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Model-Based Settings of a Conveyorized Microwave Oven for Minced Beef Simultaneous Cooking and Pasteurization

L. Boillereaux. S. Curet, M.M. Hamoud-Agha, H. Simonin

ONIRIS – GEPEA – UMR CNRS 6144 - Rue de la Géraudière, BP 82225 – 44322 Nantes cedex 3 France (Tel: +33-251785477; e-mail: lionel.boillereaux@ oniris-nantes.fr).

Abstract: A major drawback of microwave processing is the heterogeneity of treatment, which prevents from a plenty benefit of its flexibility and rapidity. Most of time, this operation is realized in continuous processes, composed of a series of microwave generators with adjustable power. In this paper is proposed a methodology leading to an optimal setting of these powers in order to warrant the expected microorganisms' inactivation during simultaneous cooking and pasteurization, while preserving quality. It consists in minimizing a multicriteria formulation including hottest and coldest points on the first hand, and final logarithmic inactivation on the other one. The simulation model is composed of a reduction of the heat equation via a finite volume scheme with a source term deduced from appropriate closed-form solutions of the Maxwell's equations, whereas the non-isothermal inactivation is described by the Geeraerd model. The methodology is carried out by considering treatment of minced beef.

Keywords: microwave, heat transfer, pasteurization, closed-form solutions, inactivation, optimization.

1. INTRODUCTION

Besides a massive and increasing use of domestic microwave ovens, this technology presents numerous advantages for the industrial thermal treatment of foods, as for example drying, tempering, blanching (Tang et al., 2008). Compared to conventional heating methods microwaves can provide a rapid rise in temperature within materials of low thermal conductivity such as food products. Thus, microwave heating reduces the processing time, which may enhance overall food quality (Cinquanta et al., 2010; Sun et al., 2007).

Microwave pasteurization has been tested on several food products, either liquid like fruit juices and milk (Cañumir *et al.*, 2002) or solid like meat (Huang and Sites, 2007) and vegetables. Moreover, microwave heating has been shown to be effective in inactivating both gram positive and gram negative bacteria (Zhou *et al.,* 2010).

Even if some publications suggest that microwave irradiation could cause non-thermal effects on microorganisms, it seems more realistic to consider that microwaves inactivate microorganisms exclusively by heat (Shaman *et al.*, 2007).

The most important drawback of microwave pasteurization is the non-uniform temperature distribution, resulting in hot and cold spots in the heated product. This can lead to the survival of pathogenic microorganisms in the less heated zones, which can be a major obstacle to the widespread development of microwave heating in industrial food pasteurization. This is particularly critical for solid food products where convection does not occur. For example, a recent study indicates that short time exposures of chicken portions to microwave heating did not eliminate E. coli O157:H7 because of the non-homogeneous heating and wide temperature variations ranging from 66.7 to 92.0 °C (Apostolou *et al.*, 2005).

The adoption of the frequency 915 MHz, instead of 2.45 GHz, improves partially this problem, reducing these effects, but presents other drawbacks. In this work we consider the most prevalent technology, i.e., at the frequency of 2.45 GHz. Industrial microwave processes are usually composed of a series of compartments equipped each with one generator, located above the conveyor belt. In each compartment, the electric field is considered as a constant, with a penetration direction normal to the surface of food. All the generators have adjustable powers.

The objective of this work is to propose a methodology permitting to assist the operators in the process parameters optimization in order to insure the microorganism's inactivation target, but without to affect its organoleptic quality. In other words, the proposed approach consists of adjusting independently each microwave generator in order to respect a multi-criterion problem: (i) the coldest point must reach a set point temperature, (ii) the temperature gradient in the food during treatment must be as small as possible, and (iii) a minimal microorganism's destruction level must be verified at any point of the food.

To reach such an objective, the choice of the cost function to minimize is trivial.

