Real Time Optimization of the thermal processing of bioproducts in batch units.

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Keywords: Thermal processing, model identification, model based control, real time optimization

Abstract

The thermal processing of packaged foods in batch retorts is a standard operation in the food industry where it is of vital importance to reduce the activity of the harmful micro-organisms to a given level and to stabilize the bioproduct for subsequent storage. However, as part of the thermal processing, organoleptic properties of the food product are also deteriorated. Thus being pertinent to find the operation conditions that may satisfy both safety and quality criteria.

This work presents the theoretical development and experimental validation of the real time dynamic optimization of the process with the objective of guaranteeing the maximization of the surface retention of nutrients while satisfying the microbiological requirements under typical perturbed process operation.

INTRODUCTION

Thermal sterilization of packaged foods in batch retorts is a standard operation in the food industry. The objective consists of the inactivation by means of heat of possible spores, microorganisms or enzymes present in foodstuffs. This is carried out by steam flowing through a retort that contains the canned product. Processing time and temperature are usually selected according to the required degree of inactivation, as measured by the microbiological lethality.

However, the thermal processing of the product also causes undesirable degradation of nutrients and sensorial quality parameters. Therefore in last decades several works focused on solving open loop optimal control problems to compute the time dependent operating conditions to achieve certain objectives related to nutrient retention, process time and energy consumption as well as constraints reflecting the required degree of microbiological inactivation (Banga et al., 1991; Durance, 1997; Banga et al.,1994).

Later Alonso et al., 1997 and 1998 proposed the implementation of those optimal profiles through the design of flexible and efficient controllers to provide near optimum performance by avoiding offsets and/or prolonged overshoots that could result in overprocessing and serious quality degradation. In their work, the authors present a complete mathematical model, based on first principles, for the thermal processing of bioproducts in steam retorts and demonstrate that a hybrid adaptive controller designed on a internal model control (IMC) framework performs efficiently in tracking constant as well as variable time-temperature profiles.

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Despite the fact that the performance of such control schemes may be in many instances more than acceptable, such regulatory layer is not commanded nor integrated on higher levels for on-line supervision and optimal control of product quality, safety and operation costs. Thus imposing difficulties to rapid adaptation to the sterilization of new products or with different objectives.

This contribution presents the theoretical development and experimental validation of such a higher level layer, a real time optimization scheme, based on the harmonious combination of the following elements: a reliable model of the process and the necessary simulation techniques, process measurements and observers to on-line estimate variables such as the thermal lethality or the retention of nutrients, together with a suitable optimization approach and a feedback logic. The first part of the work is devoted to describe model development and experimental validation; the second part focus on the description and validation of the proposed real time optimization architecture.

MODEL FORMULATION AND VALIDATION

The real-time optimization requires a complete model to simulate the whole sterilization cycle. A complete mathematical model based on the combination of the mass and energy balances for the retort and equilibrium relations and empirical equations describing the pressure and valves behavior, respectively. For the sake of brevity all equations are not shown here, the interested readers are referred to Alonso et al., 1997 and Vilas et al., 2008. Instead, the coming sections present a qualitative description of the overall model.

Pilot plant description

The thermal sterilization of canned foods is usually carried out in batch steam retorts as the one depicted in Figure 1, which corresponds to the pilot plant installed at the IIM-CSIC. As noted in the Figure, each unit has three incoming fluxes (steam, water and air) and two outgoing fluxes (drain and bleeder) regulated by motorized valves. It also presents the architecture of sensors established so as to follow the evolution of the relevant variables, temperature and pressure, during processing.

At the top of this structure, a computer system is used to gather and analyze real time data coming from the pilot plant. To this purpose, the Labview (National Instruments) graphical programming software was employed. It collects, stores and distributes data to the clients by means of a local network or by Internet and allows the remote actuation over the plant through the connections with external applications.

Modeling the complete sterilization cycle

The dynamic model that allows for the description of the different stages of the sterilization process (venting, heating and cooling) in steam retorts consist of a set of differential and algebraic equations representing the mass (liquid water, steam and air) and energy balances (temperature and pressure). The behavior of the valves is usually represented by empirical relations obtained from experiments. In this regard, several possibilities exist (Smith and Corripio, 1985), depending on whether we are considering water, air or steam valves. Basically, for liquid flows, the valve behavior is usually described by:

$$F_l = A_l \rho_l \sqrt{\frac{2(P_{in} - P_{out})}{\rho_l}}, \tag{1}$$

where A is the section of the valve and ρ the density of the liquid.

