Thermal food processing computation software

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ABSTRACT

The objective of this research consisted of developing the two following thermal food processing software: "F-CALC" is software developed to carry out thermal process calculations based on the well-known Ball's formula method, and "OPT-PROx" is software for thermal food processing optimization based on variable retort temperature processing and global optimization technique. Time-temperature data loaded from Excel-file is used by "F-CALC" software to evaluate the heat penetration parameters j_h and f_h, as well as to compute process lethality for given process time or vice versa. The possibility of computing the process time and lethality for broken heating curves is included. The diversity of thermal food processing optimization problems with different objectives and required constraints are solvable by "OPT-PROx" software. The adaptive random search algorithm coupled with penalty functions approach, and the finite difference method with cubic spline approximation are utilized by "OPT-PROx" for simulation and optimization thermal food processes. The possibility of estimating the thermal diffusivity coefficient based on the mean squared error function minimization is included. The "OPT-PROx" software was successfully tested on the real thermal food processing problems, namely in the case of total process time minimization with a constraint for average and surface retentions the "OPT-PROx" demonstrates significant advantage over the traditional constant temperature processes in terms of process time and final product quality. The developed user friendly dialogue and used numerical procedures make the "F-CALC" and "OPT-PROx" software extremely useful for food scientists (research and education) and engineers (real thermal food process evaluation and optimization).

Keywords: thermal food processing; simulation and optimization; sophisticated software.

INTRODUCTION

Food engineering is the multidisciplinary field of applied sciences combined with the knowledge of product properties [1]. Food engineers provide the technological knowledge transfer essential to the cost-effective production and commercialization of food products and services. In the development of food engineering, one of the many challenges is to employ state-of-art mathematical methods and based on these methods the sophisticated dialogue software to develop new products and processes. It is well-known, that the thermal processing of canned foods is typical topic of food engineering. This topic is of great interest due to its numerous applications and potential economic importance [1].

Thermal processing is one of the most important industrial technologies of food preservation in the manufacture of shelf stable canned foods [4]. Mainly, thermal processing is concentrated on the following factors: final product safety and quality, total processing time and energy consumption. The diversity of thermal processing objectives impose different optimal requirements to sterilization processing, which can be determined analytically or by numerical procedures and based on these procedures sophisticated dialogue software.

It is well known that dialogue software significantly simplifies an engineering calculations process from its initial stage consisted of problem definition or (and) parameterization to the final stage consisted of realizing required computations. Computer simulation or computer prototyping is an emerging alternative to handbook calculations and physical prototyping. In computer prototyping, one builds a model that is as close to a physical model as possible. An accurate computer model works just like a physical prototype, but its engine is mathematical rather than physical [3]. Thus, the objective of this research consisted of development the two following graphic user interface (GUI) software:

- "F-CALC" is software developed to carry out thermal process calculations based on the well-known Ball's formula method and Artificial Neural Networks (ANNs);
- "OPT-PROx" is software for thermal food processing optimization based on variable retort temperature processing and global optimization technique.

MATERIALS & METHODS

Problem statement for thermal sterilization of canned foods

In the particular case of a cylindrical container with radius R and height $2L$, the mathematical model describing heat transfer by conduction is a mixed boundary problem, as follows [1]:

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

where *T* is temperature, *t* is time, *r* and *z* are radial and vertical locations within the container, and alpha (α) is the thermal diffusivity of the product.

The model has the following initial and boundary conditions (by symmetry):

$$T(R,z,t) = T_{rt}(t),\ T(r,L,t) = T_{rt}(t),\ \frac{\partial T}{\partial r}(0,z,t) = 0,$$

$$\frac{\partial T}{\partial z}(r,0,t) = 0,\ T(r,z,0) = T_{in},$$

where $T_{rt}(t)$, $t \in \left[0,t_f\right]$ will be the retort temperature as a function of time, and T_{in} is the initial temperature at $t = 0$. The lethality constraint can be specified as follows: i) $F_0(t_f) \geq F_0^d$, where F_0^d is the final required lethality and is calculated according to the following equation:

$$F_0(t) = \int_0^{t_f} 10^{\frac{(T-T_{ref})}{z}} dt,$$

where T is the temperature at the critical point or cold spot, and T_{ref} is the reference temperature.