The simulator, implemented in Matlab®, is based on a reduction of the heat equation via a finite volume scheme (Lakner and Plazl, 2008), coupled with closed-form solutions of the Maxwell's equations (Bhattacharya and Basak, 2006) to describe the source term induced by microwaves. The equations of the Geeraerd model (Geeraerd *et al.*, 2000) were adopted to describe the non-isothermal inactivation. The minimization of the cost function is realized under constraints thanks to the *fmincon* procedure implemented in Matlab®.

To illustrate the interest of such a methodology, parameters and characteristics of minced beef are considered in this contribution through a simultaneous pasteurization/cooking operation. Indeed, Minced beef is, in Europe, the most consumed meat in out-of-home dining, especially in the school canteens. But it represents a real sanitary risk and, during cooking, the core temperature must reach a set point value equal to 65°C. At last, supply of already treated meat for the school kitchens, where only a fast final passage in the steak pan would be necessary, would constitute a real progress.

This paper is organised as follows: section 2 is dedicated to the construction of the simulation model. In section 3, the optimization approach is described. In the last section, the approach is carried out for different conditions and the results are discussed.

2. MODEL DERIVATION

2.1 Modelling heat transfer with microwave heating

Numerous works are proposed in the literature (Rattanadecho, 2006) to model heat transfer with a microwave source term; the complexity of the problem lies in the fact that temperature evolution is governed by the heat transfer equation, whereas the evolution of the electromagnetic field in the material is governed by the Maxwell's equations. Recently, Bhattacharya and Basak (2006) proposed closed-form solutions of the Maxwell's equations, under the following assumptions: (i) the dielectric properties are constant, (ii) the electric field is constant at the surface of sample, and (iii) the incident wave is normal to the surface. Concerning the conveyorized microwave oven, assumptions (ii) and (iii) are usually admitted. The dielectric properties of foods vary on the pasteurization temperature range, but several tests have shown that these variations can be taken into account in the closed-form solutions provided that they are smooth, which is usually verified except for phase change (during thawing/freezing).

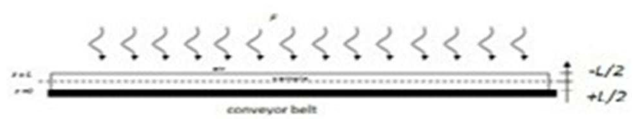

Fig. 1. Schematic description of heat transfer and electromagnetic radiation

The food sample is a plate sufficiently thin (Figure 2) to consider a one dimensional heat transfer along the z direction (thickness L << surface). The microwaves penetrate in the foodstuff through the top and bottom surfaces, with propagation along the z direction. The heat equation is thus reduced to the following form,

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + Q(z) \tag{1}$$

where ρ, Cp and k are the density (kg.m^{-3}), the specific heat (J.kg^{-1}.K^{-1}) and the thermal conductivity (W.m^{-1}.K^{-1}), T is the temperature in °C and Q is the source term induced by the electric field.

The resolution of heat transfer equation, with or without source term, is widely tackled in the literature. Finite volumes or finite differences are successfully employed to reduce the heat equation (1) into a lumped parameters system (2). Let us consider n the number of nodes in the z direction, it comes for the internal nodes ($i \in [2; n-1]$):

$$\frac{dT_i}{dt} = \frac{k}{\rho C_p \delta z^2} \cdot \left(T_{i+1} - 2T_i + T_{i-1}\right) + Q(z_i) \tag{2}$$

where $T_i = T(z_i); z_i = (i-1) \cdot \delta z$; $\delta z = \frac{L}{n-1}$.