The most popular types of mathematical structures to describe gas flows are:

$$F = (3.4 \times 10^{-8}) C_v C_f P_{in} \sqrt{G_f} (w - 0.148 w^3) \tag{2}$$

where G_f represents the gas specific gravity (equal to one for air) and C_v and $C_f = 0.9$ are characteristic parameters of the valve. P_{in} and P_{out} are the pressures upstream and downstream into the valve and w depends non linearly on the pressures and the characteristic parameter C_f.

On the other hand depending on the inherent flow, the characteristic valve parameter (C_v) has different dependencies with the percentage of opening leading to a battery of different models that may be suitable to describe the process in the real plant.

To finish with, the distribution of the temperature inside the food product is represented by the Fourier law and the thermal degradation of microbial spores or quality (nutrient or organoleptic) factors are modeled following the well-known TDT equation (complete model description may be found in, for example, Banga et al., 1991).

Model calibration

A battery of models was initially established based on different valves behavior descriptions. Several unknown parameters related to the valves and heat transfer, had to be obtained by fitting the models to experimental data. The first experimental data were obtained by the use of a factorial plan design considering different valves opening values, and were used to select the most promising candidate from the battery.

The model calibration was performed by using a global optimization method based on Scatter Search (SSm, Egea et al., 2007) to guarantee convergence to the global solution. Unfortunately the use of the factorial plan resulted in large uncertainties for the parameters estimates and in very limited predictive capabilities of the model.

A sequential/parallel experimental design was then performed by using a Fisher Information Matrix based method (Banga et al., 2002 or Asprey and Macchietto, 2002). The best experiments in terms of the expected uncertainty of the parameters were performed in the pilot plant and the experimental data were used to recalibrate the model. The final uncertainty on the parameter estimates was of the order of magnitude of the experimental noise which is reasonable.

In order to validate model predictive capabilities, two different experiments were performed and the experimental data were then compared to model predictions showing a very good agreement (Figure 2).

REAL TIME OPTIMIZATION

The RTO policy considered in this work, consists of a hierarchy of two, the upper and the lower, layers summarized in Figure 3.

The upper layer: Dynamic optimization

The dynamic optimization problem to be solved is stated as finding the valves openings in order the maximize surface nutrient retention:

$$\max_{u_s, \Delta t^h} SR \quad \text{with} \quad SR = 10^{-\frac{1}{D_{N,ref}} \int_{t_i}^{t_f} 10^{\frac{T_s - T_{N,ref}}{Z_{N,ref}}} dt}, \tag{3}$$

subject to the following constraints:

- The final temperature at the hottest point of the canned foodstuff must be less than 80^0C
- The final lethality at the hottest point of the canned food must be greater than $8\ min$
- Equality dynamic constraints representing the behavior of the retort, valves and product in the whole sterilization cycle.

It should be pointed out that two important factors have to be considered to employ this optimization to a real time application: the computation time of the optimizations has to be smaller than the time scales of the system and at each new optimization the initial conditions for the whole state vector must be available. Both aspects were addressed by building up a reduced order model for the partial differential equations describing the canned foodstuff behavior and an open-loop observer for the unmeasurable states.

Open-loop observer

As suggested in Balsa-Canto et al. 2002, a reduced order model (ROM) was used to solve the Fourier equation and to compute the concentrations of nutrients and microorganisms inside the food product. This allows to observe the non measurable variables (superficial nutrient retention, lethality and temperature in the center of the food product) which are required for real time optimization purposes.

Here, the ROM, consisting of 5 ordinary differential equations, was obtained by the application of the methodology proposed in (García et al, 2007) which exploits the finite element method structure to systematize the computation and projection of the spatial basis functions.

Open-loop optimal control

Once all the elements are available, the first step consists of implementing an off-line optimization starting from the usual initial conditions (room temperature, atmospheric pressure, etc.) using a sequential hybrid method. ICRS (Constrained Integrated Controlled Random Search) was selected as the global approach due to its past successful stories in the context of hybrid methods (Balsa-Canto et al., 2005). The solution is refined with a direct local optimizer, NOMAD (Abramson, 2002), since it allows handling the model discontinuities.