Quality retention is greatly affected by the non-uniform temperature distribution within the package from the heated boundary to the cold spot, and it 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) $\overline{C(t_f)} \geq C^d$, where C^d is the desired volume-average final quality retention value and is calculated as shown in the following equation:

$$\overline{C(t)} = C_0 \frac{2}{LR^2}\int_0^L\int_0^R \exp\left[-\frac{\ln 10}{D_{ref}}\int_0^{t_f} 10^{\frac{(T-T_{ref})}{z}}\right] drdz$$

The following types of single thermal process optimization problems were considered over the last few decades [5]:

1. Find such a retort function, where the final quality retention is maximized, while the final process lethality is held to a specified minimum.
2. Find a retort function, such that the total processing time is minimized subject to the same lethality requirement above, while the quality retention must not fall beneath some specified minimum;
3. Find a retort function, such that the final process time is minimized subject to the same lethality requirement above, while the quality retention must not fall beneath some specified minimum, and energy consumption must not exceed a specified maximum; minimum and maximum values are computed at constant retort temperature profiles.

In the general case, the retort function $T_{rt}(t)$ over $t \in [0:t_f]$ can be parameterized using N_p points, and during each time interval $t'_k = [t_k, t_{k+1})$, $k \in 0:(N_p - 1)$, the value of $T_{rt}(t'_k)$ remains constant at u_k. However, in this case, the use of a cubic spline in approaching global optimization problems with random search techniques can produce superior results over discrete step-wise functions [5], mainly because the cubic spline approximation allows for significantly reducing the number of decision variables and therefore the necessary number of objective function computations to reach the global solution. Therefore, the cubic spline approximation coupled with adaptive random search algorithm [5] are utilized in this study in order to find optimal variable retort temperature (VRT) profiles.

Adaptive random search algorithm

The adaptive random search algorithm belongs to a specific class of global stochastic optimization algorithms [6]. This class of algorithms is based on generating the decision variables from a given probability distribution, and the term ‘‘adaptive” consists of modifications to the probability distribution utilized in the searching process, which, throughout the whole search process, act as minimum computations of the objective function, locating global solutions. The pedestal probability distribution is utilized in the adaptive random search. After every calculation of objective function, the pedestal distribution of decision variables is modified so that the probability of finding the optimal value of the objective function is increased. For example, Fig. 1 shows a pedestal frequency distribution for the two-dimensional case of an optimization problem can be obtained in the middle of the search process.

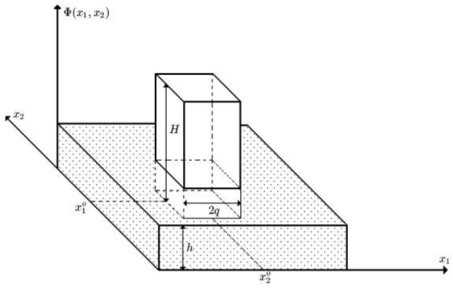

Figure 1. Pedestal frequency distribution for a two-dimension case.

Ball's formula method

Ball's formula method is a classical method used in the thermal processing industry, the basis and the precursor of a number of most recent methodologies. It has received a lot of attention, being reviewed, criticized, compared and evaluated by several investigators [4]. The method makes use of the straight-line heating section of the semi-logarithmic heat penetration curve. The following equation is used to model the temperature distribution during heating [2]:

$$\log(T_1 - T) = (-t/f_h) + \log[j_h(T_1 - T_0)],$$

where T is the required temperature distribution, T_1 is the processing (retort) temperature, T_0 is the initial temperature of the can contents, t is the time, and f_h and j_h are the heat penetration parameters. The value of $(T_1 - T)$ at the end of heating is referred to as g, and $\log g$ is given by the equation

$$\log g = (-t_B/f_h) + \log\left(j_h(T_1 - T_0)\right),$$

where t_B is referred to as the process time [2].

"F-CALC" software

Borland C++ Builder 6.0 was used to design the "F-CALC" software. "F-CALC" contains four worksheets oriented to (Fig. 2): a) heat penetration data loading and heat factors computation, b) computing the process lethality for given process time and vice versa for the case of smooth heating curve; c) computing the process lethality for given process time and vice versa for the case of broken heating curve; d) ANNs using for computing the process lethality for given process time.