For the top surface, a convective heat exchange is considered with a constant air temperature T_a:

$$\frac{dT_1}{dt} = \frac{k}{\rho C_p \delta z^2} \cdot \left(2T_2 - 2T_1\right) + \frac{h}{\rho C_p \delta z}\left(T_a - T_1\right) + Q(z = L) \tag{3}$$

For the bottom surface, in contact with the belt, a perfect insulation is considered:

$$\frac{dT_n}{dt} = \frac{k}{\rho C_p \delta z^2} \cdot \left(2T_{n-1} - 2T_n\right) + Q(z = 0) \tag{4}$$

Closed-form solutions allow to generalize the expression of the dissipated microwave energy within any material, according to its dielectric and geometric specificities. The energy absorbed by the material at each node can be expressed thanks to the expression (Bhattacharya and Basak, 2006):

$$Q(z) = \frac{8\pi f \varepsilon_r'' \kappa_0^2}{C_0} \times \left(\frac{C^-}{C^d} F^j_{bottom} + \frac{C^+}{C^d} F^j_{top} + \frac{C^\pm}{C^d} \sqrt{F^j_{top} \cdot F^j_{bottom}} \right) \tag{5}$$

$\kappa_0 = \frac{2\pi f}{C_0} = 51.3\, m^{-1}$ is the propagation constant in free space.

F^j_{top} and F^j_{bottom} are the incident electromagnetic power densities supplied by the top and bottom generators of the j^{th} generator of the microwave oven. ε_r'' represents the loss factor of the material. $C_0 = 3.10^8\, m \cdot s^{-1}$. $f = 2.45\, GHz$.

The penetration depth and the wavelength can be respectively expressed as follows:

$$D_p = \frac{C_0}{\pi . f}\left[2.\varepsilon_r' . \left(\left(1 + \left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2\right)^{1/2} - 1\right)\right]^{-1/2} \tag{6}$$

$$\lambda_m = \frac{C_0\sqrt{2}}{f}\left[\varepsilon_r' \left(\sqrt{1 + \left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2} + 1\right)\right]^{-1/2} \tag{7}$$

where ε_r' is the dielectric permittivity. Let us denote $z' = \frac{2z}{L}$; $\kappa_{2a} = \frac{2\pi}{\lambda_m}$; $\kappa_{2b} = \frac{1}{D_p}$

The parameters C of equation (5) are (Bhattacharya and Basak, 2006):

$$C^- = c_1 \cos(\kappa_{2a}L(1-z')) + c_2 \cosh(\kappa_{2b}L(1-z'))...$$
$$...+ c_3 \sin(\kappa_{2a}L(1-z')) + c_4 \sinh(\kappa_{2b}L(1-z'))$$
$$C^+ = c_1 \cos(\kappa_{2a}L(1+z'))) + c_2 \cosh(\kappa_{2b}L(1+z')))...$$
$$...+ c_3 \sin(\kappa_{2a}L(1+z'))) + c_4 \sinh(\kappa_{2b}L(1+z'))$$

$$C^\pm = [c_1 \cos(\kappa_{2a}L) + c_3 \sin(\kappa_{2a}L)]\cosh(\kappa_{2b}Lz')...$$
$$... + [c_2 \cosh(\kappa_{2b}L) + c_4 \sinh(\kappa_{2b}L)]\cos(\kappa_{2a}Lz')$$
$$C^d = (c_3^2 - c_1^2)\cos(2\kappa_{2a}L) + (c_2^2 + c_4^2)\cosh(2\kappa_{2b}L)...$$
$$... - 2c_1c_3 \sin(2\kappa_{2a}L) + 2c_2c_4 \sinh(2\kappa_{2b}L)$$
$$c_1 = \kappa_{2a}^2 + \kappa_{2b}^2 - \kappa_0^2 \ ; \ c_2 = \kappa_{2a}^2 + \kappa_{2b}^2 + \kappa_0^2$$
$$c_3 = -2\kappa_0\kappa_{2b} \ ; \ c_4 = 2\kappa_0\kappa_{2a}$$

2.2 Modelling microbial inactivation under non-isothermal conditions

The inactivation model structure and parameters chosen for this work have been experimentally validated in previous works (Hamoud-Agha *et al.*, 2013), and concerned a material composed of a calcium alginate gel inoculated with *E. coli* K12 CIP 54.117, obtained from the Pasteur Institute, France.

