VIRTUALIZATION STRATEGIES FOR MODELING THE ENERGY TRANSFER IN A FOOD UNDERGOING RF HEATING

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ABSTRACT
Heating uniformity in radiofrequency (RF) heating of agricultural and food commodities is a challenge to overcome for the development and dissemination of commercial RF heating systems at industrial scale. Different experimental studies have been carried out to test the effectiveness of RF heating in different food processing techniques. Modeling and simulation remains as one of the best tool used to virtualize the challenges of heating non-uniformity and effective tool to analyze and characterize the heating patterns during RF heating. Different strategies used to build-up virtualization of RF heating were briefly discussed in this paper. Dielectric and thermos-physical properties of the product subjected RF heating the key-factors to link the fundamental modeling approach with the data related to the investigated food material. The energy transfer across the food sample due to the RF heating and external convection effects have been discussed. Alternatively, using representative food samples like tylose with known thermo-physical and dielectric properties are also another strategy to be used to describe RF heating system.

Keywords: modelling, RF heating, energy transfer, food heating

1. INTRODUCTION

In recent years, the application of radio-frequency (RF) heating in agro-food processing has got wide applications due to the advantage of fast heating. Recently, a lot of interesting studies have been carried out on the application of RF heating in meat processing (Farag et al., 2008 and 2011; Marra et al., 2007; Uyar et al., 2014 and 2015), in post-harvest treatment and disinfestation of fruits (Birla et al, 2004; Wang et al., 2002, 2003 and 2006a; Alfaifi et al., 2012 and 2015).
In RF heating applications in agricultural and food processing technologies, the heating non-uniformity is mainly dependent on the power absorption capacity of the material subjected to heating. This heating non-uniformity remains a challenge to be solved to widen the application of RF heating commercially in industrial scale.
Different authors have been studied different methods and strategies to improve the heating uniformity during RF heating. For example, Birla et.al. (2008) reported that placing the sample at the center point between two parallel electrodes improved heating uniformity during RF disinfestation of fruits. Similar strategy was also proposed and used by Tiwari et al. (2011a) and Liu et. al. (2013). The use of forced air surface heating, mixing and product movement to improve heating uniformity during RF treatment of walnuts was also promising strategy proposed and applied by Wang et. al. (2005 and 2007). In their recent study, Wang et.al. (2014) also demonstrated a systematic means to evaluate RF heating uniformity by using polyurethane foams in drying of agricultural commodities.
The use of model materials such as tylose with consistent and stable properties to replace more complicated heterogeneous materials is the first step to gain insights about the RF heating patterns during RF assisted heating of food products.

2. COMPUTER VIRTUALIZATION OF RF HEATING

Computer virtualization of processes is a powerful tool which can be used as virtual laboratory to get insights of heating patterns and to during RF heating. The mathematical modeling of RF heating systems has been discussed by (Neophytou and Metaxas, 1998; Yang et al., 2003; Chan et al., 2004; Marra et al., 2007 and 2009; Birla et al., 2008; Romano and Marra, 2008; Tiwari et al., 2011; Wang et al., 2012; Uyar et al., 2015; Llave et al., 2015) for different types of products in different heating systems. The heating system in RF heating fall into two categories of energy transfer, which are the heat transfer within the material subjected to RF heating and the electric and magnetic fields.

The mathematical description of heat transfer in the food product which is placed between two electrodes is given by unsteady state heat equation with a generation term derived from electromagnetic equations.
The heat equation is given by:

$$\rho\, C_p \frac{dT}{dt} = \underline{\nabla} \cdot k \underline{\nabla} T + P_{abs} \qquad (1)$$

where T is the temperature within the sample, t is the time, k is thermal conductivity, ρ is the density, C_p is the heat capacity and P_{abs} is the power absorbed due to RF.

The power density or power dissipation per unit volume:

$$P_{abs} = 2\,\pi\,f\,\varepsilon_0\,\varepsilon_r''\,\left|\underline{E}\right|^2 \qquad (2)$$

The power density absorbed by lossy dielectric material is proportional to the frequency applied and the dielectric loss factor and proportional to the square of electric field.
The prediction of electromagnetic field distribution in RF heating is important to determine the power absorption density within the food product. Hence Maxwell's equations which relate the electric charge density, ρ_c; electric field, $\underline{E}$; electric displacement, $\underline{D}$; current, $\underline{J}$; magnetic field intensity, $\underline{H}$ and magnetic flux density, $\underline{B}$.

