Solid Food Pasteurization by Ohmic Heating: Influence of Process Parameters

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Abstract: Pasteurization of a solid food undergoing ohmic heating has been analyzed using a mathematical model based on a previously validated (Marra et al., 2008) multi-physic model solved with COMSOL 3.3.
Modelling ohmic pasteurization involved simultaneous solution of:
1) Laplace's equation which describes the distribution of electrical potential within a food;
2) heat transfer equation using a source term involving the displacement of electrical potential;
3) kinetics of inactivation of microorganisms likely to be contaminating the product.
In the model, thermo-physical and electrical properties as function of temperature are used.
Previous work by the current research team has shown the occurrence of heat loss from solid products to the ohmic cell wall and electrode surfaces. The current model predicted that, when temperature gradients established in the proximity of the outer curved surface, more cold areas were present at junctions of electrodes with lateral sample surface. For these reasons, colder external shells were the critical areas to be monitored, instead of internal points (typically geometrical center) as in classical pure conductive heat transfer.
Analysis was carried out in order to understand the influence of pasteurization process parameters on this temperature distribution. A successful model helps to improve understanding of these processing phenomena which in turn will help to reduce the magnitude of the temperature differential within the product and ultimately provide a more uniformly pasteurized product.

Keywords: Ohmic heating, meat pasteurization, heat transfer, microorganism inactivation.

1. Introduction

Electroheating processes, such as microwave, radio-frequency or ohmic heating, can help industry to develop faster and more efficient thermal processes, including microbial inactivation. Inactivation of microorganism potentially affecting foods is an important industrial application using heat as principle responsible of microbial inactivation.

Nowadays, a large number of potential future applications exist for ohmic heating: blanching, evaporation, dehydration, fermentation, and pasteurization/sterilization of liquid or liquid containing particulates. The main advantages of ohmic processing are the rapid and relatively uniform heating achieved. This is expected to reduce the total thermal abuse to the product in comparison to conventional heating, where time must be allowed for heat penetration to occur to the center of a material and particulates heat slower than the fluid phase of a food. While some evidence exists for non-thermal effects of ohmic heating, the principal mechanisms of microbial inactivation in ohmic heating are thermal in nature. Being fundamentally a thermal-based process, temperature and time are the principal critical process factors and, as in conventional thermal processes, the key problem is locating the spot or the areas of minimum thermal treatment, as in other electroheating applications (Datta and Davidson, 2000).

Goal of this paper is analyzing the influence of process parameters in locating the cold spot or areas during ohmic heating of solid like foods, using a model developed and validated in a previous work (Marra et al. 2008).

2. Governing Equations

Modelling ohmic pasteurization involveed simultaneous solution of:
1) Laplace's equation describing the distribution of electrical potential within a food;

2) heat transfer equation using a source term involving the displacement of electrical potential;
3) kinetics of inactivation of microorganisms likely to be contaminating the product.
In the model, a cylinder filled of meshed potatoes was considered as sample, its thermo-physical and electrical properties being function of temperature (Marra et al., 2008). Configuration of heating system is reported in figure 1. The sample is contained in the light blue cylinder that is held by the dark blue electrodes.

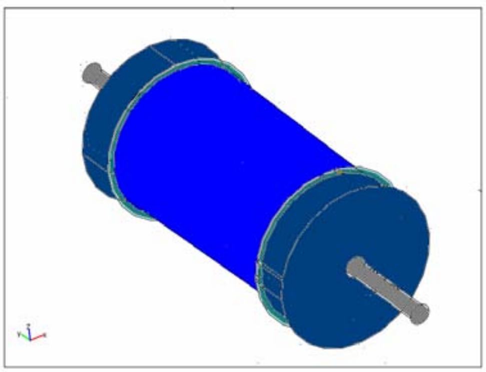

Figure 1. A sketch of the ohmic cell used to derive the simulation model. Details about dimensions and configuration can be found in Marra et al., 2008.