Without incorporating the tailing effect, as it was not observed in the experimental data, the reduced equations of the model were adopted to describe the non-isothermal inactivation kinetics (Geeraerd *et al.*, 2000). It consists of two coupled ordinary differential equations as follows:

$$\frac{dN}{dt} = -k_{max} \cdot \left(\frac{1}{1+C_c}\right) \cdot N \quad (8)$$

$$\frac{dC_c}{dt} = -k_{max} \cdot C_c \quad (9)$$

Where N represents the microbial population (CFU/g), C_c (critical component) relates to the physiological state of the cells (-), and k_{max} is the specific inactivation rate (1/min).

Thermal inactivation parameters, i.e. the asymptotic decimal reduction time ($AsymD_{ref}$) and the thermal resistance constant (z value), which is the temperature change required to achieve a tenfold change in *AsymD*, were integrated into the Bigelow model (Eq. (8)) to yield predictions for the specific inactivation rate at a given temperature.

$$k_{max}(T) = \frac{\ln 10}{AsymD_{ref}} e^{\left(\frac{\ln 10}{z}.(T-T_{ref})\right)} \quad (10)$$

3. OPTIMIZATION PROCEDURE

Let us denote M the number of compartments of the microwave oven, t_r the residence time of the food sample in each compartment. In the j^{th} compartment, the food sample is submitted to the incident power densities denoted F_j

Let us denote U the vector of microwave fluxes ($W.m^{-2}$) to optimize:

$$U = [F_0 \quad F_1 \quad \cdots \quad F_M]^T \quad (11)$$

In the sequels, $\hat{T}_i(\cdot, U)$ represents the temperature of node i issued from the model simulator by applying U.

The multi-criterion cost function J is defined as the sum of three sub-criterions:

$$J_1(U) = \sqrt{\frac{1}{M \cdot t_r}\sum_{j=1}^{M\times t_r}\left(T_{sp}(t_j) - \min\left(\hat{T}_1(t_j, U), \ldots, \hat{T}_n(t_j, U)\right)\right)^2} \quad (12)$$

The role of J_1 is to force the coldest point to be as close as possible to the setpoint temperature T_{sp} at each process time.

$$J_2(U) = \sqrt{\frac{1}{M \cdot t_r}\sum_{j=1}^{M\times t_r}\left(T_{sp}(t_j) - \max\left(\hat{T}_1(t_j, U), \ldots, \hat{T}_n(t_j, U)\right)\right)^2} \quad (13)$$

In the same way, J_2 forces the hottest point to be as close as possible to T_{sp}, that is, as close to the coldest point.

At last, J_3 permits to warrant that at least the targeted destruction N_{sp} is reached at each point of the food sample. Let us denote $\Delta N_i^{Log} = Log_{10}\frac{\hat{N}_i(t_{M\times t_r}, U)}{N_0} - Log_{10}\frac{N_{sp}}{N_0}$ the logarithmic destruction obtained for node i at the final processing time, where N_0 represents the initial population of microorganisms

$$J_3(U) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1 + sign(\Delta N_i^{Log})}{2} \times \Delta N_i^{Log}\right)^2} \quad (14)$$

where
$$sign(x) = \begin{cases} 1 & if \ x > 0 \\ 0 & if \ x = 0 \\ -1 & if \ x < 0 \end{cases}$$

Using the *sign* function permits to eliminate from the criterion all the points where the destruction is superior to the target.

Finally, the cost function is $J(U) = J_1(U) + J_2(U) + J_3(U)$

The optimal control vector is consequently $U_{opt} = \arg\min J(U)$, and is obtained using the *fmincon* procedure of the optimization toolbox of Matlab® release 7.0. This algorithm permits to constrain the power densities between 0 and a maximal value depending on the generators.

