A MODELING-BASED APPROACH TO DESIGNING MICROWAVE STERILIZATION PROCESSES FOR LOW ACID FOODS

T.N. Koutchma[•], *E.K. Murphy*[°•] *and V.V. Yakovlev*[°]

[•]Agriculture and Agri-Food Canada, Guelph, ON, Canada
[°]Worcester Polytechnic Institute, Worcester, MA, USA
[•]Rensselaer Polytechnic Institute, Troy, NY, USA

In order to design a sterilization process for low acid foods, a time-temperature profile in the coldest point of the product is needed to determine required process lethality (the F value) and processing time. In microwave sterilization, the location of the coldest spot is generally unknown – it varies in time and depends on a number of process and product parameters. In addition, there are substantial technical difficulties in measurement of temperature in that point. In this paper, we introduce an original modeling technique which may assist in designing microwave sterilization processes. Computer simulation is employed for determining 3D temperature distributions in the food processed in an applicator of a chosen design. We adopt here microwave processing in a pulsing regime eventually leading, due to the heat diffusion, to a uniform temperature field. The developed computational procedure monitors the location and temperature of the coldest spot and calculates microbial reduction and quality degradation of foods based on kinetic rate parameters. The technique is illustrated by its application to a rectangular cavity containing a food product (mashed potato). Time-temperature characteristics of the process considered against the F value varying in time demonstrate the ability of the proposed technique to characterize microwave sterilization processes by correlating process lethality with the level of temperature uniformity.

Introduction

Microwave-based technology has the potential to provide food processors with opportunities of rapid volumetric heating and benefits of superior quality that are not available from conventional heating for a wide variety of products including sterilization of pre-packaged low acid foods (LACF) (pH > 4.5). The general performance objective of LACF sterilization process is to achieve a required reduction of pathogenic and spoilage microbial spores. In particular, 12-logs reduction of *Clostridium botulinum* spores in the coldest spot of the product is traditionally considered as minimum process lethality $F_p = F_0$ characterized as equivalent time necessary for thermal treatment at the reference temperature T_R to achieve that reduction [1, 2]; for instance, for $T_R = 121°C$, $F_0 = 2.4$ min.

In general, calculation of process lethality can be performed with the use of the expression [1, 2]:

$$F_p = \int_0^t 10^{\frac{T(t)-T_R}{Z}} dt \qquad (1)$$

where t is heating time, $T(t)$ is time-temperature history in the coldest spot, and Z is microbial thermal resistance (determined experimentally – e.g., $Z = 10°C$ for microbial spores). When this approach is used for characterizing conventional sterilization, process lethality F_p is evaluated as the equivalent processing time with the coldest spot taken in a geometrical center of the package and variable temperature $T(t)$ measured at this point.

Non-uniformity of microwave-induced temperature within the product is generally acknowledged as a critical limitation for using microwaves for sterilization of LACF. Indeed, a time-temperature profile of the coldest spot is very difficult to measure since, in the course of microwave heating, a position of the point with minimum temperature T_m may unpredictably vary. Moreover, it is commonly accepted that evaluation of microwave process lethality on the basis of the assumption that the coldest spot is located in a geometrical center may be fairly inadequate (see, e.g., [3]).

In this paper, we propose a modeling-based approach to these issues that may be helpful in designing microwave sterilization processes. With the use of a computational procedure determining 3D microwave-induced temperature distributions, we monitor the migration of the point with minimum temperature. The obtained profile $T_m(t)$ is then used to calculate microwave process lethality F_p from (1). To demonstrate the functionality of this approach, we apply it to a microwave sterilization process with a characteristic $T_m(t)$ associated with different points of the food product. To imitate such a scenario, we consider a process with pulsing microwave energy and modify the computational procedure the way that heat relaxation in power-off periods is accurately taken into account. It is shown that the developed technique allows for correlating the time-temperature profiles of the food sample (leading to the uniform temperature distribution) with the process lethality F_p.

