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Modeling Aspects in Simulation of MEF Processing of Solid Behaving Foods

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Moderate Electric Field (MEF) processes involve electric fields less than or equal to 1000 V/cm (Sastry, 2008) and found applications in food heating processes. Industrially, systems based on MEF at 50 Hz (traditionally addressed as ohmic) are employed for heating of liquid food products (sauces, fruit juices) or particulate-dispersed-in-liquid food products (soups).
Solid-behaving heterogeneous systems have been less studied, especially due to the not easy coupling between the physical and electrical characteristics of the materials that constitute the food system subjected to MEF assisted heating.The set-up of a virtual lab able to simulate the MEF assisted heating of a heterogeneous food system allows to investigate on the role played by main process parameters (applied electrical potential, MEF cell geometry and electrode configuration) as well as on materials' electrical conductivity and thermos-physical properties, and also on geometric characteristic of the food system itself. On the other hand, the set-up of such virtual tool is not trivial because it requires the coupling of phenomena of different nature (the passage of electric current in the MEF circuit, including the food loading system; the heat transfer within the food system and its coupling with the local gradient of the electrical potential).
In this work, the modeling aspects related to the simulation of MEF processing applied to a heterogeneous food system are presented. Particularly, the study was devoted to analyzing the MEF heating performances in a food system made by 3 meatballs dispersed in 145 g of reconstituted potatoes. The food system was put in a experimental MEF cell 100 mm long, 51 mm wide, with electrodes made in stainless steel.
The model set-up has been built following the work presented by Marra et al. (2009). Comparison of experimental results with heating trends provided by simulations in different operating conditions (applied potential gradient of 3 and 4 V/cm) have shown a good agreement when dissipative effects were considered on applied potential. Discrepancies may be due to electrolysis happening near the electrodes.

1. Introduction

MEF processing has reemerging in different industrial food processes fields only the last 10 to 15 years, the scientific and technical developments achieved having finally allowed its safe application at the industrial scale. The heating consists by a passage of electric currents in the food matrix. Throughout the joule heating phenomena, the treated electroconductive material could be heated (Sastry, 2008). Comparing the Ohmic heating processes to other electrical methods such as induction, microwave, and radio frequency heating, it has flexibility on the frequency and waveforms of the electric field (Samaranayake and Sastry, 2016). Popular frequencies of ohmic heating tend to be those of power supplies (50 or 60 Hz); However no limitation are present for the use of different voltages and frequencies different from the popular ones and this technology has becoming widely used because it's remarkably rapid and relatively spatially uniform in comparison with other electrical methods (Sastry, 2008). MEF could involve electric fields up to 1000 V/cm depending on the specific desired heating rate and compatibly with the analyzed sample. The MEF processing could be used in many and many applications specially in food industry. Initially, it was adopted to heat liquid-like foods such as fruit juices, soups, sauces, milk etc. (Sepulveda et al. 2005) However, the wide improvements of MEF became attractive for many more types of foods and it started to be adopted in solid foods processing. In spite of the increasing use of MEF in solid foods processing, the MEF heating of heterogeneous systems still represents a challenging problem that has received a limited coverage in the scientific literature, both for the different coupling problems between the physical and electrical characteristics of the materials and for the interfacial

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transfer phenomena that could play a key role and could represent the bottleneck of the overall process performance. Modeling and simulation approaches are receiving more and more interest in different scientific and technological areas and could be quoted as the enabling technology of science and engineering that could describe various scales of complex systems (Jinghai and Kwauk, 2003). Many engineering modelling applications have demonstrated the potential of these tools in a wide variety of fields from bioengineering (Petrosino et al., 2020) to fluid dynamics (Turek et al. 2016).
Modelling and simulation also play a key role in the MEF processes area. Different works are present in the literature. Sastry and Salengke (1998) proposed a comparison among mathematical models for ohmic heating of solid-liquid mixtures; Soojin and Sastry (2005) proposed a modeling and optimization study of a pulsed ohmic heating system of a flexible package for food reheating and sterilization for long-duration space missions food supplies; Shim, Seung, and Soojin (2010) proposed the modeling of the thermal behavior of multiphase food products with various electrical conductivities under ohmic heating; a comprehensive 3D, transient-free convection, and multiphase model was developed by Hashemi et al. (2019) to determine the performance of ohmic heating.In the present work, a modeling and simulation tool of MEF processing applied to a heterogeneous food system is proposed. In particular, an experimental MEF heating cell was used to investigate the performances of a food system made by 3 meat balls (MB) dispersed in 145 g of reconstituted potatoes. The MEF cell was 100 mm long, 51 mm wide, with electrodes made in stainless steel.
The model set-up was built following the work presented by Marra et al. (2009). Comparison of experimental results with modelling in different operating conditions shows a good agreement.