4. RESULTS AND DISCUSSION

4.1 Model parameters, operating conditions and food properties

The operating conditions implemented in the simulator are based on assumptions that are as realistic as possible:

- Natural convection ($h = 10 W.m^{-2}.K^{-1}$) is considered at the top surface.
- The process is composed of 5 compartments
- 12 portions of minced beef (thickness 1 cm, diameter 6 cm) are irradiated in each compartment, which represents a surface to treat of 0.034 m^2 per compartment.

- Each generator can supply a varying power in the range [0, 4 kW].
- The initial temperature of beef is equal to 4°C and the ambient temperature is equal to 20°C.
- The initial contamination is 10^9 CFU/g

Due to the high variability of thermophysical and dielectric properties of beef, the values are issued from a food analogue product, tylose, which is widely used as an experimental material in food-related research. In the range [20, 80°C], the thermophysical properties of tylose are taken from a previous study (Curet et al., 2008).

Density and thermal conductivity are considered as a constant and the specific heat capacity is temperature dependant:

$$\rho = 1068\ kg.m^{-3}$$
$$Cp = 3.7 \times (\mathrm{T} - 273.15) + 3682.7 \text{ in J.kg}^{-1}.\mathrm{K}^{-1}$$
$$k = 0.52\ W.m^{-1}.K^{-1}$$

The dielectric properties are also temperature dependant (Curet *et al.,* 2013)

$$\left.\begin{aligned}\varepsilon_r' &= -3.80\times10^{-1}T + 1.82\times10^{2}\\ \varepsilon_r'' &= -1.28\times10^{-1}T + 5.52\times10^{1}\end{aligned}\right\} \text{ with } T \text{ in Kelvin}$$

The inactivation model parameters are based on the Bigelow model with a reference temperature of 57°C (Hamoud-Agha *et al.*, 2013).

AsymD_{57} = 3.9 min ; z=6.3°C ; Cc(0)=0.23

4.2 Results and discussion

Several cases are reported in this section. In conventional pasteurization, foods are submitted to a temperature slope followed by a plateau to respect the schedule. It is proposed to study the influence of processing time (3 and 4 minutes), the influence of the heating scenario, i.e., the set point temperature evolution (temperature ramp without plateau, temperature ramp and short plateau, stronger ramp and longer plateau), the influence of sample thickness (10, 12 and 15 mm).

Scenario S1 is composed of a ramp from 4°C to 65°C spread over the 5 compartments. Scenario S2 is composed of a ramp from 4°C to 65°C spread over the first 4 compartments, and a final plateau at 65°C for the last compartment. Scenario S3 is composed of a ramp from 4°C to 65°C spread over the first 3 compartments, and a final plateau at 65°C for the last 2 compartments.

Results are analysed in terms of (i) maximal value of the hottest point, (ii) level of inactivation, and (iii) energy required by the product in kJ per kg of treated minced beef.

Figures 2-8 represent the temperature evolution of coldest and hottest points (upper subfigures) during processing time and lower subfigures represent the logarithmic inactivation versus the sample depth. The optimal values of power at each generator are indicated in the figures legends.

Table 1. Results obtained with the different configurations

Sample thickness (mm)	Process. Time (min)	Scenario	T of hottest point (°C)	destruction	Energy (kJ/kg)	Fig. number
10	3	S1	80	>2	244	2
		S2	100	>2	240	3
	4	S1	90	>2	236	4
		S2	80	>2	233	5
		S3	75	>2	225	6
12	4	S3	75	>2	260	7
15	4	S3	78	>8	157	8

The review of the results reported in Table 1 permits to derive trends:

- the prolongation of the processing time permits to limit the maximal temperature reached by the sample, and to avoid eventual overcooking effects,
- Keeping the temperature plateau during a sufficient time permits too to limit the eventual overcooking, and reduces significantly the energy required.
- The multi-criteria formulation allows a total destruction of microorganisms in at least half sample, and to respect the target of 2 Log in the whole product.

