Microwave Inactivation of Bacteria under Dynamic Heating Conditions in Solid Media

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Abstract: In this study, COMSOL® Multiphysics 4.2a is used to model a microwave heating process in a TE_{10} rectangular waveguide (3D geometry). The sample consists of a small cylindrical Ca-alginate gel ($D = 8$ mm, $H = 10$ mm) inoculated with bacteria *Escherichia Coli* K12. The sample is placed along the microwave propagation direction into the waveguide. Maxwell's equations and heat transfer are coupled to a microbial inactivation model (Geeraerd et al., 2000) under dynamic heating conditions (use of RF module, heat transfer and 2 ODE equations). The microwave inactivation of bacteria is compared to a conventional inactivation by conduction with the same heating ramp during 4 min 30 s. The study clearly demonstrates that the microwave heating of small cylindrical sample is not homogeneous under dynamic heating conditions resulting in lower bacteria inactivation comparing to conventional heating.

Keywords: microwave, modeling, inactivation, gel media, *Escherichia Coli*

1. Introduction

In food industry, the pasteurization process is a thermal unit operation that enables to insure the microbiological quality of food products. Among recent innovative technologies, the microwave heating process has been successfully applied to inactivate pathogen organisms (Giuliani et al., 2010, Zhou et al., 2010). Nevertheless, the development of this technology needs to be improved, especially with a better knowledge concerning the interaction of bacteria with the electromagnetic field. One of the major drawback of microwave heating remains the non uniformity of temperature distribution inside the processed material (Vadivambal & Jayas, 2010). This phenomena is highly dependent on the geometry and can be predicted from numerical modeling (Curet et al., 2009). In the case of pasteurization of food products, hot and cold spots need to be predicted accurately to insure the global inactivation of bacteria. Recent studies depicts modeling of temperature distribution on cylindrical sample for lateral and radial irradiation (Basak, 2007, Basak, 2011). These theoretical studies are dedicated to plane electromagnetic waves and 2D geometries. To our knowledge there is no study dealing with the 3D modeling of small cylindrical solid sample during a microwave pasteurization process. The sample is a cylindrical shaped Ca-alginate gel and inoculated with bacteria *Escherichia Coli* K12.

The first part of the article concerns the governing equations that describe the coupling between physical phenomenons. Then, the modeling approach with COMSOL® is presented with the geometry and the mesh generation. The numerical results are then compared and discussed between the microwave pasteurization process and the conventional thermal treatment.

2. Governing equations

The objective consists in modeling the microwave heating of two small cylindrical samples placed into a TE_{10} rectangular waveguide. Due to symmetry consideration, only one half of a cylinder is considered (figure 1).

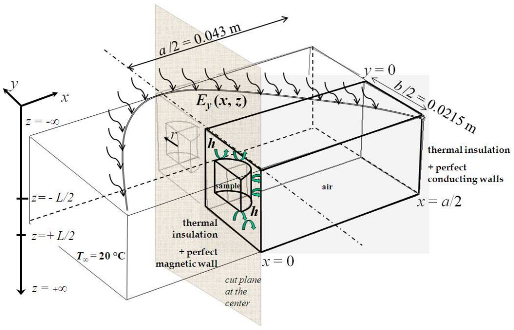

Figure 1. Model design

The reduced geometry enables to save computational time to insure a better efficiency during simulation.

2.1 Electromagnetic modeling

The classical Maxwell's equations describe the electric field propagation following the *z*-direction (sinusoidal time-varying fields) with a pulsation $\omega = 2\pi f$ with $f = 2.45$ GHz. Within dielectric mediums without free charges and free currents, COMSOL® solves the governing equation for the electric field propagation in the fundamental TE_{10} mode, as follows:

$$\nabla \times \mu_r^{-1}(\nabla \times E) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0 \;\; with \;\; k_0 = \omega\sqrt{\varepsilon_0\mu_0}$$

where k_0 is the propagation constant (m^{-1}) within vacuum.