$$\underline{\nabla} \times \underline{H} = \underline{J} + \frac{\partial D}{\partial t} \qquad (3)$$

$$\underline{\nabla} \times \underline{E} = -\frac{\partial B}{\partial t} \qquad (4)$$

$$\underline{\nabla} \cdot \underline{D} = \rho_c \qquad (5)$$

$$\underline{\nabla} \cdot \underline{H} = 0 \qquad (6)$$

Based on the assumption of fields to be time-harmonic (Neophytou and Metaxas, 1998), combination of Maxwell's equation could be reduced to the following wave equation in frequency domain (Marra et al., 2009).

$$\underline{\nabla} \times \frac{1}{\mu_r} \underline{\nabla} \times \underline{E} - \omega^2\,\mu_0\,\varepsilon_0\,\varepsilon_r\,\underline{E} = 0 \qquad (7)$$

When a quasi-static approach is assumed, equation (5) could be reduced to the following:

$$\underline{\nabla} \cdot \left[(\sigma + j\,\omega\,\varepsilon) \underline{\nabla}\,V \right] = 0 \qquad (8)$$

where the electric potential, V is related to the electric field by:

$$\underline{E} = -\underline{\nabla}\,V \qquad (9)$$

The solution of the both heat equation and electromagnetic field equation are subjected assigning appropriate to initial and boundary conditions to come up with consistent and valid mathematical simulation of the process. The common initial and boundary conditions (BCs) used in solving heat equation are, uniform initial temperature of product and convection heat transfer on the boundaries of the product subjected to RF heating respectively. For the case of electromagnetic field distribution, an electric potential value or distribution is applied to the upper electrode while the bottom electrode is at ground condition. The RF applicator walls are also electrically insulated. Figure 1, where typical configuration of parallel electrode RF system is shown, allow to better focus on the whole domain representation and to visualize where the previously discussed BCs are applied.

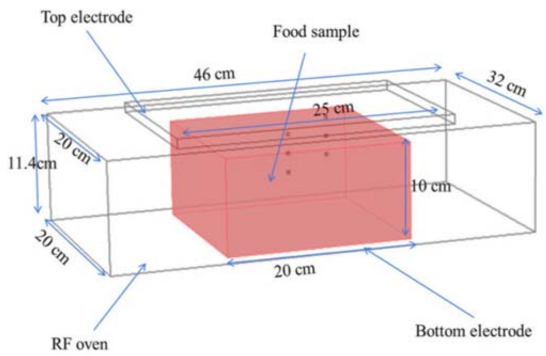

Figure 1: Typical configuration of parallel electrode RF system (adapted from Uyar et al., 2015)

3. VIRTUALIZATION STRATEGIES IN RF HEATING

Modeling of RF heating involves characterization of possible parameters and consideration of best configurations in the RF heating system. Different virtualization strategies have been proposed by different researchers since the first 3D FEM based mathematical model of RF heating by Neophytou and Metaxas, (1998). These strategies involve a number of issues which arise when processes assisted by RF are considered. Before modeling RF heating of foods, a number of questions require proper answers:

a) In order to describe the electric field displacement, it is necessary to consider the whole set of Maxwell's equations?
b) When the so called quasi-static approach is allowed?
c) It is possible to use constant values of dielectric (and thermos-physical) properties? Or it is always recommended to use empirical values/expressions as functions of the local temperature?
d) In the last case of point c), it is sufficient to consider the dielectric and thermos-physical properties as functions of the temperature, or also their dependence on moisture content (and, in some cases, in ionic concentration)?
e) What is the importance (and the role) of mass transfer? In other words, it is always sufficient to consider the set of equations previously introduced or also mass transfer equation(s) must be considered?
f) If also mass transfer has to be considered, what mass component is the more relevant? Moisture content? Ionic content? Fraction of free water with respect to bounded water?

g) If also moisture transfer has to be considered, what is the more appropriate mass transfer approach? The porous media approach (Datta, 2007)? The kinetic like approach (Marra et al., 2010)?
h) What happens when phase change has to be considered?
i) What about boundary conditions? When external convective heat transfer should be taken into account by solving the momentum transfer and the heat and mass transfer in the environment surrounding the food sample?
j) What about validation?

The answers to the questions listed above are not unique and the strategy of virtualization must be driven by the objective(s) of the research. Some examples are discussed below.

Under the hypothesis of quasi-static approach, Marra et al. (2007) solved coupled heat transfer and electromagnetic equations for a cylindrical shaped meat batters and demonstrated that quasi-static hypothesis to be successful in lab scale RF system. Different strategies have been applied by different researchers to find out how to improve the heating uniformity of the RF heating. Moving or rotating in water surrounding system has been proposed and used in modeling/experimental study about RF heating of high water content commodities like fruits (Birla et al., 2008) and for low moisture foods, use of polyetherimide (PEI) blocks, hot air assistance, intermittent stirring, electrode configuration and use of plastic sheets surrounding the product to enhance heating (Jiao et al, 2015; Alfaifi et al., 2014).