However, the effects of an increasing of the minced beef thickness raise questions. Indeed, between 10 and 12 mm, it appears that the energy required for a thicker piece (at constant weight) increases considerably (more than 15%). But it decreases of 30% for a thickness of 15 mm. In fact, reflected power and resonances phenomena occurring in microwave treatment especially for thin product layers (< penetration depth) vary with the thickness, inducing non smooth and monotonous behaviours. For illustrative purpose, Figures 9a, 9b and 9c show the internal volumetric heat flux according to the product thickness at each processing time, for a constant power of 2 kW in order to compare. The different curves are relative to the evolution of the microwave absorbed power as a function of processing time. It can be noticed that between 10 and 12 mm (figure 9a, 9b), this flux is considerably reduced. On the contrary, this one increases for 15 mm (figure 9c).

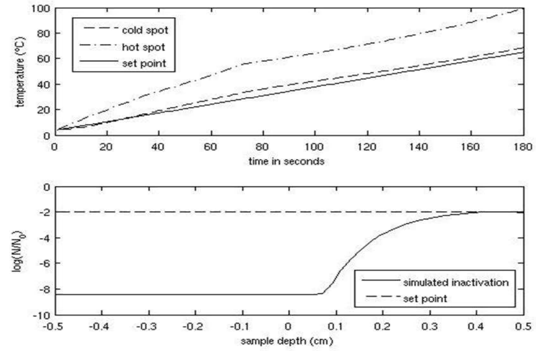

Fig. 2. Temperatures (a) and inactivation (b) with optimal powers [3.9 – 3 – 1.6 – 1.5 – 1.6] kW. 10mm thickness

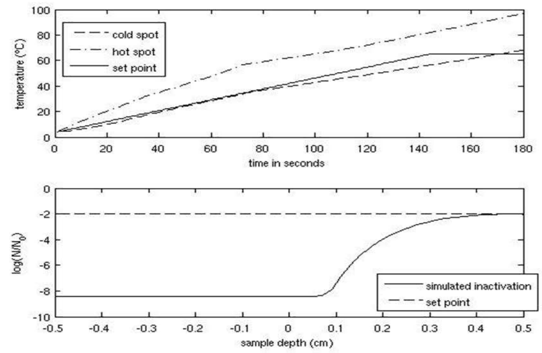

Fig. 3. Temperatures (a) and inactivation (b) with optimal powers [4 – 3 – 1.5 – 1.5 – 1.4] kW. 10mm thickness

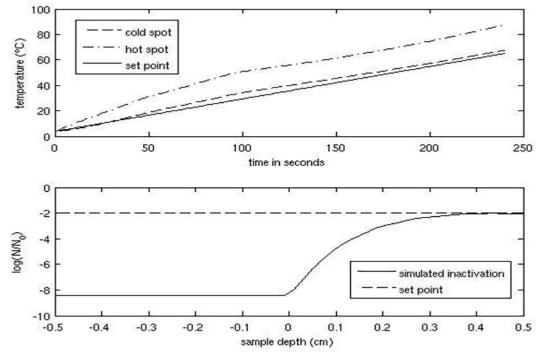

Fig. 4. Temperatures (a) and inactivation (b) with optimal powers [2.8 – 2 – 1.2 – 1.2 – 1.2] kW. 10mm thickness

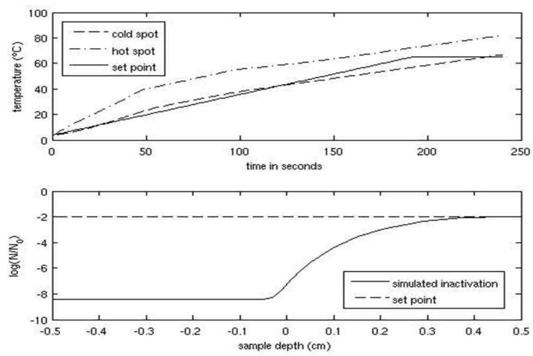

Fig. 5. Temperatures (a) and inactivation (b) with optimal powers [3.7 – 1.7 – 1.0 – 1.0 – 0.9] kW. 10 mm thickness

