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Performance of mobile metallic temperature sensors in high power microwave heating systems

Donglei Luan [a], Juming Tang [a,*], Patrick D. Pedrow [b], Fang Liu [a], Zhongwei Tang [a]

[a] Department of Biological Systems Engineering, Washington State University, P.O. Box-646120, Pullman, WA 99164-6120, USA
[b] School of Electrical Engineering and Computer Science, Washington State University, P.O. Box-642752, Pullman, WA 99164-2752, USA

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ABSTRACT

The goal of this study was to investigate the performance of mobile metallic temperature sensors in a packaged food processed in high power microwave assisted thermal sterilization (MATS) systems. A validated computer simulation model based on conformal finite difference time domain (FDTD) method was used to evaluate the influences of the microwave power intensity, probe tip geometry and diameter on the accuracy of the sensors. The simulation results revealed that a higher temperature zone was created near the probe tip. This temperature alteration was caused by the distortion of electric field at the probe tip area. Increasing the microwave power setting of MATS system amplified the temperature alteration. Proper sensor designs could help to reduce the temperature alterations. The flat probe tip was most sensitive to high power setting. Changing the probe tip to a spherical geometry and decreasing diameter of the probe significantly reduced the temperature alterations.

1. Introduction

Microwaves can be used to facilitate thermal processing of packaged foods (Tang et al., 2006, 2008). In those processes, alternating electromagnetic (EM) fields directly interact with polar molecules and ions in food materials to cause volumetric heating that sharply reduces thermal processing time and greatly improves the quality of thermally processed foods (Guan et al., 2002, 2003). Earlier studies have demonstrated potential of microwave thermal processes for production of high quality shelf stable food products (Ohlsson, 1987, 1990; Ahmed and Ramaswamy, 2007). In commercial thermal processes, sufficient thermal energy needs to be delivered to inactivate food pathogens. In developing a new thermal process, temperature sensors are placed at target locations (i.e. cold spots) to measure the time–temperature profiles over the processing time. Accurate measurement of temperature history is critical to the design of a thermal process to ensure the processed foods to be safe (Lund, 1977; Ohlsson, 1980; Holdsworth, 1985; Awuah et al., 2007). If the temperature is overestimated, an insufficient thermal treatment will lead to a food safety problem. On the other hand, underestimated temperatures would cause quality degradation of food products by overcooking.

Appropriate selection of temperature sensors for thermal process development is based on the process conditions and the performance of the sensors such as the requirement of accuracy, response time, cost and stability of calibration (Wang et al., 2003). In a microwave heating environment, an effective temperature measurement device should not disturb the EM field or be affected by the EM field (Datta et al., 2001). Fiber-optic temperature sensors are commonly used in microwave heating measurements (Kyuma et al., 1982; Tang et al., 2008). But fiber-optic sensors require light sources that are heat sensitive and expensive. In addition, the long fragile optical fibers that connect sensors in food and the light source outside of the system are not suited for the temperature measurement in moving samples within high temperature pressurized chambers. The above disadvantages make fiber-optic sensors impractical in commercial industry applications.

Temperature sensors with metal components are generally not suitable for microwave heating because metallic materials interact with EM field. The interaction alters EM field distribution and reduces the sensor accuracy. Nevertheless, many attempts have been made to modify metallic thermocouples for temperature measurements in microwave environments (Van de Voort et al., 1987; Ramaswamy et al., 1991; Kermasha et al., 1993). Ramaswamy et al. (1998) reported that metallic thermocouples could be used in domestic microwave ovens with adequate accuracy (errors < 2 °C) by proper design of the shield isolation and body insulation. However, this accuracy is inadequate for

* Corresponding author. Tel.: +1 509 335 2140; fax: +1 50 335 2722.
E-mail address: jtang@wsu.edu (J. Tang).

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developing the commercial thermal processes. Correct measurements of metallic temperature sensors in a high power microwave environment may be affected by two sources: the intrinsic accuracy of the sensor type and the interaction between metallic body and the electric field.

A temperature sensor with a higher intrinsic accuracy, such as the resistance temperature detector (RTD), could be used to replace a thermocouple in designing a shield metallic sensor applied in a microwave environment. However, local electric field distortion will occur at the metallic surface especially at the probe tip area (Pert et al., 2001). This could result in incorrect temperature measurement. Other techniques need to be developed to reduce this type of temperature alteration. Luan et al. (2013) studied a commercial mobile metallic temperature sensor (Tracksense Pro data logger, Ellab Inc., Centennial, CO, USA) used in a pilot scale microwave assisted thermal sterilization (MATS) system. Results indicated that at pilot scale power settings (2.7–6 kW), the mobile metallic sensors could be used in microwave heating environment. But to reduce the temperature alteration, the sensor probe should be placed perpendicular to the dominant electrical field component. This type of small metallic mobile sensors with build-in memory for storing data can be extremely convenient for use in measuring temperatures inside packaged foods during a continuous commercial process. But in industrial applications, a much higher microwave power may be used to meet the requirement for designed production capacities. Possible temperature alterations caused by the electric field distortion around the probe tips were unclear in high power microwave environment.