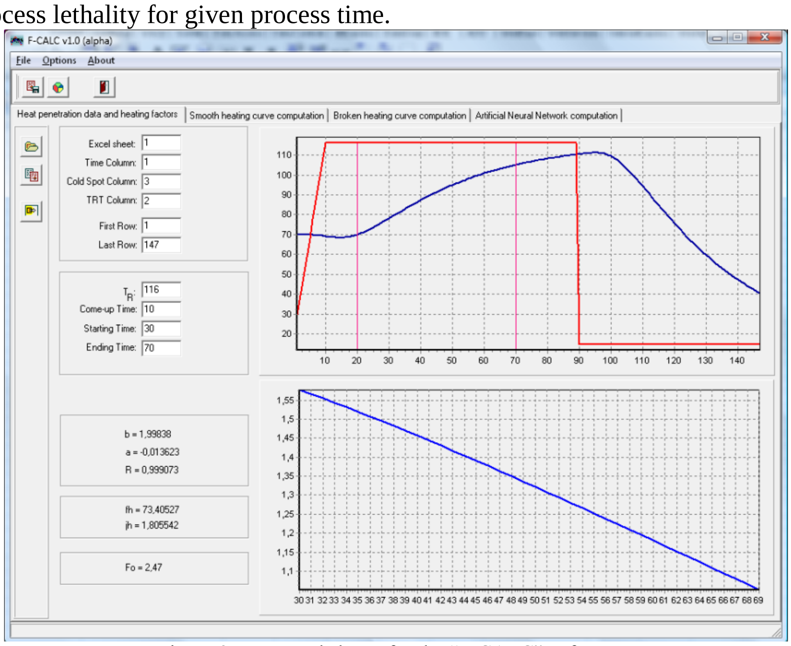

Figure 2. Four worksheets for the "F-CALC" software.

"OPT-PROx" software

Borland C++ Builder 6.0 was used to create the "OPT-PROx" software [7]. "OPT-PROx" software contains two worksheets oriented to the numerical determination of heat transfer coefficient (Fig. 3) and thermal food processing optimization (Fig. 4). The diversity of thermal food processing optimization problems with different objectives and required constraints are solvable by "OPT-PROx" package. The adaptive random search algorithm coupled with penalty functions approach, and the finite difference method with cubic spline approximation are utilized by "OPT-PROx" for simulation and optimization of the thermal food processes [5]. The mean square error minimization principle is utilized in order to estimate the heat transfer coefficient of food to be processed under optimal condition.

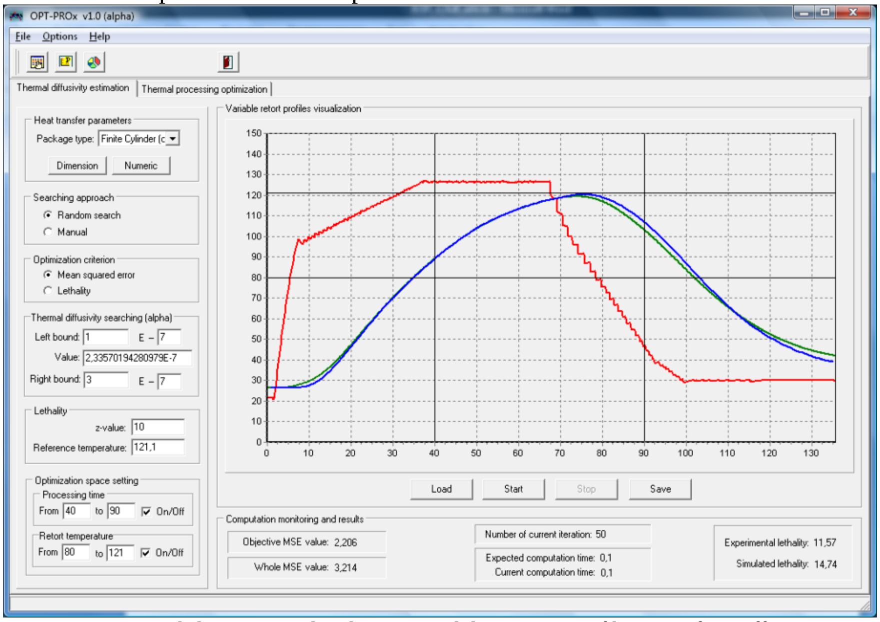

Figure 3. Worksheets oriented to the numerical determination of heat transfer coefficient.