2. MEF heating setup

2.1 Food sample preparation

Mashed potato (MP) samples were prepared by mixing flakes (potato flakes, Crastan, Italy), pure dried salt (Conad Soc. Coop., Italy), unsalted butter (Conad Soc. Coop., Italy), and distilled water. Two different salt concentration were investigated equal to 2.9% w/w (MP29) and 5.7% w/w (MP57) following the preparation and mixing procedure published by Lyng et al. (2014). The prepared samples were allowed to cool overnight at 5°C in a refrigerator where they were stored until use in the experimental runs.
Pre-cooked and frozen chicken MB (Ikea Italia, Italy) were composed of chicken meat (61%), onion, potato starch, salt (1.6%) and spices. The chicken balls were stored in freezer at -20 °C and, before the use for the experiments, they were transferred to a refrigerator where they thawed naturally overnight at 5 °C.

2.2 MEF equipment and meatball configuration

The MEF heating system was configured with an AC variable power supply unit (VAM20F-1N, K-Factor, Italy), three T-type thermocouples to monitor the temperature of the sample at three different selected points of the system (T1, T2 and T3 corresponding to the linear equally spaced MB core points) and a treatment cell, in which the samples were placed (Figure 1). The cooking glass cell (height 60 mm, length 100 mm and width 51 mm) was equipped with two AISI304 stainless steel electrodes (height 60 mm, width 43 mm and thickness 2 mm). The cooking system was installed inside a commercial oven (Whirlpool Europe, Biandronno, Italy) and an ad-hoc wiring was realized with a power supply panel consisting of a residual current device, current circuit braker and self-interlock dispositive. A PicoLog data logger (KA028 TC 08 USB, Pico Technology Ltd, St. Neots, UK) was used to record temperatures and a Hold-Peak meter (Yongtian Road, Zhuhai, China) was used to record currents and voltages (Figure 1)

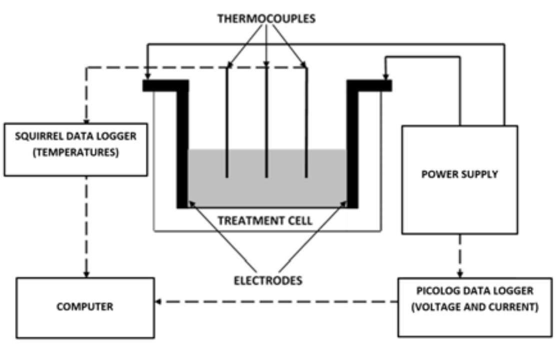

Figure 1. MEF heating equipment

2.3 MEF heating procedure

For each heating experiment the cell was filled carefully to avoid air presence by 3 MB dispersed in 145 g of MP (resulting in an average height up to 36 mm) and placed into positions T1, T2 and T3, according to the configuration illustrated in section 2.2. Once the cell was filled, electrically insulated thermocouples were inserted in each meat ball, taking care to locate each probe tip at the meat ball center. Thermocouples were fixed with a home-made stand to avoid possible movements during the experiment.
Two different applied potential gradients (APG) were investigated, respectively 3 and 4 V/cm, for both MP29 and MP57, compatibly with any thermal degradation of the samples. Every heating experiment was performed in triplicate for 4.5 minutes. Considering the cell length of 10cm, the applied potentials resulted of 30 and 40 V.

2.4 Measurement of physical properties

Physical properties were evaluated according to published procedures (Lyng et al. 2014; Marra et al. 2009). MP and MB electrical conductivity was investigated by using the same cell equipment filled with MP and minced MB only, respectively. Conductivity was so calculated according to the Eq.1 of Marra et al. (2009). Thermal conductivity and volumetric heat capacity were measured with a portable handheld device for thermal properties (KD2 Pro, Decagon, WA, USA). The measurements were performed on sets of 50 single tests on MP and MB at different temperatures. Finally, density measurements were performed on samples at a single temperature (298.15 K) using analytic balance and the volume of the MEF cell.

