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Radio frequency disinfestation treatments for dried fruit: Model development and validation

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ABSTRACT

Non-uniform heating is one of the most important challenges during the development of radio frequency (RF) heat treatments for pest control and other applications. A computer simulation model using finite element-based commercial software, COMSOL, was developed to investigate the heating uniformity of raisins packed in a rectangular plastic container ($25.5 \times 15.0 \times 10.0\ cm^3$) and treated in a 6 kW, 27.12 MHz RF system. The developed model was then experimentally validated. Simulated and experimental temperature distributions in raisins after RF heating were compared in three different horizontal layers (top, middle, and bottom) within the container. Simulated and experimental average and standard deviation of the temperature values were highest in the middle layer, followed by the top and bottom layers. A sensitivity study indicated that the heating uniformity of the samples was most affected by the density of the raisins followed by the top electrode voltage, the dielectric properties, the thermal conductivity and the heat transfer coefficient. Corners and edges were heated more than the centers in each layer of the RF treated raisins. The model developed here can be used for future investigations to improve the heating uniformity for insect disinfection of dried fruit and other similar applications.

1. Introduction

Insect infestation is one of the most important sanitary or quarantine considerations limiting domestic and international trade of dried fruits including raisins, dates, apricots, figs, and prunes. Postharvest control of insects that attack dried fruits such as: Indianmeal moth (*Plodia interpunctella*), navel orangeworm (*Amyelois transitella*), raisin moth (*Cadra figulilella*), fig moth (*Ephestia cautella*), driedfruit beetle (*Carpophilus hemipterus*), and sawtoothed grain beetle (*Oryzaephilus surinamensis*) is essential if quarantine regulations required in many countries (Johnson et al., 2009) are to be met. On the other hand, total postharvest product losses from insect infestation are conservatively estimated to be between 10% and 40% worldwide through direct damage; contamination with fecal matter, webbing and insect parts (Pimentel and Raman, 2002). Insect infestation promotes increased mold growth, toxin production, and product degradation. Traditionally, chemical fumigation has been the most widely used treatment for insect control due to its efficacy and relatively low cost (Barreveld, 1993). However, environmental and public health concerns about the hazards of chemical fumigation have increased the demand for non-chemical pest control methods for dried fruits.

The interest in non-chemical methods for insect disinfestations in agricultural commodities has grown in recent years due to increased food and environmental safety requirements. One alternative to chemical fumigation is radio frequency (RF) treatment, which has been shown to be lethal to insects at low intensity (Wang et al., 2007b). RF dielectric heating employs electromagnetic waves of 13.56, 27.12, and 40.68 MHz for industrial applications (Metaxas, 1996). However, major challenges with adopting RF heating in the food industry are non-uniform heating and runaway heating, which cause overheating in corners, edges, and center parts, especially in foods of intermediate and high water content (Fu, 2004). Temperature variations among and within processed agricultural commodities reduce the efficiency of a treatment and may cause severe thermal damage to its quality and adversely affect product safety. During RF processing, several interacting factors influence heating uniformity (Wang et al., 2005). These factors include the design of RF heating systems (e.g. the electrode shape and power output), packaging geometries, dielectric, thermal and physical properties of the treated materials,

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position of the treated materials within the RF units, and the surrounding media (Fu, 2004).

The trial and error procedure often practiced to adjust these parameters to improve the heating uniformity is ineffective and costly. Mathematical modeling and computer simulation serve as valuable tools for shedding light on the complex mechanisms underlying the heating uniformity of food products subjected to RF treatments without the necessity of extensive time consuming experiments. The first attempt to model RF systems was reported in the 1990s (Neophytou and Metaxas, 1996, 1997, 1998, 1999). These efforts attempted to model the electrical field for industrial-scale RF heating systems and compared solutions from both electrostatic and wave equations. Yang et al. (2003) investigated temperature distributions for alfalfa and radish seeds placed inside rectangular polystyrene boxes after RF heating using commercial software TLM-FOOD HEATING. The developed model was then validated with experimental data. Chan et al. (2004) developed an effective model to simulate an actual RF heating system using a finite elements method to solve wave equations. The simulated and experimental data for different sized loads and positions of a 1% solution of carboxymethyl cellulose showed good agreement. Marra et al. (2007) analyzed the temperature profiles of cylindrical meat batters treated with a 50 Ω, 27.12 MHz RF system at different output power levels using commercially available finite element-based software, FEMLAB. The model was then validated by comparing simulated and measured temperature profiles. The authors reported uneven temperature distributions within the sample; the higher the applied power, the more uneven the temperature distribution. Heating non-uniformity in fresh fruits subjected to a 12 kW, 27.12 MHz RF system has been investigated mathematically using FEMLAB (Birla et al., 2008). Factors such as dielectric properties, shape, surrounding media, and position of fruit were found to affect the heating uniformity of fresh fruits. Tiwari et al. (2011a) developed and validated a computer simulation model for a 12 kW, 27.12 MHz RF system using COMSOL to compare the simulated temperature profiles of wheat flour with transient experimental temperature profiles in RF heating. The validated model was further used to predict the influence of the shape, positions, configuration of the top electrode, and other related factors on the RF power distribution in dry food materials (Tiwari et al., 2011b).