For the TE_{10} fundamental mode ($E_x = E_z = 0$), the mathematical simplification leads to:

$$\left(\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2}\right) + \omega^2\mu\varepsilon'\left(1 - j\frac{\sigma}{\omega\varepsilon'}\right)E_y = 0$$

where σ is the electrical conductivity (S/m) of the lossy material:
$\sigma = 2\pi f\varepsilon_0\varepsilon_r''$

The initial and boundary conditions can be described as follows:

$$\begin{cases} E = 0 \;\; at \;\; t = 0 \; \forall xyz \\ E_y(x) = E_0 \cos\left(\frac{\pi x}{a}\right) at \; z = -\infty, \forall xy; \;\; E_0 = 4Z_{TE}\frac{P_{in}}{ab} \\ E_y = E_{\tan} = 0 \; at \; y = 0, \; y = b/2, \forall xz \; and \; at \; x = a/2, \forall yz \\ n \times H = 0 \; at \; x = 0, \forall yz \\ n \times (H_{air} - H_{sample}) = 0 \; at \; r = R, \forall z \; and \; z = \pm L/2, \forall r \end{cases}$$

Z_{TE} is the impedance (Ω) of the electromagnetic wave within the TE_{10} waveguide.

The microwave input power is fixed at 130 W. The Maxwell's equations are solved in both air surrounding medium and the sample.

2.2 Heat transfer modeling

The temperature evolution within the sample is described from the general heat equation which depends on thermophysical properties of the sample:

$$\rho C_p \frac{\partial T}{\partial t} = div.(k\nabla T) + Q_{abs}$$

The initial and boundary conditions for the thermal problem are the followings:

$$\begin{cases} T = T_0 & at \;\; t = 0, \forall xyz \\ k\nabla T = h(T - T_\infty) & at \; r = R, \forall z \; and \; z = \pm L/2, \forall r \end{cases}$$

As a first approximation, the heat transfer coefficient *h* due to natural convection between air surrounding medium and the sample surface is obtained from an empirical correlation dedicated to vertical isothermal cylinder with a correction factor (Cebeci, 1974).

The heat source term represents the heat generated by microwaves due to dielectric losses.

$$Q_{abs} = \frac{1}{2}\omega.\varepsilon_0.\varepsilon_r''.|E_{local}|^2$$

where E_{local} is the local electric field strength at any point of the sample.

2.3 Modeling thermal inactivation

The thermal inactivation of bacteria is modeled as a function of classical *D* and *z*-values and physiological state of the cells (Geeraerd et al., 2000). In this study, the tailing effect is not considered for *Escherichia Coli* K12.

$$\begin{cases} \frac{dN}{dt} = -k_{\max}\cdot\left(\frac{1}{1 + C_c}\right) . N \\ \frac{dC_c}{dt} = -k_{\max} . C_c \end{cases}$$

where k_{max} is the specific inactivation rate (s^{-1}) linked to the kinetics of microbial destruction. The Bigelow model (Bigelow, 1921) characterizes the inactivation kinetics during dynamic heating. This model is coupled through the thermal problem by the following expression.

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

The reference temperature, T_{ref}, is the middle temperature within the lethal range of bacteria from 50 to 64 °C (Valdramidis et al., 2008).

The D_{ref} and z-values were already identified from preliminary experiments performed during a dynamic water bath inactivation. For this study, the following inactivation parameters were used: $D_{57} = 234$ s, $z = 6.28$ °C
The initial cell concentration over the whole sample volume is fixed at $N_0 = 10^9$ CFU/g.

2.4 Thermophysical and dielectric properties

The table 1 depicts the thermophysical and dielectric properties of the sample which are directly taken from the literature for a sodium alginate gel (Lin et al., 1995). Those properties remain a first approximation to avoid complex experimental measurements with the calcium alginate gel. Thermophysical properties are considered as constant and dielectric properties are temperature dependant.

Table 1: Thermophysical and dielectric properties of the sample

Density, ρ ($kg.m^{-3}$)	1010
Specific heat, C_p ($J.kg^{-1}.K^{-1}$)	4120
Thermal conductivity, k ($W.m^{-1}.K^{-1}$)	0.84
Dielectric constant, ε'_r	$81.79-0.299\times T$(°C)
Loss factor, ε''_r	$22.6-0.378\times T+2.93\times10^{-3}\times T^2$

3. Use of COMSOL® Multiphysics

The time dependant model is solved with COMSOL® Multiphysics 4.2a (RF module, heat transfer module and 2 ODE equations).
The mesh is controlled and consists of 26750 tetrahedral elements (figure 2).