Table 1a: physical properties as function of temperature of MP29

Property	Description	Units	Function (T in °C)
σ	Elec. cond.	S/m	0.0644 T+1.9898
K	Therm. cond.	W/(m K)	0.0005 T+0.4554
Hp	Vol. heat cap.	MJ/(m^3 K)	0.0024 T+3.1624
ρ	Density	kg/m^3	946.72

Table 1b: physical properties as function of temperature of MP57

Property	Description	Units	Function (T in °C)
σ	Elec. cond.	S/m	0.1093 T+3.6994
K	Therm. cond.	W/(m K)	0.0026 T+0.4262
Hp	Vol. heat cap.	MJ/(m^3 K)	0.0092 T+2.9604
ρ	Density	kg/m^3	991.80

Table 1c: physical properties as function of temperature of meatball (MB)

Property	Description	Units	Function (T in °C)
σ	Elec. cond.	S/m	0.0708 T+1.5675
K	Therm. cond.	W/(m K)	0.0044 T+0.2985
Hp	Vol. heat cap.	MJ/(m^3 K)	0.0082 T+2.977
ρ	Density	kg/m^3	1131.77

3. Model implementation

A mathematical model of MEF heating was developed for the ohmic cell described in Section 2.2.

3.1 Transport equations and modeling tools

The heat transfer phenomena that take places during ohmic heating of a solid-like food-domain such as the analyzed heterogenous system, are described by the classical unsteady state heat transfer equation by conduction considering a heat generation term (Marra et al. 2009).

$$\rho\, C_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + \sigma \mid \nabla V \mid^2 \qquad (1)$$

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 mass heat capacity and the last term represent the ohmic heat generation source where $\boldsymbol{\sigma}$ is the electric conductivity and $\mid \nabla V \mid$ the modulus of the gradient of electrical potential. The product $\rho\, C_p$ is equal to the measured volumetric heat capacity.
The electrical potential distribution within the sample can be computed using the following Laplace equation:

$$\nabla \cdot \sigma \nabla V = 0 \qquad (2)$$

While the electrical conductivity depends on temperature, Eqs. (1) and (2) are dependent on each other and the problem must be solved in a coupled form. The complete MEF cell geometry was designed using Solidworks software (Solidworks corp., Dessault Systems, Paris, France) and a final assembled design was imported into Comsol Multiphysics software (Comsol AB, Sweden) to define the model builder structure.

Custom materials were created for MP and MB according to their measured physical properties. Silica glass and AISI 304 stainless steel Comsol library materials were used respectively for ohmic cell and electrodes. In order to model the overall MEF equipment behaviour, the appropriate coupling with multi-physics-correlated electromagnetic heating module were computed. A reduced temperature variable was defined as:

$$T_{red} = \frac{T - T_0}{T_{sat} - T_0} \tag{3}$$

where T denotes the instantaneous temperature, T_0 the starting temperature of the measured position, and T_{sat} the upper limit temperature imposed equal to 373.15 K.

3.2 Initial and boundary conditions

It is assumed that the entire sample is at a uniform initial voltage, V_0=0 and temperature T_0 (301.15 K, as it was the average value of the sample temperature measured after the cell filling manual operations).
As boundary conditions for the heat transfer equation, continuous domains were considered assuming ideal conductive transport between MP, electrodes, and glass interfaces domains. For the external surfaces, different considerations were made. The external lower face of the glass cell was considered adiabatic due to the oven insulation. All others glass and steel surfaces in contact with external surrounding air were considered as convective heat walls with external natural convection. The upper MP face is in free air and the moisture loss heat transfer was assimilated to an overall convective heat flux as:

$$q_{eq} = h\,(T_{air} - T) \tag{4}$$

where h was considered ranging from $5\ to\ 100\ W/\,m^2K$ and different simulation tests were preliminary performed in accordance with the literature (Carson, Willix, and North 2006).
The electric equation boundary conditions were considered as perfect insulation surfaces for all boundaries except of the hereafter considered ones. A fixed voltage drop over the cell electrodes was imposed. The interfacial surfaces between MP and electrodes and between MP and MB were considered as surfaces in electric contact where current flux J is described by:

$$J = h_c\,(V_1 - V_2) \tag{5}$$

h_c was the electric conductance in S/m^2 and after different parameter optimization runs, its values were estimated and reported in table 2 for every interface type. Finally, half body symmetry boundary condition was considered also to reduce the simulation computational efforts. See section 4 figures for details.

