semilog heating curve and the vertical line representing the effective beginning of the process.

k Thermal conductivity

l Come-up period; in batch processing operation, the retort requires some time for reaching the operating condition; the time from stream to when the retort reached T_r is called the come-up period

PF Porosity factor

pH Hydrogen potential

P_t Operator's process time

Q Heat low rate

R_{mn}^{cond} Conduction resistance radial and angular

R_{mn}^{Rad} Radiation resistance radial and angular

t Time (min)

T Temperature (ºC)

TDT Thermal death time

Te Centre temperature

T_{ic} Food temperature when cooling started

T_{ih} Initial food temperature when heating is started.

To Initial temperature

T_{pic} Pseudo-initial temperature during cooling; temperature indicated by the intersection of the extension of the cooling curve and the vertical line representing the start of cooling

T_{pih} Pseudo-initial temperature during heating; temperature indicated by the intersection of the extension of the heating curve and the vertical line representing the effective beginning of the process (0.58*l*).

T_r Retort temperature

T_w	Cooling water temperature
T_m^i	Iteratively radial temperature
T_n^i	Iteratively angular temperature
ΔT	Temperature gradient
ΔV_m	Volume radial gradient
V_c	Critical volume
V_t	Absolute volume
x	Length (m)
y	Radio (m)
Z	Is the change in death rate based on temperature

Author details

Rudi Radrigán Ewoldt
Faculty of Agricultural Engineering, Agroindustries Department,
Development of Agroindustries Technology Center, University of Concepción, Chile

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