According to quasi-static approach, the electrical potential distribution within the sample can be computed using the following Laplace equation:

$$\nabla \cdot \sigma \nabla V = 0 \qquad (1)$$

Electrical potential distribution and, then, electrical conduction, generates into the product a certain density of power, as described by the following equation:

$$Q_{GEN} = \sigma \left| \nabla V \right|^2 \qquad (2)$$

where σ is the electrical conductivity, and $|\nabla V|$ represents the modulus of the gradient of electrical potential.

The heat transfer occurring during the process was described by the classical unsteady state heat equation by conduction plus the generation term described by eq. (2), as reported below

$$\rho \, Cp \frac{\partial T}{\partial t} = \nabla k \, \nabla T + Q_{GEN} \qquad (3)$$

where T is the temperature within the sample, t is the process time, k is the thermal conductivity, ρ is the density, Cp is the heat capacity and Q_{GEN} represents the ohmic power source, as in the equation (2).
Since the electrical conductivity is a function of temperature, equations (1) and (3) are strictly related to each other and must be solved simultaneously (Jun & Sastry, 2007).

Once temperature distribution is known, coldest point or areas can be determined and, in their correspondence, lethality of micro-organisms can be calculated, as in the following expression

$$L = 10^{\frac{T - Tref}{z}} \qquad (4)$$

where L is the lethality, T is the cold spot temperature at any time t, T_{ref} is the reference temperature of the target microorganism and z is the corresponding z-value.

The accumulated lethality was calculated following the well-known equation for the pasteurization factor

$$F = \int_0^{t_f} 10^{\frac{T - Tref}{z}} \, dt \qquad (5)$$

where F is the pasteurization factor and t_f is the total duration of the heating. Simple explanation of mathematical meaning of lethality and accumulated lethality is given by Marra and Romano (2003).

Target microorganism was *Escherichia coli*, usually considered the main microorganism for hygienic safety of meat, that is the product we intend to treat in the final pilot plant based on the application proposed in this work.

3. Initial and Boundary Conditions

The quasi-static representation of electric potential balance in Laplace equation (1) needed only boundary conditions to be solved, being a stationary-state equation; the heat transfer equation (3) needed initial condition and boundary conditions.

For the Laplace equation the following boundary conditions were assumed: an applied voltage between the two electrodes and a complete electrical insulation of the lateral external sample surface.

Prior to commencing ohmic heating it was assumed that the entire sample was at a uniform temperature T_0. As boundary conditions for the heat transfer equation, two different cases were considered: the first one assumed that the entire sample is thermally insulated; the second one assumed a general external heat transfer given by

$$q_{ext}=U\,(T-T_{inf}) \qquad (6)$$

where U is an overall heat transfer coefficient, that takes into account any possible composite resistance such as multi-layers around the ohmic cell and T_{inf} is the external environment temperature.

The thermally insulated case represents the best (ideal) process condition, given that no heat is lost toward the external environment. The second case represents one of possible conditions when heat is lost toward the external environment: particularly, $5<U<10$ W m^{-2} K^{-1} corresponds to the typical range of values for overall heat transfer coefficient under conditions similar to the ones considered in this work (Singh and Heldman, 2001). An experimental validation of the model suggested the value of U is 5 W m^{-2} K^{-1} as best fitting value provided by experimental validation of model (Marra et al., 2008).

4. Numerical Solution

The set of equations above introduced, with their relative initial and boundary conditions, were solved by means of Comsol 3.3, running on a PC, equipped with two Intel Xeon CPUs, at 2.00 GHz, with 4 Gb of RAM, running under Windows XP Professional.

An implicit time-stepping scheme was used to solve time-dependent problems: at each time step, the software solved a possibly nonlinear system of equations. The nonlinear system was solved using a Newtonian iteration. An arbitrary linear system solver was then used for the final resulting systems (Comsol 3.3 User Guide). For the purposes of this research, a direct linear system solver (UMFPACK) was used. Relative tolerance was set to 1×10^{-2} whereas absolute tolerance was set to 1×10^{-3}.