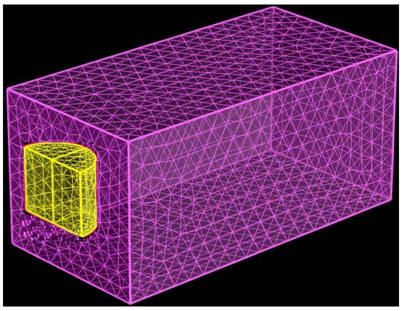

Figure 2. Mesh of the computational domain: ½ of cylindrical sample (yellow), air filled waveguide (magenta)

The mesh independence of numerical results was also tested successfully. In order to simulate 270 s (4 min 30 s) of the complete microwave heating process, the total CPU time required was approximately 10 minutes on a SUN® Microsystems U40 Workstation, equipped with 2×AMD® Opteron processors, at 3 GHz, with 20 GB of RAM, running on RedHat® Enterprise LINUX 5, 64 bits.

4. Numerical results

4.1 Inactivation of bacteria

The inner temperature of the sample is detected at the centre of the cylinder. The thermal treatment is performed from 20 °C to 62 °C. A mean heating rate of 9 °C/min corresponds to the temperature increase during microwave heating experiments (figure 3). The microbial inactivation equations are successfully coupled to the thermal and electromagnetic problems. The numerical model enables to predict the local inactivation of bacteria during dynamic heating at any point of the sample (figure 4).

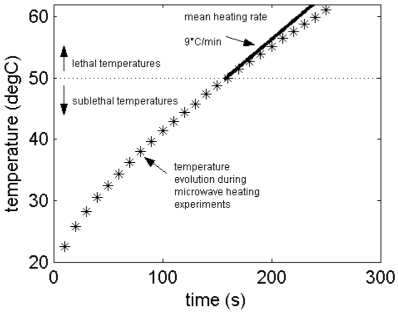

Figure 3. Temperature evolution during microwave heating experiments.

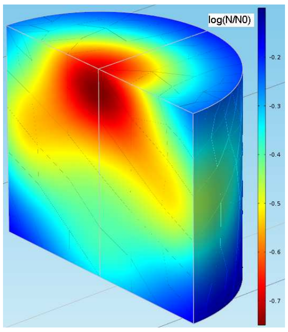

Figure 4. Local microbial inactivation at the end of microwave processing (t = 270 s)

In figure 4, the COMSOL® simulation highlights the non uniform inactivation of bacteria during microwave heating. The highest microbial reduction is achieved near the centre of the cylinder (≈ -0.7 log) whereas surrounding edges are still un-affected.

The global inactivation is computed with COMSOL® by integrating the results over the whole sample volume.
Results are compared to a conventional thermal treatment by conduction with the same heating ramp of 9 °C/min (figure 5).

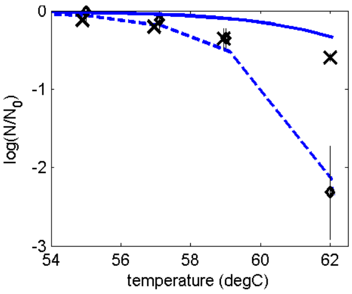

Figure 5. Global inactivation of bacteria as a function of lethal temperatures; ◊ water bath experiments with 9°C/min; -- simulation for water bath inactivation; × microwave experiments; — simulation for microwave inactivation

From 54 °C to 59 °C, microwave and water bath inactivation data give similar results (≈-0.5 log). For $\theta > 59$°C, the dynamic heating with microwaves leads to lower microbial inactivation comparing to conventional water bath treatment. The numerical results are in good agreement with experimental data.

The inactivation of bacteria during microwave heating can be successfully modeled with the D and z values issued from water bath experiments. Hence, this result demonstrates that the microwave inactivation of bacteria is mainly due to a thermal phenomenon. It is now proposed to model the temperature distribution inside the sample to explain the differences between microwave and water bath inactivation.