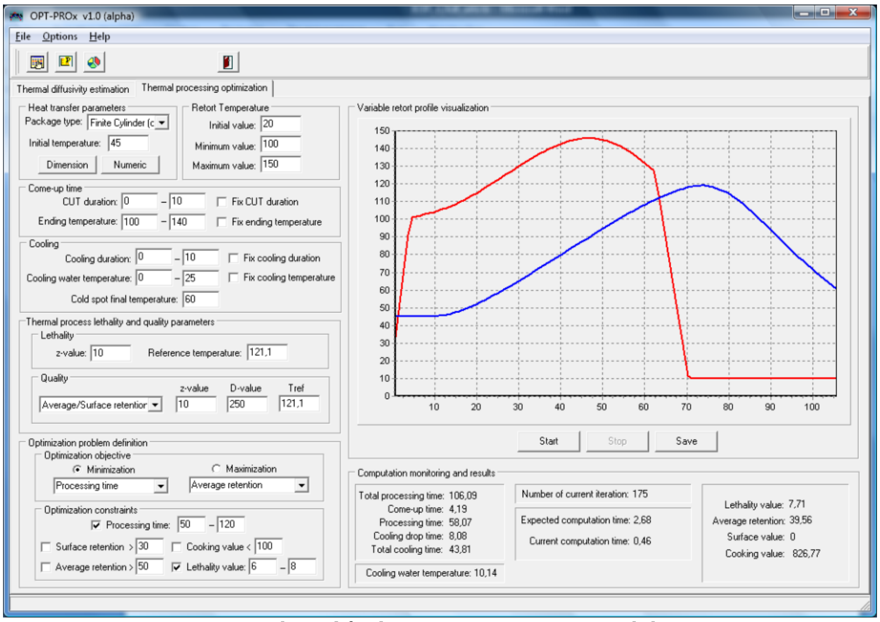

Figure 4. Thermal food processing optimization worksheet.

The following types of objective functions and constraints are supported by "OPT-PROx" software. Types of objective functions: 1) minimization of total processing time, 2) minimization of cooking value, 3) maximization of aurface quality retention, 4) maximization of average quality retention.

Optimization constraints for: 1) surface quality retention, 2) average quality retention, 3) cooking value, 4) thermal lethality value, 5) total thermal processing time. "OPT-PROx" GUI's allows formulating a required optimization problem combining the mentioned above optimization objectives and constraints (Fig. 3).

RESULTS & DISCUSSION

As a first step, it was necessary to find all those combinations of constant retort temperature (CRT) and process time for the conditions listed in Table 1 that would deliver the same final target value of lethality.

Table 1. Parameters utilized in the thermal process simulation study

Can radius (m)	0.04375
Can height (m)	0.1160
Thermal diffusivity α ($m^2 s^{-1}$)	1.5443×10^{-7}
T_0 (°C)	71.11
Microorganism	*Bacillus stearothermophilus*
$Z_{M,ref}$ (°C)	10
$T_{M,ref}$ (°C)	121.11
Nutrient	*Thiamine*
$Z_{N,ref}$ (°C)	25.56
D_{ref} (s)	10716.0
$T_{N,ref}$ (°C)	121.11

In this example, a target lethality of $F_0^d = 8$ minutes was chosen to produce the iso-lethality curve shown in Figure 4. Each point on this curve defines a constant retort temperature and process time resulting in a final target lethality $F_0^d = 8$ of minutes (typical for many canned foods). For each of these equivalent processes, the final level of quality (thiamine) retention $\overline{C(t)}$ was calculated, and presented as an optimization curve in Figure 4. We can see from Figure 5 that the maximum level of thiamine retention possible with a CRT was approximately 53% over the range of possibilities, which could be as low as 40% [6].

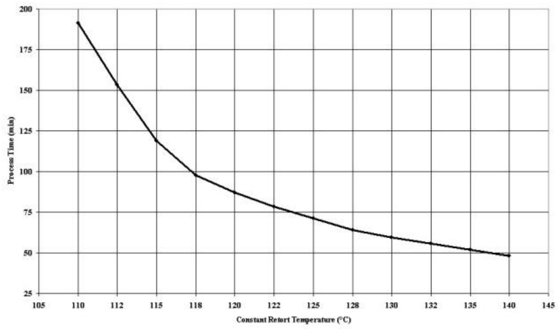

Figure 4. Iso-lethality curve for, showing equivalent process combinations of retort temperature and process time.