Numerical tests were performed with different mesh parameters in order to evaluate the simulation results and to find the best mesh settings. The set providing the best spatial resolution for the considered domain and for which the solution was found to be independent of the grid size, was composed of 10217 tetrahedrons, 1396 boundary elements, 100 edge elements, with 30170 of degree of freedom.

5. Results

The solution of the system composed by the equations (1)-(5), with the conditions stated in section 3, provided the distribution, in the space and during the time, of temperature, lethality and accumulated lethality. In order to understand the influence of some process parameters, such as the conditions (represented by coefficient U and external temperature T_{inf}) of heat exchange with the external environment, the thermal diffusivity of the sample and its electrical conductivity, the difference of potential applied between the electrodes, a sensitivity analysis was accomplished by varying each parameter and then reading the corresponding change in temperature, lethality and accumulated lethality.

Different temperature distributions, reported as slice plots after 150 seconds of ohmic heating driven by a differential of electrical potential between electrodes of 100 V, are shown in figure 2, where no external heat exchange (U=0 W m^{-2} K^{-1}, Figure 2a), best fitting value for convective heat exchange coefficient with cold external temperature (U=5 W m^{-2} K^{-1}, T_{inf}=286.15 K, Figure 2b) and with warm external temperature (U=5 W m^{-2} K^{-1}, T_{inf}=314.15 K, Figure 2c) are considered.

While in the perfectly insulated case the sample heated up evenly, when a convective heat transfer from or toward the external environment was considered colder areas appeared, especially in correspondence of sample edges. These areas were critical zones that needed to be monitored in terms of lethality and accumulated lethality. The computation of lethality and accumulated lethality emphasized that the three above mentioned cases needed almost the same heating time in order to achieve a 12D reduction of target microorganism in the less favorite heating zones, as shown in figure 3, where required 12D time is reported for five different sets (S1-S5).

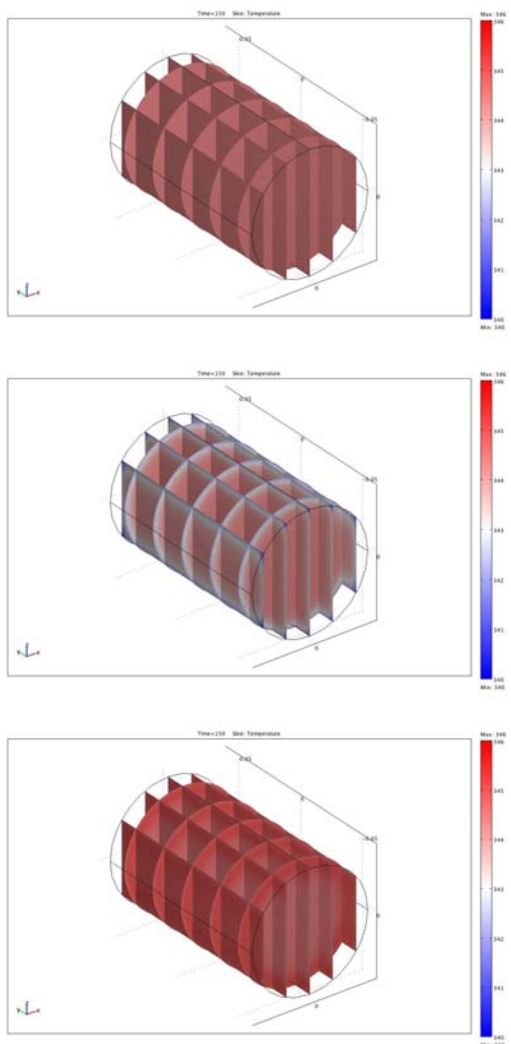

Figure 2. Slice plots representing temperature after 150 seconds of ohmic heating: applied voltage set-point 100 V, initial temperature 279.15 K, $U=0$ W m^{-2} K^{-1}(*a*), $U=5$ W m^{-2} K^{-1} (*b* and *c*) external temperature 286.15 K (*b*) and 314.15 (*c*).