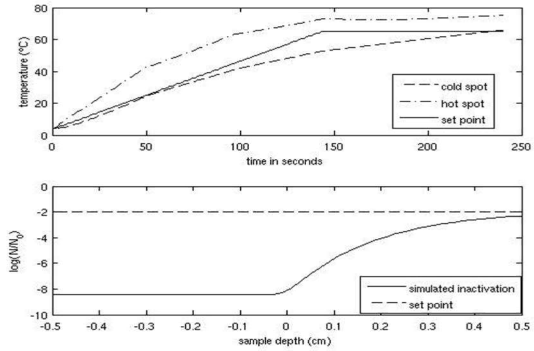

Fig. 6. Temperatures (a) and inactivation (b) with optimal powers [3.9 – 2.1 – 1.1 – 0.45 – 0.45] kW. 10 mm thickness

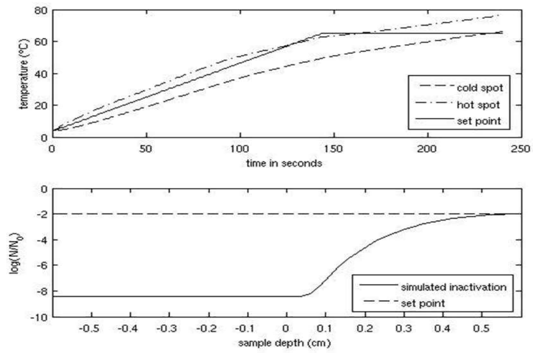

Fig. 7. Temperatures (a) and inactivation (b) with optimal powers [2.8 – 3.2 – 2.3 – 1.4 – 1.4] kW. 12 mm thickness

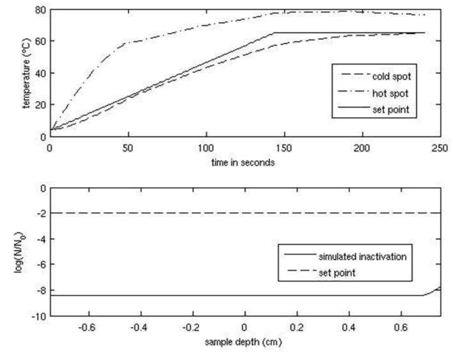

Fig. 8. Temperatures (a) and inactivation (b) with optimal powers [3.8 – 2.3 – 1.8 – 0.5 – 0] kW. 15 mm thickness

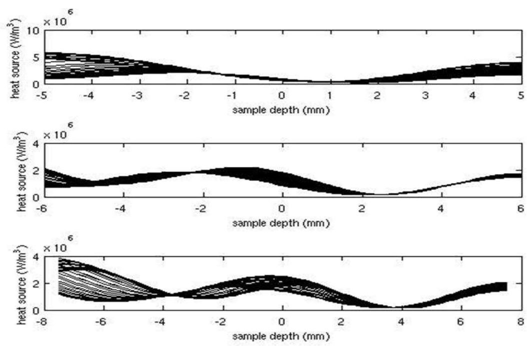

Fig. 9. Volumetric heat flux according to the product thickness for a constant power of 2 kW and 3 different thicknesses: a) 10 mm b)12 mm c)15 mm

5. CONCLUSIONS

The tool proposed in this contribution has the objective to assist operators in the settings of parameters of a conveyorized microwave process, as the power of the successive generators and the conveyor belt velocity. The Illustration of the relevance of this approach has been proposed for simultaneous cooking and pasteurization, but it can be adapted to other problems such as cooking, thawing, tempering (…) provided that the thermal and dielectric properties are known.

At last, it illustrates perfectly the difficulties met with microwaves especially in terms of heterogeneity, reinforced by resonance phenomena and thermal runaway widely dependent of the geometry and dielectric parameters.

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