Virtualization of the processes also includes the assumptions and specific considerations about numerical parameters and also about process parameters involved in it. When a rough solution is sufficient for a preliminary analysis, one may choose to work with a coarse mesh, in order to deal with a numerical procedure less demanding in terms of computing power. The same strategy is not acceptable when the goal of virtualization is to have a model which is independent by the mesh grid. Another example, the latent heat peak during thawing of foods needs special consideration in order to simplify simulation complexities and time. Uyar et al. (2015) used apparent specific heat method in virtualization of lean beef meat undergoing thawing assisted by RF heating. The following section is about this topic.

As mentioned above, the virtualization strategy should include also a motivated decision on the set of BCs to be considered. In case of relevant convective contributions from the external environment toward the food product, the model should take into account (and, thus, should include) also the heat and mass transfer in the surrounding environment, and with it the momentum transfer too.

3.1 An example: meat thawing assisted by RF

In food processing industries tempering and thawing are the two main processes involved in heating frozen food products to required temperature for further processing or to make it ready for consumption. Tempering is considered as pre-thawing process, since it is used to increase the temperature of the product from frozen state to a temperature point where it is usable without causing harm to subsequent processing operations. Thawing is increasing frozen product temperature to melted or unfrozen state. RF assisted tempering and thawing have been experimentally studied and models were also developed to virtualize the heating patterns as well as to allocate the hot and cold spots during the process (Farag et al., 2008 and 2011; Llave et al., 2015; Uyar et al., 2015).

As shown in figure 2, where the temperature distribution (in °C) in a sample of beef meat during RF thawing is reported, the thawing process cannot be followed as a simple problem of monitoring the cold spot (which is located in the heart of the sample) but also in terms of a problem of overheating (as it happens in the areas colored in brown-red). Thus, here the virtualization strategy cannot ignore complex mechanisms happening at boundaries (at corners especially). These areas undergo phase change with subsequent severe changes in thermos-physical and dielectric properties.

Determination of RF power density (P_{abs}) distribution in the sample during the process is a key-step as well. Figure 3 shows the power density (in W/m^3) distribution (at side slice) in lean beef thawed by RF assisted heating at early stage of the process. In this figure it is possible to appreciate the great variability of power density values. At same time, it is possible to appreciate that in the strategy of virtualization – in this case – is to have a preliminary rough solution, being the mesh grid quite coarse.

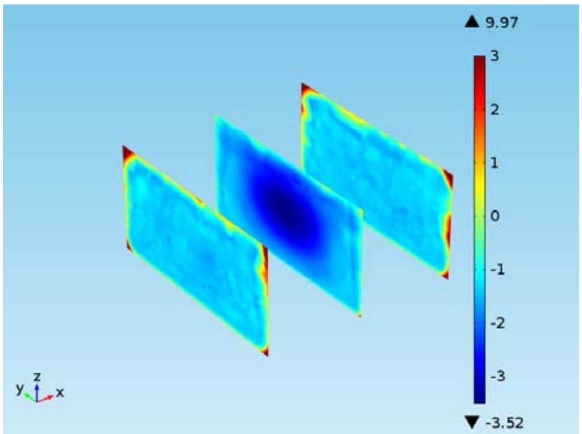

Figure 2: Temperature distribution [°C] in the sample during RF thawing of beef meat.

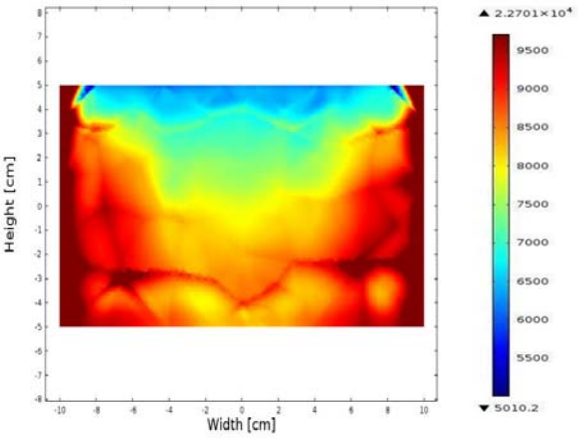

Figure 3: Power density [W/m^3] distribution (at side slice) in lean beef thawed by RF assisted heating, after 1 minute of processing.

4. CONCLUSIONS

Virtualization of complex processes, such as food heating assisted by radio-frequencies, should be based on a strategy which includes a number of steps related to what is simulated (definition of the process), where it is simulated (definition of a domain), how it is simulated (definition of the equations' set and of the solution procedure). A number of essential questions as been proposed and example of virtualization strategy have been discussed, with a focus on RF thawing of foods.

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