4.2 Sensitivity analysis

A sensitivity analysis is performed in order to quantify the uncertainty of simulated temperatures on model parameters. Three input parameters are selected for the sensitivity analysis (dielectric constant ε'_r, loss factor ε''_r and convective heat transfer coefficient h). The parameter variation is fixed to ± 10 % around the nominal values of each parameter (figure 6).

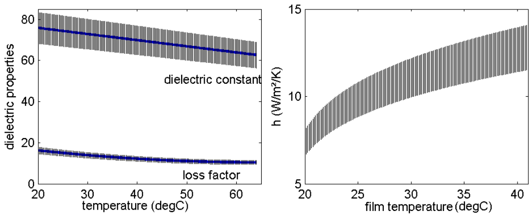

Figure 6. Variations of dielectric parameters (left) and convective heat transfer coefficient (right) as a function of temperature.

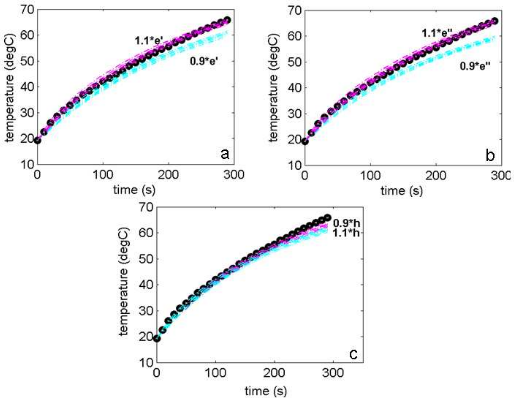

Figure 7. Influence of dielectric constant (a), loss factor (b) and heat transfer coefficient (c) on temperature evolution within the sample; -- simulation (+10% = pink; -10% = cyan), ◙ experiments

The microwave heating process is simulated during 270 s and the temperature is detected at the geometrical centre of the cylinder.

Within the range of ±10% around nominal values, the sensitivity analysis reveals the following conclusions (figure 7):

- The simulated temperatures at the centre are in good agreement with experimental measurements. The temperature is not highly modified due to dielectric properties variations (except for $0.9\times\varepsilon''_r$ where simulated temperatures slightly deviate for $t > 200$ min). The sensitivity analysis for dielectric properties demonstrates the reliability of predicted temperature. The literature values for the sodium alginate gel may be a good start point without knowledge of real dielectric characteristics of our sample.
- The natural convection at the cylinder's surface does not significantly influence the temperature distribution at the centre. Even if the temperature of the cylinder is non isothermal, this result demonstrates the reliability of using an empirical correlation to model natural convection at the sample surface.

4.3 Temperature distribution

The following simulations are performed with thermophysical and dielectric properties of the sodium alginate gel (table 1).

The numerical model highlights the thermal heterogeneities at the end of microwave processing (figure 8). For a small cylindrical volume (0.5 mL), the temperature gap between the cold and hot spot is 5°C. The probe location was initially chosen close to the centre which is not far away from the theoretical hot spot.

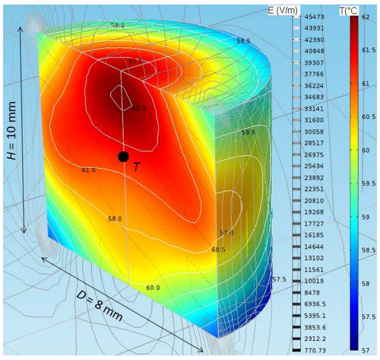

Figure 8. Temperature and electric field patterns at the end of microwave processing (t = 270 s)

Local electric field concentrations can be detected around the sample edges. This heterogeneous electric field distribution is mainly due to the geometry and dielectric properties of the processed material.

5. Conclusions

This study highlights the non uniform heating patterns within a small cylindrical volume during the microwave pasteurization. As a consequence, this process leads to lower bacteria inactivation comparing to conventional heating treatments. The simulations and the experiments demonstrate the thermally induced bacterial inactivation during the microwave pasteurization process. However, the lowest bacteria inactivation rate was observed during a dynamic heating with a linear heating ramp from 20 to 62°C. During microwave processing, the bacteria are submitted to lethal temperatures during a few seconds. The numerical simulations should now include the dynamic heating process with a temperature controlled loop that enables to maintain the temperature within the lethal range in order to insure better cells inactivation.

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