3.3 Numerical solution solver implementation

The implemented model was solved by the Comsol Multiphysics software. A multi-sweep study respectively for APG (3 and 4 V/cm) and materials (MP29 and MP57) was implemented.
Numerical tests were performed with different mesh parameters 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 125311 tetrahedrons, 16634 triangles boundary elements, 988 edge elements, 58 vertex elements with 367894 of degrees of freedom. The numerical solution was attained on a workstation equipped with a motherboard MSI X79A-GD65 (8D), CPU Intel I7-3820 @ 3600 GHz FSB (front side bus): 1.600 MHz Socket: Socket R (LGA 2011) 4 cores; equipped with a RAM of 64 Gb DDR3 1600 MHz. The workstation runs under Windows 7 Professional operating system at Dipartimento di Ingegneria Industriale, Università degli studi di Salerno, Italy.

4. Results and discussions

The numerical solution of the proposed model allows to acquire the transient spatial (3D) distribution of temperature and intensity of the electric field, thus following also the local distribution of the heat source (given by the interaction of the electric field whit the food undergoing heating). The analysis of such model output is presented below and discussed in terms of heating uniformity.

4.1 Spatial representation of the Model outputs

Figure 2 shows four examples of a temperature distribution (as slices on XZ planes) plot after 4 minutes of MEF heating for MP29, assuming for the heat transfer coefficient h the values 5, 25, 50 and 100 W/(m^2 K), for APG the value 3 V/cm, and for h_c the values reported in Table 2. The MEF heating of the considered system, heaven if non-homogeneous, reveals a uniform temperature distribution in a large portion of the investigated domain. Whatever the heat transfer coefficient h, the less heated zones remain confined at the outer shells. Ad-hoc test experiments run on the same system discussed in this work revealed a different temperature between the core and surface of the food system of 3°C, which is the value obtained by numerical solution when a heat transfer coefficient of 5 W/(m^2 K) was used. For this reason, all other numerical solutions discussed in this work were obtained considering this value.

Figure 3 shows three examples of electric field slice plot after 4 minutes of ohmic heating for MP29 and MP57, considering a value of 5 W/(m^2 K) for the heat transfer coefficient h, an APG of 3 and 4 V/cm, and the values reported in Table 2 for h_c. The larger APG, the higher is the resulting electric field as expected. Moreover, a considerable reduced electric field homogenization could be observed for a higher salt concentration of MP.

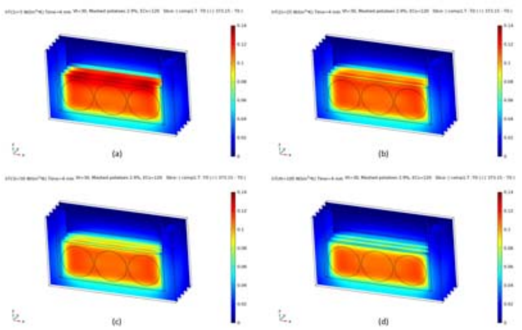

Figure 2. Slice plot of temperature after 4min. APG = 3 V/cm, MP29, (a) 5 W/(m^2 K), (b) 25 W/(m^2 K), (c) 50 W/(m^2 K) and (d) 100 W/(m^2 K)

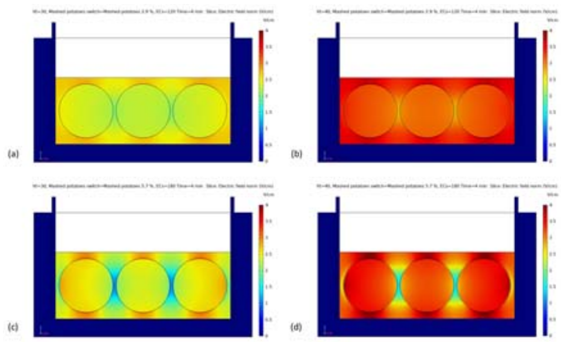

Figure 3. Electric field at 4min. APG=3 V/cm (a, c) and 4 V/cm (b, d), MP29 (a, b) MP57 (c, d), h=5 W/(m^2 K)