Feedback implementation

Real time implementation of the optimal control policy needs to consider the effect of unmeasured disturbances not being part of the prediction model. To that purpose, feedback is implemented by regularly measuring the current retort variables and observing the relevant variables of the canned product to compute efficient on-line optimization.

It should be emphasized that the control objective in batch processing is not to reach a steady state, but to reach some desired objective at the end of the batch and since the process will have a maximum allowed duration, a receding horizon optimization is not suitable. Therefore, under the usual (not too large) plant perturbations and plant/model mismatch, a local optimizer would be able to obtain the best retort temperature profile with low computational effort provided that it is initialized in the region of attraction of the global optimum. The optimal profiles obtained in previous optimization are used to initialize subsequent optimization, except for the first on-line optimization, where the initialization corresponds to the global optimum profile obtained off-line by the hybrid optimizer.

Unfortunately, in the presence of too large perturbations or plant/process mismatch, the local solver may end up in non-feasible solutions, thus resulting in products which may not be safe for consumption. In order to avoid such possibility, whenever a feasible solution is not reachable by the local optimizer, the upper layer has been complemented with a strategy to find a feasible solution to initiate the next optimization. This is based on successively opening the steam valve and increasing the heating time until a feasible solution is found. From this feasible solution the hybrid global-local optimization method is launched to guarantee that next solution is a global optimum.

The lower layer: PI controller in the framework of IMC

Before each optimization (local or global), the steady state temperature corresponding to the current step of the steam valve is included in the lower layer as set point. Here the objective is to control the temperature in the heating stage at a certain constant value by acting on the steam valve (u_s) while the bleeder is kept fixed at a constant position. The control law designed for the pilot plant consists of a PI-type controller designed in an IMC framework as the one presented in (Alonso et al, 1997 and Vilas et al.,2008).

EXPERIMENTAL VALIDATION OF THE RTO

Two situations were implemented in the pilot plant to check the performance of the RTO policy proposed: under the perturbations in a usual sterilization cycle and under a fault of the boiler where the steam entering the retort experiments a considerable pressure drop.

RTO under usual perturbations

The RTO experimental results performing the policy proposed are shown in Figure 4-a, where the retort temperature measurements (blue line) and the off-line (orange line) and on-line optimal (green line) set points are plotted. As it can be seen, the successive on-line optimization updates the temperature profile to compensate for differences between the expected off-line optimal profile and the PI controlled temperature. Moreover, since all the batch has been operated under the perturbations in a usual sterilization cycle, only local optimizations were required.

Remark that the lethality at final time, as predicted by the mathematical model, is almost the value of the constraint imposed (8 minutes) and the product satisfied the legislation requirements preserving more than 65% of Thiamine in the can surface.

RTO under a pressure drop

In order to check the performance of the RTO policy under more important perturbations which could happen in the plant, in the middle of the heating stage the bleeder before the steam valve is opened until the pressure of the reducing valve (3 bares) downs to the atmospheric pressure during 30 seconds, this would simulate and excessive boiler demand. The results, again comparing with a perfect off-line profile, are depicted in Figure 4-b.

It should be noted that when the system seems to be recovered from the perturbation, non-feasible solutions are obtained thus a global optimization is launched. From this optimization the open-loop set points and the ones obtained by RTO result to be substantially different.

Remark that despite the relevance of the perturbation included, the RTO is able to achieve the objectives while satisfying the constraints without increasing the duration of the batch. Note that the lethality constraint is satisfied while preserving, again, the 65% of Thiamine.

CONCLUSIONS

This work presented the development of a real time optimization scheme which is based on the harmonious combination of a reliable model of the process, an open loop reduced order model based observer to compute the non measurable variables, a efficient and robust optimization structure and a regulatory layer.

The objective was to operate the thermal sterilization of packaged food in batch retorts so as to maximize nutrient retention while satisfying safety related constraints under usual perturbations in the plant.

Two situations were implemented in the pilot plant installed at the IIM-CSIC to check the performance of the RTO policy proposed: under the perturbations in a usual sterilization cycle and under a fault of the boiler where the steam entering the retort experiments a considerable pressure drop. In both cases the RTO was able to drive the system to accomplish the desired objectives while satisfying the imposed constraints.