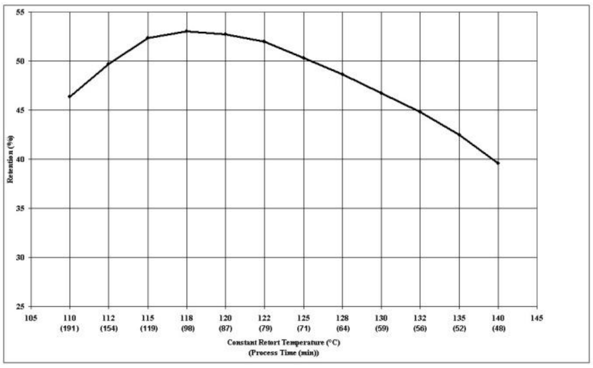

Figure 5. Curve showing thiamine retention as a function of equivalent CRT processes.

Minimization processing time problem

This numerical experiment deals with searching for the optimum VRT profile to minimize processing time within the constraints of assuring both minimum required target lethality and quality retention. In this case, the search routine was restricted in two ways, first to satisfy the lethality constraint of $F_0^d = 8$ minutes, and secondly that the quality thiamine retention could not fall below 55%, in other word the objective consisted of obtaining the product of better quality for minimal processing time is chosen. Reference to Figures 4 and 5 show that the optimum CRT process that will deliver minimum processing time while holding thiamine retention equal to 53% is a process with constant retort temperature at 118 °C and a process time of 98 minutes. The result obtained by "OPT-PROx" software is shown in Figure 6. In this case, the thiamine retention of 55% was achieved with a further reduction in processing time down to 62 minutes.

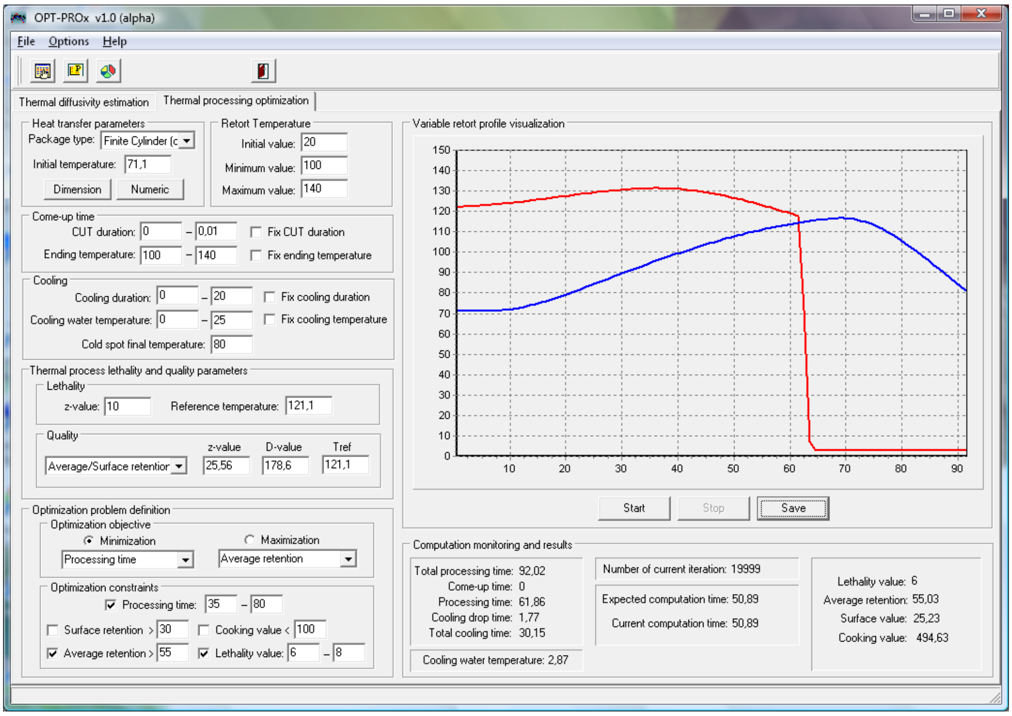

Figure 6. Result obtained by "OPT-PROx" software for minimization processing time problem.

CONCLUSION

Findings from the work reported in this study would suggest the following conclusions:

- Testing results have shown that F-CALC software basing on the Ball's formula coupled with ANN's modelling demonstrates better abilities in estimating an actual thermal lethality.
- The "OPT-PROx" software was successfully tested on the real thermal food processing problems. Testing results have shown a significant advantage over the traditional constant temperature processes in terms of process time and final product quality.
- The developed user friendly dialogue and used numerical procedures make the "F-CALC" and "OPT-PROx" software packages extremely useful for food scientists (research and education) and engineers (real thermal food process evaluation and optimization).

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