There are no reports on the computer simulation for RF heating of high sugar and intermediate moisture materials. To investigate the RF heating characteristics in these materials and select operational parameters to improve the RF heating uniformity, it is desirable to develop a computer simulation model and validated it by experiment. The objectives of this study were to investigate RF heating behavior in raisins using computer simulation, estimate dielectric properties and thermal conductivity of raisins packed in a container using published mixture equations, develop computer simulation model for a 6 kW, 27.12 MHz RF system using commercial finite element software COMSOL, and validate the computer model with experimental temperature profiles of raisins.

2. Materials and methods

2.1. Development of computer model

2.1.1. Physical model

A free-running oscillator, 6 kW, 27.12 MHz parallel plate RF heating system (COMBI 6-S, Strayfield International Limited, Wokingham, UK) was used for the RF heating experiments. Fig. 1 provides a schematic view of the RF unit used in this study. The RF system consisted of a generator and an applicator comprising a pair of parallel plate electrodes inside a large rectangular metallic enclosure. The electrodes were connected to a tank oscillatory circuit. The samples were sandwiched between the two electrodes. This configuration has been shown to achieve greater temperature uniformity in the top and bottom layers in a container (Tiwari et al., 2011b).

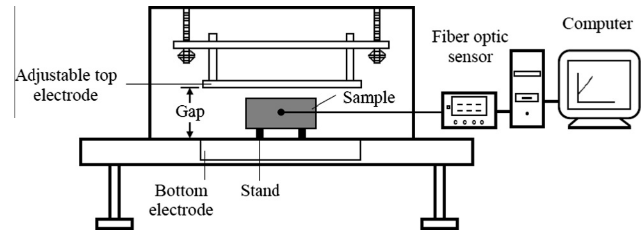

Fig. 1. Schematic view of the pilot-scale 6 kW, 27.12 MHz RF unit showing the rectangular plastic container placed in between the top and bottom electrodes (Adapted from Wang et al., 2010).

2.1.2. Governing equations

2.1.2.1. Electric current. A quasi-static approximation was used to solve Maxwell's electromagnetic field equations. Since the wavelength (11 m) in the 27.12 MHz RF system is often much larger than the electrode gap, Maxwell's equations were simplified to Laplace equations (Metaxas, 1996):

$$-\nabla \cdot ((\sigma + j2\pi f\varepsilon_0\varepsilon')\nabla V) = 0 \qquad (1)$$

where σ is the electrical conductivity of the heated material (S m^{-1}), $j = \sqrt{-1}$, f is the frequency (Hz), ε_o is the permittivity of free space (8.86×10^{-12} F m^{-1}), ε' is the dielectric constant of the material, and V is the voltage between the two electrodes (V). The electric field strength is $\vec{E} = -\nabla V$.

2.1.2.2. Heat transfer. The heat conduction was considered within the food material, convection at the material's surface, and heat generation due to RF heating. The governing heat transfer equation in the electromagnetic field is described as:

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + Q \qquad (2)$$

where ρ is the density (kg m^{-3}), C_p is the specific heat of the heated material (J kg^{-1} K^{-1}), T is the temperature inside the material (°C), t is the process time (s), k is thermal conductivity (W m^{-1} K^{-1}), and Q is the RF power conversion to thermal energy (W m^{-3}) within the food material for a given electric field intensity, $\vec{E}$. Q is described as (Choi and Konrad, 1991):

$$Q = 2\pi f\varepsilon_0\varepsilon''|\vec{E}|^2 \qquad (3)$$

where $|\vec{E}|$ is the magnitude of electric field intensity (V m^{-1}).

2.1.3. Geometrical, thermal, and electrical boundary conditions

Figs. 2 and 3 show the geometrical, thermal and electrical boundary conditions of the 6 kW, 27.12 MHz RF system used in the simulation. Electrical insulation ($\nabla \cdot \vec{E} = 0$) and thermal insulation ($\nabla T = 0$) were assigned to the inlet and outlet of the system, while electrical insulation ($\nabla \cdot \vec{E} = 0$) only was assigned to the walls of the RF applicator. The bottom electrode was set as ground ($V = 0$ V). The top exposed surface of the sample was assigned with convective heat transfer ($h = 20$ W m^{-2} K^{-1}) for free convection of ambient air. The raisin samples were equilibrated at room temperature prior to RF heating and, therefore, it was assumed that these samples were at a uniform temperature, $T_{initial}$. In all cases, the initial temperature, $T_{initial}$, was set at 23 °C. The voltage on the top electrode was assumed to be uniformly distributed because its dimensions (68.6×49.5 cm^2) were only 30% of the RF wavelength