Acknowledgments

This work was supported by the Spanish Government, as part of the project C-PROS (DPI2004-07444-C04-03), and by the Xunta de Galicia (PGIDIT05PXIC40202PN).

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Figures

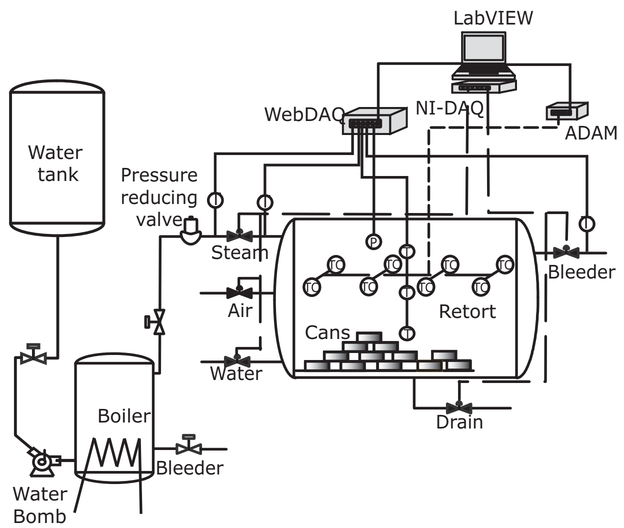

Figure 1: Schematic of a batch sterilization steam retort

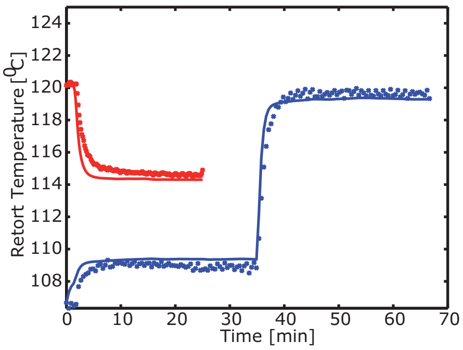

Figure 2: Validation of the model: Crosses and lines represent experimental data and the model predictions, respectively

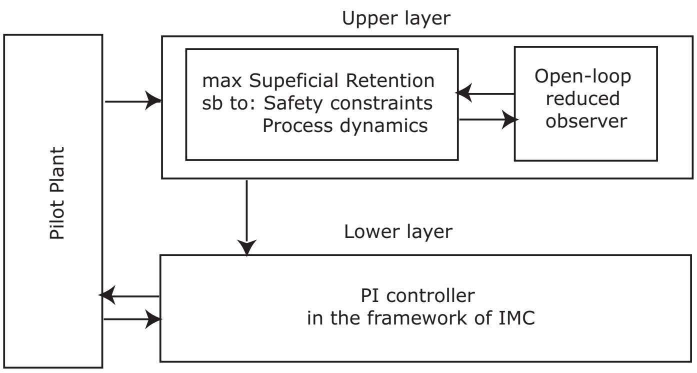

Figure 3: Real Time optimisation structure.

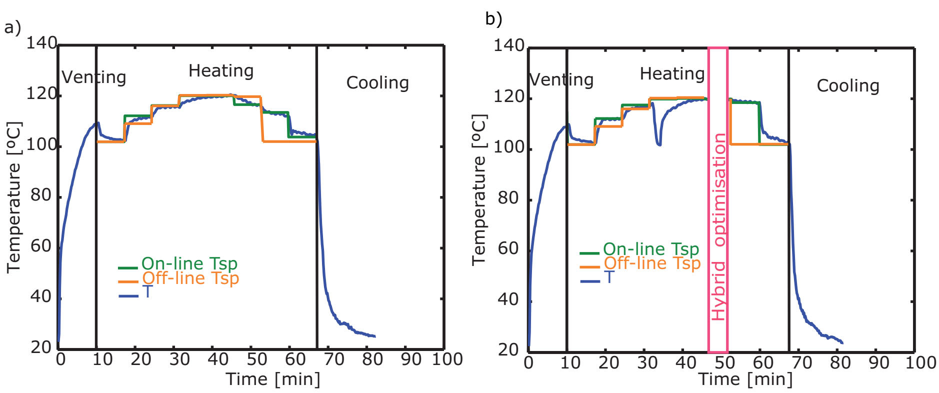

Figure 4: RTO temperature profile a) under usual perturbations and b) under a pressure drop in the pilot plant. The orange and green lines represent the off-line and on-line temperature set points.