Table 2: electric conductance, h_c, for MP - steel and MP –MB interfaces

Property	interface	El. Cond. [S/m^2]
h_c	MP29-steel	120
h_c	MP57-steel	180
h_c	MP29-MB	800
h_c	MP57-MB	800

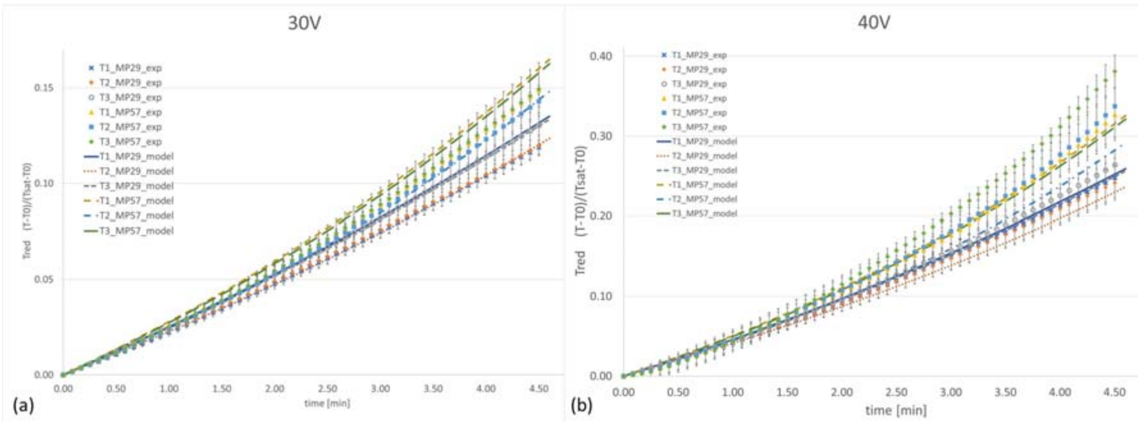

Figure 4. Comparison between experimentally measured and model predicted temperature evolution for an APG of 3 V/cm (a) and 4 V/cm (b), MP29 and MP57 compositions. MP29 concentration model profiles are solid blue for T1, dotted dark red for T2, short-dashed grey for T3. MP57 concentration model profiles are dashed brown for T1, point&dash blue for T2, long dashed green for T3.

4.2 MEF profiles experimental comparison

Hereafter an experimental MEF heating of the investigated heterogeneous system, respectively for APG of 3 and 4 V/cm, for both MP29 and MP57 are reported and compared with the model predictions. Every experimental test is performed at least in triplicate. Average and standard deviation are also reported. In Figure 4a, the comparison of temperature evolution (model predicted and experimentally measured at the chosen points) for an APG of 3 V/cm, is reported. The model prediction shows a good agreement with the experimental results and drives the heating curve within the maximum of experimental standard deviation of 5%. It is worthwhile remarking that the model predicts temperature at external locations to be higher than at the central one as expected for the electrode proximity. For higher APG (Figure 4b), the experimentally measured temperature evolution in position 3 for MP57 shows a deviation from the model prediction for longer times probably due to the rising of other phenomena not considered by the model. The agreement between the model and experimental set is satisfactory.

5. Conclusions

The implemented model for the simulation of a static ohmic heating cell delivers good results, providing satisfactory correlation between predicted and experimental data. An optimal set of electric conductance, h_c, of the MP/steel and MP/MB interfaces was estimated by an overall analysis of all experimental tests and it was applied in all the simulations. With the proposed cell configuration, when MEF heating is used for sterilization of solid foods, colder external shells are the critical areas to be monitored and limited with additional insulations. Future developments will deal with a microscopic modeling of the crucial interfaces where current conductance plays a key role and a multiscale model implementation reducing the number of parameter optimization. Moreover, higher applied potential gradients (5 V/cm and more) will be investigated to better describe the rising deviation already observed at 4 V/cm.

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