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Variable retort temperature optimization using adaptive random search techniques

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Abstract

Global optimization algorithms and software based on adaptive random search techniques show considerable promise as more rapid and efficient approach to process optimization in the food industry. This paper describes use of the method in finding optimum variable retort temperature profiles that would maximize quality retention or minimize process time without compromising target lethality or minimum required quality retention in the case of thermal processing of canned foods. Results agreed well with those previously published by others who used more traditional approaches for similar optimization problems. Results also showed that the method lent itself well to the use of a cubic spline approximation for the dynamic temperature profiles, thereby reducing significantly the number of variables and dimensional space of the problem, in contrast to other methods, while producing superior results.

Keywords: Random search; Global optimization; Process optimization; Thermal process

1. Introduction

Thermal processing is an important method of food preservation in the manufacture of shelf stable canned foods, and has been the cornerstone of the food processing industry for more than a century (Teixeira, 1992, Chap. 11) the basic function of a thermal process is to inactivate bacterial spores of public health significance as well as food spoilage microorganisms in sealed containers of food using heat treatments at temperatures well above the ambient boiling point of water in pressurized steam retorts (autoclaves). Excessive heat treatments should be avoided because they are detrimental to food quality, and underutilize plant capacity (Simpson, Almonacid, & Teixeira, 2003).

Thermal process calculations, in which process times at specified retort temperatures are calculated in order to achieve safe levels of microbial inactivation (lethality), must be carried out carefully to assure public health safety and minimum probability of spoilage. Therefore, the accuracy of the methods used for this purpose is of importance to food science and engineering professionals working in this field, (Holdsworth, 1997). Considerable work has been reported in the literature showing that variable retort temperature (VRT) processing can be used to marginally improve quality of canned food and alternatively reduce the sterilization process time in comparison to traditional constant retort temperature (CRT) processing (Banga, Perez-Martin, Gallardo, & Casares, 1991; Banga, Balsa-Canto, Moles, & Alonso, 2003; Teixeira, Zinsmeister, & Zahradnik, 1975; Almonacid-Merino, Simpson, & Torres, 1993).

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Optimization of thermal sterilization is an optimal control problem, where it is necessary to search for the best retort temperature as a function of process time. Banga et al. (1991) showed that this optimal control problem could be transformed into a nonlinear programming (NLP) problem, and in most cases the NLP problem became a multi-modal optimization problem with several types of constraints. These types of optimization problems make use of classical deterministic optimization methods within a local search domain, such as Hooke–Jeeves, Nelder–Mead, and Quasi-Newton; and are frequently limited in their effectiveness. In order to ensure a global solution of these problems it would be more suitable to use global optimization methods.

The usefulness and advantages of some global optimization algorithm based on the utilization of Gaussian probability distribution for VRT thermal processing optimization were presented by Banga et al. (1991,2003). Other global optimization algorithms – genetic algorithms (GA) were also successfully implemented for VRT thermal processing Chen and Ramaswamy (2002).

This work deals with implementation of a global stochastic method – adaptive random search for finding the optimum VRT in thermal processing of conduction heated canned food. Specific objectives were to

- search for the optimum variable retort temperature profile to maximize retention of a specified quality factor (thiamine) within the constraint of assuring minimum required target lethality.
- search for the optimum variable retort temperature profile to minimize process time within the constraints of assuring both minimum required target lethality and quality retention.
- explore the use of a cubic spline approximation for the optimum dynamic temperature profiles to simplify the problem by reducing the number of variables (dimensional space of the random search).

2. Material and methods

2.1. Problem statement for thermal sterilization of canned foods

We deal with the particular case of a cylindrical container with the radius R and the height $2L$. The mathematical model describing heat conduction in this case is the following mixed boundary problem (Teixeira, Dixon, Zahradnik, & Zinsmeister, 1969):

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right), \tag{1}$$

where T is temperature, t is time, r and z are radial and vertical location within the container, and alpha (α) is thermal diffusivity of the product.With the following initial and boundary conditions (according to symmetry):

$$\begin{aligned} &T(R,z,t) = T_{\mathrm{rt}}(t),\\ &T(r,L,t) = T_{\mathrm{rt}}(t),\\ &\frac{\partial T}{\partial r}(0,z,t) = 0,\\ &\frac{\partial T}{\partial z}(r,0,t) = 0,\\ &T(r,z,0) = T_{\mathrm{in}}, \end{aligned} \tag{2}$$

where T_{rt}(t), $t \in [0 : t_{\mathrm{f}}]$ will be the retort temperature as a function of time, and T_{in} is the initial temperature at $t = 0$.

The objective is: to find for problem (1) such retort function: $\underline{T_{\mathrm{rt}}}(t)$, $T_{\mathrm{low}} \leqslant T_{\mathrm{rt}}(t) \leqslant T_{\mathrm{hight}}$, that final quality retention $\overline{C(t)}$ is maximized, while final process lethality, F_0^d, is held to a specified minimum. A second objective is to find for problem (1) such retort function: $T_{\mathrm{rt}}(t)$, $T_{\mathrm{low}} \leqslant T_{\mathrm{rt}}(t) \leqslant T_{\mathrm{hight}}$, that final process time t_{f} is minimized subject to the same lethality requirement above, while quality retention must not fall beneath some minimum.

The lethality constraint can be specified as follows:

(i) $F_0(t_{\mathrm{f}}) \leqslant F_0^d$, where F_0^d is the final integrated lethality required, and is calculated as a function of time and temperature at the critical cold spot according to Eq. (3):

$$F_0(t) = \int_0^t 10^{\frac{(T - T_{\mathrm{ref}})}{z}} \mathrm{d}t, \tag{3}$$

where T is the temperature at the critical point or cold spot, normally the geometric center of the container (in the case of conduction heated canned foods). The lethality at the end of the process was estimated by summing up the lethality at the center point for each time interval utilizing Gaussian's quadratures method.

Quality retention, on the other hand, is greatly affected by the non-uniform temperature distribution existing at any point in time from the heated boundary to the cool center cold spot, and must be integrated in space over the volume of the container, as well as over time. To accomplish this integration over both space and time, the following approach was used:(ii) $\overline{C(t_{\mathrm{f}})} \geqslant C^d$, where $C^{\boldsymbol{d}}$ will be the desired volume-average final quality retention value, and would be calculated as shown in Eq. (4):

$$\overline{C(t)} = C_0 \frac{2}{LR^2} \int_0^L \int_0^R \exp\left[-\frac{\ln 10}{D_{\mathrm{ref}}} \int_0^t 10^{\frac{(T - T_{\mathrm{ref}})}{z}}\right] \mathrm{d}r\mathrm{d}z. \tag{4}$$

The $\overline{C(t)}$ values evaluated by Gaussian's quadratures method included six nodes in the radial and vertical direction.

2.2. Adaptive random search method

The adaptive random search method is a global stochastic optimization method (Sushkov, 1969). This method, like many stochastic methods, does not require any *a priori* information about an optimization problem. Let the global optimization problem be formulated as follows, in which