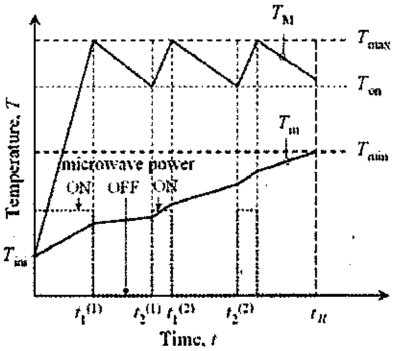

Fig. 1. Conventional interpretation of pulsing microwave heating towards uniform temperature field [6].

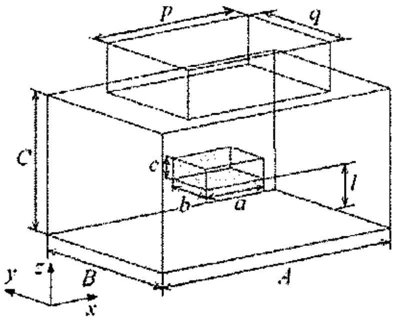

Fig. 2. 3D view of the considered microwave system.

Table 1. Temperature Dependent Material Parameters of Mashed Potato [8, 9]

T (°C)	ε'	σ[S/m]	c[g°C]	ρ[g/cm³]	k[cm°C]
20	56.4	1.1336	3.72	1.05	0.005585
40	56.8	1.2048	3.73	1.05	0.005858
60	55.3	1.3268	3.74	1.05	0.006116
80	53.6	1.5606	3.75	1.05	0.006374
100	52.8	1.8249	3.76	1.05	0.006650
120	52.5	2.2570	3.77	1.05	0.006900
140	52.5	2.8975	3.78	1.05	0.007160

Technique

One of the critical problems of microwave sterilization is measurement of temperature in the coldest spot of the product while location of this spot is unknown. To this end, we suggest to design microwave sterilization processes with the use of a suitable modeling technique allowing for finding 3D distributions of the temperature field in different time instances and process lethality.

The underlying technique used in this study deals with two physical processes – electromagnetic wave propagation and heat diffusion. A numerical solution for the corresponding coupled problem with temperature-dependent material parameters is obtained using an appropriate iterative framework in which each sub-problem is solved independently [2]. Numerical results are obtained using the full-wave 3D conformal FDTD simulator *QuickWave-3D* (*QW-3D*) and the *QW Basic Heating Module* (*QW-BHM*) that employs the special routine called *QW Heat Flow Module* (*QW-HFM*) [4]. The latter communicates with *QW-BHM* by getting information about the initial state of the heated product in an `*.hfe` file and by generating an `*.hfi` file which contains the updated temperature fields [2, 5]. The computed volumetric temperature fields are processed by a MATLAB code that locates the coldest spot, monitors its movements in the course of heating time, and records the time-temperature profile of this point. This information is then used for calculating process lethality in accordance with (1).

To make our approach practically valuable, we ensure its applicability to the scenarios with realistic $T_m(t)$ characterized by increasing temperature and associated with the coldest spot migrating within the product. Such a process is imitated with the use of pulsing microwave energy. As a result, the heating occurs not only due to microwaves, but also with the mechanism of heat diffusion. The pulsing regime provides the condition for raising T_m and excludes overheating of the product in the hot spots (by limiting maximum temperature T_M). In this consideration, we follow the concept of homogenization of temperature field with pulsing microwave energy (Fig. 1) originally introduced as a part of the modeling-based synthesis of microwave heating processes with minimized time-to-uniformity t_u [5-7].

The developed computational procedure possesses the capability to simulate pulsing microwave heating by accurately taking into account heat relaxation in the periods when microwave power is off ($t_1^{(i)}$ to $t_2^{(i)}$, $i = 1, 2, \ldots$). This function is implemented here similarly to [5-7] by appropriately modifying the `*.hfi` file used in communications between *QW-BHM* and *QW-HFM*.