Computer simulation methods that numerically solve the coupled Maxwell's and heat transfer equations are effective tools to assist the microwave heating designs (Dibben, 2001; Pathak et al., 2003; Chen et al., 2007, 2008; Resurrection et al., 2013). An experimentally validated computer model can be used to provide insightful information about complicated microwave heating process and facilitate process developments.

A computer simulation model based on conformal finite difference time domain (FDTD) method (Holland, 1993; Yu et al., 2000) was developed and validated in a previous study for the MATS system (Luan et al., 2013). In the current research, the same model was adapted to evaluate the temperature alterations caused by the mobile metallic sensors in a 915 MHz single mode microwave heating system. The results of the study would provide a general guidance for designing appropriate temperature sensors applied in industrial microwave heating systems.

2. Methodology

2.1. Physical model

The microwave heating system we attempted to model in this study was a portion of a pilot scale, 915 MHz, single mode microwave heating system developed by Washington State University (Pullman, WA). This system consisted of four sections: preheating, microwave heating, holding and cooling (Tang et al., 2006). The microwave heating section that contained four microwave heating cavities was the key unit of the system. Only one microwave heating cavity was simulated to reveal the detailed interaction between EM field and metallic sensors. The selected microwave heating cavity had a rectangular load box and two identical horn shaped applicators on its top and bottom (Fig. 1A). A standard waveguide WR975 delivered microwave energy from a generator to the applicators. Within the waveguide only a TE10 microwave propagation mode was supported and transmitted (Fig. 1B). The symbols 1 and 0 in a mode type denoted the number of semi-sinusoidal variations in *x* and *y* direction, respectively. For a TE10 mode in a rectangular waveguide, the electrical field component only existed in *y* direction (E*y*) and it formed a standing wave in *x* direction with one semi-sinusoidal variation. Microwaves propagated in *z* direction to the load box which was filled with circulating hot water and food packages. The packages were transported in the negative *x* direction through a conveyor belt. Both the conveyor belt and packages were immersed in a water bed with a thickness of 76 mm. The materials of packages and conveyor belt were not considered in the simulation model since they were both transparent to microwave.

We selected commercial mobile metallic sensors, Tracksense Pro data logger, manufactured by Ellab Inc. (Centennial, CO, USA) for this evaluation. The mobile metallic sensor had two parts: a cylindrical base and a long probe (Fig. 1C). The base part had a diameter of 15 mm and a length of 22 mm. A RTD (PT 1000) was installed in a shielding tube (316 stainless steel) 2 mm in diameter and 50 mm in length. The sensor was imbedded in a model food prepackaged in a polymeric pouch that had a dimension of $95 \times 135 \times 16\ \text{mm}^3$ in *x*, *y* and *z* direction, respectively. The sensor probe was placed at the validated cold spot location detected using chemical marker method (Pandit et al., 2006, 2007). A previous study revealed that the sensor accuracy was affected by the relative direction between the sensor orientation and electric field component (Luan et al., 2013). In the current study, a similar orientation angle (φ) was defined to describe the orientation of a sensor within the *x*–*y* plane of food (Fig. 2). The orientation angle was defined as zero when the length of sensor from probe to base was along positive *y* direction. The angle increased with the rotating base in counter-clockwise direction and vice versa. The two particular orientation angles in the previous study ($\varphi = 0°$ and 90°) had the same definition in this orientation angle system. Other than particular orientation angels, a general angle of $\varphi = 45°$ was simulated to identify the best orientation angle for analyzing the temperature alterations affected by different sensor designs and microwave power settings.

Three different geometries of the probe tip were simulated in this study: flat, sphere and truncated cone. Top view (*x*–*y* plane) of these probe tips are shown in Fig. 3. The sensing element of the metallic sensor was a RTD that shielded by a metallic tube. There was a 3 mm distance between the probe tip and the resistance element of the RTD. To investigate the influence of the probe tip size on temperature alteration, a simulation run for the flat probe tip in 1 mm diameter with the best orientation angle and highest power setting within this study was performed in addition to the simulation for the flat probe tip in 2 mm diameter.

2.2. Numerical model and parameter settings

The computer simulation model used in current research was modified based on a previously model. This model was built using commercial software QuickWave version 7.5 (QW3D, Warsaw, Poland), and verified using a whey protein gel containing D-ribose (Luan et al., 2013). The metallic sensors (Ellab) were embedded in whey protein gels at two orientations $\varphi = 0°$ and 90°. The sensor tip was placed at the same cold spot location for each sample. Heating pattern of whey protein gel was displayed through computer vision method (Pandit et al., 2006, 2007). The validation results of heating pattern and temperature profiles are shown in Fig. 4. Good agreements on heating pattern and temperature profiles between experimental result and simulation results were observed. In current study, all the fundamental parameters such as numerical method, boundary conditions and basic assumptions were the same as those for the validated model (Luan et al., 2013). The parameters having different settings from the validated model