The model suggested that the process is much more sensitive to changes in the electrical conductivity of the sample: in fact, an increment of 10% of electrical conductivity leaded to a 12D time almost 20% shorter than the one required for standard set (S1). When a 10% lower value of electrical conductivity was considered, the treatment time required increases of 8%. Changes in thermal diffusivity played a minor role.

When a good insulation of the sample was not provided, external heat transfer conditions changed and treatment time could overcome 200 seconds. While this value was still competitive with respect to pasteurization time required for traditional heating processes (such as steam or water immersion, that can require up to 150 minutes for product of same size), it must be considered that a long exposure to ohmic power of the internal zones of the samples can result in a product damage, both in terms of texture and sensory quality attributes. For this reason, in the design of a unit for pasteurization of solid foods by means of ohmic heating, the developing of an effective control system is necessary.

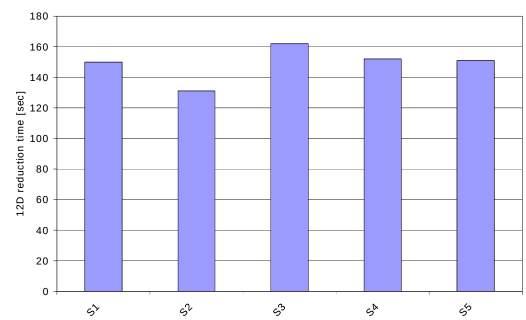

Figure 3. Time required to attain a 12D reduction of target microorganism. S1: $U=0$ W m^{-2} K^{-1}; S2: $U=0$ W m^{-2} K^{-1} and electrical conductivity +10% with respect to S1; S3: $U=0$ W m^{-2} K^{-1} and electrical conductivity –10% with respect to S1; S4: $U=5$ W m^{-2} K^{-1} , with electrical conductivity as in S1 and external temperature of 286.15 K; S5: $U=5$ W m^{-2} K^{-1} , with electrical conductivity as in S1 and external temperature of 314.

Furthermore, two special cases were considered between the electrodes for the runs with perfected insulated walls: 1) maintaining a constant applied voltage and 2) maintaining a constant heat generation. These two cases were very interesting because, while the sample temperature after 150 seconds was virtually the same, its time evolution (and so the lethality and the accumulated lethality) was different. This aspect will be better investigated in future developments of this research.

6. Conclusions

Numerical analysis of ohmic heating of solid foods allowed understanding the role played by some process parameters in temperature distribution within the product and achievement of required time for pasteurization (12D reduction of *E. coli*). Results showed that, according with the appropriate boundary condition, external areas of the product present the slower heating and have to be monitored in term of target microorganism lethality. Pasteurization time is particularly influenced by the sample electrical conductivity, since the generation term appearing in the heat equation is predominant with respect to thermal conduction.

Mathematical modeling is a useful tool for designing an ohimc heating unit for pasteurization of solid foods and virtual experiments can provide important information for developing an effective control system for this process.

7. References

1. Marra, F., Zell, M., Lyng, J.G., Morgan, D.J., and D.A. Cronin, Analysis of heat transfer during ohmic processing of a solid food, *Journal of Food Engineering*, in press (2008), doi:10.1016/j.jfoodeng.2008.08.015

2. Salengke, S., and Sastry, S.K., Experimental investigation of ohmic heating of solid–liquid mixtures under worst-case heating scenarios, *Journal of Food Engineering*, 83 (3), 324-336 (2007).

3. Datta, A.K., and Davidson, P.M., Microwave and Radio Frequency Processing, *Journal of Food Science*, SUP (1 p.1/4), 32-41 (2000).

4. Marra, F., and Romano, V., A mathematical model to study the influence of wireless temperature sensor during assessment of canned food sterilization, *Journal of Food Engineering*, 59, 245-252 (2003).

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