Illustrative Results

In order to demonstrate the functionality of the proposed technique, we consider a simple microwave system (Fig. 2) consisting of a rectangular cavity ($A \times B \times C$ = 400×200×264 mm) with a rectangu-

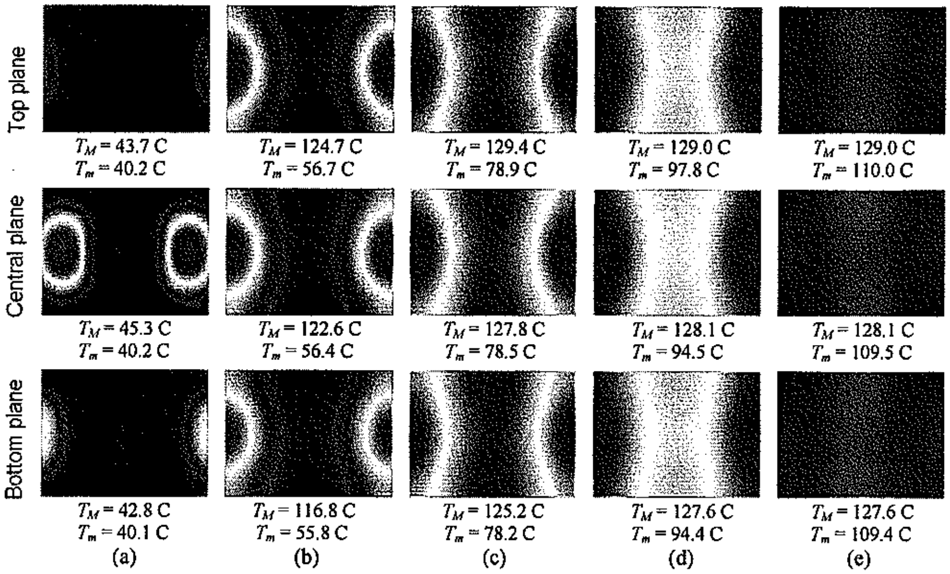

Fig. 3. Temperature patterns in the horizontal (*xy*-) planes through the load in the course of homogenization of the temperature field: initial pattern after 10 s (a), intermediate patterns after 18.9 min (b), 48.3 min (c), and 77.2 min (d) and nearly final pattern after 120.8 min (d) normalized to maximum temperature of the product at each time step.

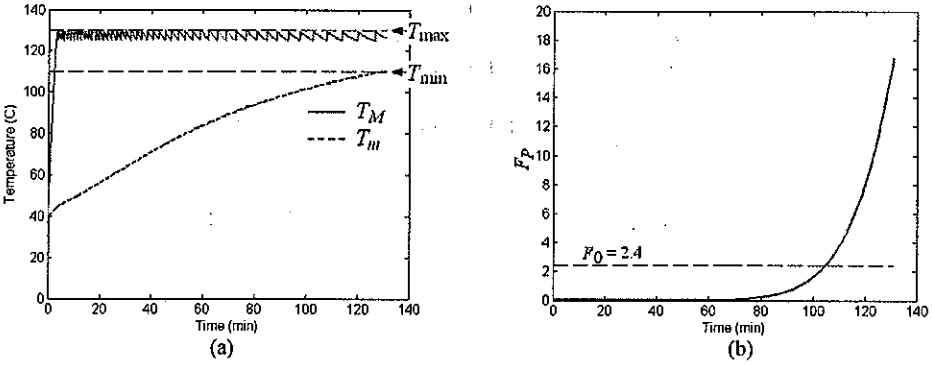

Fig. 4. Time-temperature characteristics of the product in the microwave system (Fig. 2) operating in pulsing regime (a) and time characteristics of process lethality (b).

lar load ($a \times b \times c$ = 100×76×30 mm) centered at the level of l = 75 mm above the bottom. The system is excited via the rectangular waveguide ($p \times q$ = 248×186 mm) by the TE_{10} mode; the level of input power is 1 kW and the operating frequency is 915 MHz. The food product is mashed potato – its electromagnetic characteristics (relative dielectric constant ε' and electric conductivity σ) and thermal characteristics (specific heat c, thermal conductivity k, and density ρ) are temperature dependent in accordance with the experimental data (Table 1) taken from [8] and [9] respectively. For the considered sterilization temperature T_s, the level of uniformity of temperature field is defined by the values of $T_{\min} < T_s < T_{\max}$. The product is assumed to have the initial temperature T_{ini} and a temperature step in relaxation is $T_{\text{on}} = T_{\max} - 5$ °C.

The temperature field produced by the 10 s microwave heating time step (Fig. 3 (a)) shows the heating pattern of "continuous" microwave processing; it is obvious that microwave sterilization cannot be achieved with this pattern due to the inevitable overheating of the product in the hot spots and poor thermal processing (and thus insufficient microbial reduction) in the underheated zones. However, the heating pattern can be evened with pulsing microwave heating – this is illustrated by a series of temperature distributions shown in Fig. 3 (b)-(e) and generated for T_s = 121°C, T_{ini} = 40°C, $T_{\max}$ = 130°C, and $T_{\min}$ = 110 °C. Corresponding time characteristics of T_M in the hottest point and T_m in the coldest point of the product are given by Fig. 4 (a) whereas the time history of process lethality F_P is plotted in Fig. 4 (b). The graph in Fig. 5 shows the trace of the locations of T_m in its 3D migration

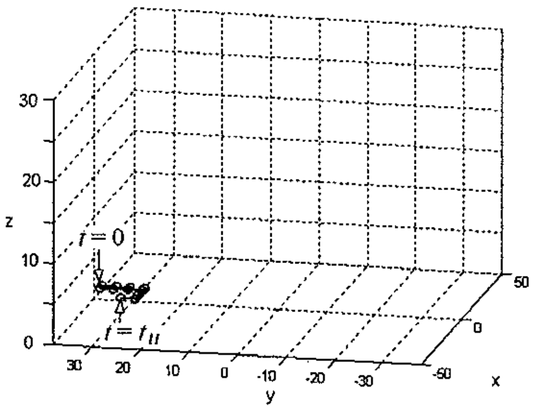

Fig. 5. Variable position of the minimum temperature within the load in the process represented by Fig. 4.

Table 2. Process Lethality and Level of Temperature Uniformity in the Microwave Heated Product

T_{max} / T_{min} (°C)	$\Delta T = T_{max}-T_{min}$ (°C)	Time to uniformity, t_u (min)	Time at F = 2.4, $t_{F=2.4}$ (min)	F_P at time to uniformity, F_{tu}
122.5 / 117.5	5	324	150	111
125 / 115	10	192	132	32
127.5 / 112.5	15	154	117	22
130 / 110	20	130	105	16

within the load in the course of heating. The effect of temperature interval ΔT between the prescribed maximum and minimum temperatures around T_s on the total heating time needed to achieve uniform temperature t_u and on process lethality F_P at t_u is demonstrated by the data in Table 2. In particular, the increase of ΔT results in decrease of t_u and F_P.

It can be seen that in a microwave sterilization process characterized by slowly raising T_m, process lethality does remain below minimum process lethality $F_0 = 2.4$ min for a large fraction of time t_u. On the other hand, the level of F_0 can be reached not necessarily through a high level of temperature uniformity, but with sufficiently long processing time.

Conclusion

A computational procedure has been developed to accurately calculate process lethality of microwave sterilization of LACF on the basis of time-temperature history in the coldest spot of the product; the latter is proposed to be obtained from modeling. Along with the option to correlate process lethality with the level of temperature uniformity of microwave-induced temperature field, this makes the proposed approach a unique, convenient and accurate tool having the potential to assist in designing processes of microwave sterilization.

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