



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



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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.

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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

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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 ($\varphi = 0^\circ$ and 90°) had the same definition in this orientation angle system. Other than particular orientation angles, a general angle of $\varphi = 45^\circ$ 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 $\varphi = 0^\circ$ 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

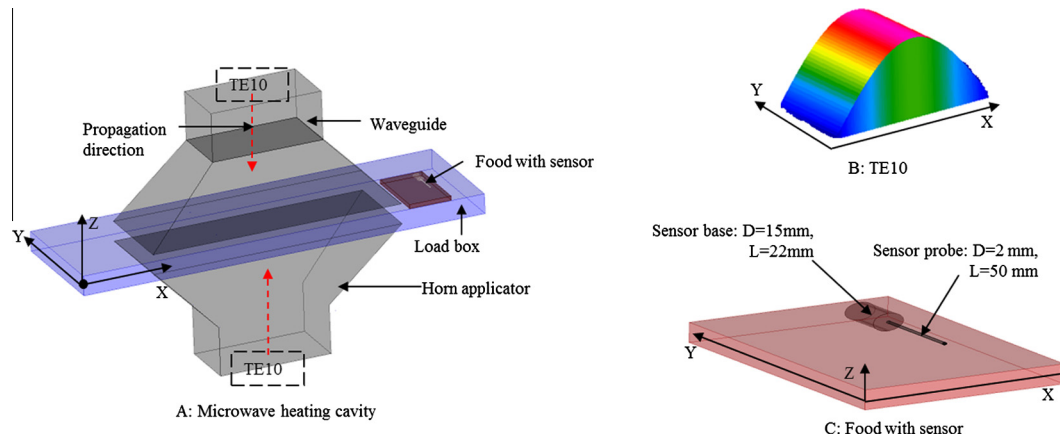


Fig. 1. Physical model in 3-D view. A: microwave heating cavity, B: electrical field distribution of TE10 model in the rectangular waveguide, C: food with an imbedded metallic sensor.

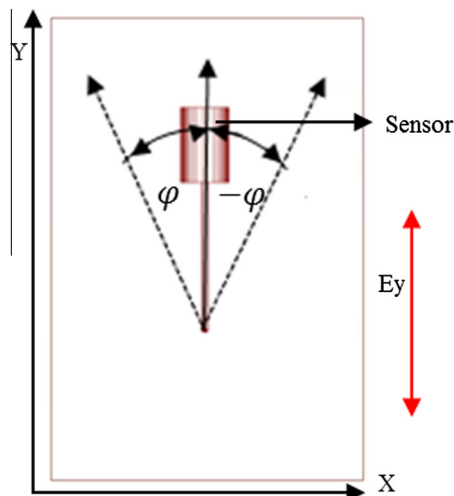


Fig. 2. Definition of the orientation angle for the mobile metallic sensor.

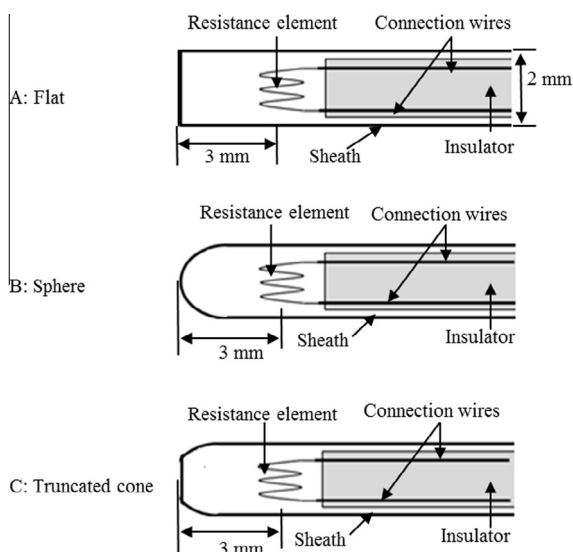


Fig. 3. Sketch of different tip geometries in top view. A: flat, B: sphere, C: truncated cone.

were the mesh size and moving step of food package. A finer mesh size and smaller moving step were used to improve the simulation accuracy.

The mesh size of a general FDTD cell in different materials was set following the rules of more than ten cells per wavelength (Rattanadecho, 2006). However, in the proximity of the metallic probe tip domain (within 3 mm distance from the tip) a much finer mesh size of $0.5 \times 0.5 \times 0.5 \text{ mm}^3$ (Fig. 5) was set to reveal detailed information of the electrical field and the corresponding temperature distribution within this area. This arrangement resulted in an overall cell number of $423 \times 92 \times 103$ for the simulation model and a cell number of $54 \times 52 \times 24$ for the food sample. A HP Z800 workstation with a dual processor of X5680, 3.33 GHz and a memory of 96 GB was used to run the simulation model. Ten discrete moving positions were uniformly distributed over the length of the cavity to simulate a continuous moving process. At each position from entrance to the exit of the cavity, food sample was simulated in sequence. It took 2 h to finish one moving position and 20 h for a whole run. The power setting of the initial model was 6.0 kW with an overall heating time of 39 s and 3.9 s for each moving position. To study the performance of metallic sensor in high microwave power environment, the simulation model with power settings of 12 kW and 24 kW and corresponding heating time of 19.5 s and 9.75 s were also run. The governing equations for EM field and heat transfer with corresponding boundary conditions were the same as those in Luan et al. (2013). Preliminary convergence and sensitivity tests were conducted to ensure reliable simulation results.

2.3. Data analysis

Once the simulation of each moving position was finished, the temperature distribution within each FDTD cell was saved in a data file as the initial temperatures for next position. The temperature distribution within a food sample at each moving position was extracted from the corresponding $54 \times 52 \times 24$ FDTD cells for heating pattern and temperature profile analyses. A heating pattern image of a given cross section of the food sample was generated by setting different colors to represent different temperatures. The image of temperature distribution in the middle layer (z direction) of x-y plane was the best illustration of the heating pattern, because the cold spot was located in this layer and it received lowest influence from hot water heating. All the heating patterns shown in this study were the middle layer x-y plane images of the last (10th) moving position.

The time-temperature profile was obtained by extracting the average temperature at the probe tip area from each temperature distribution file. All the FDTD cells within 3 mm distance from the probe tip were used to calculate the average temperature. Each

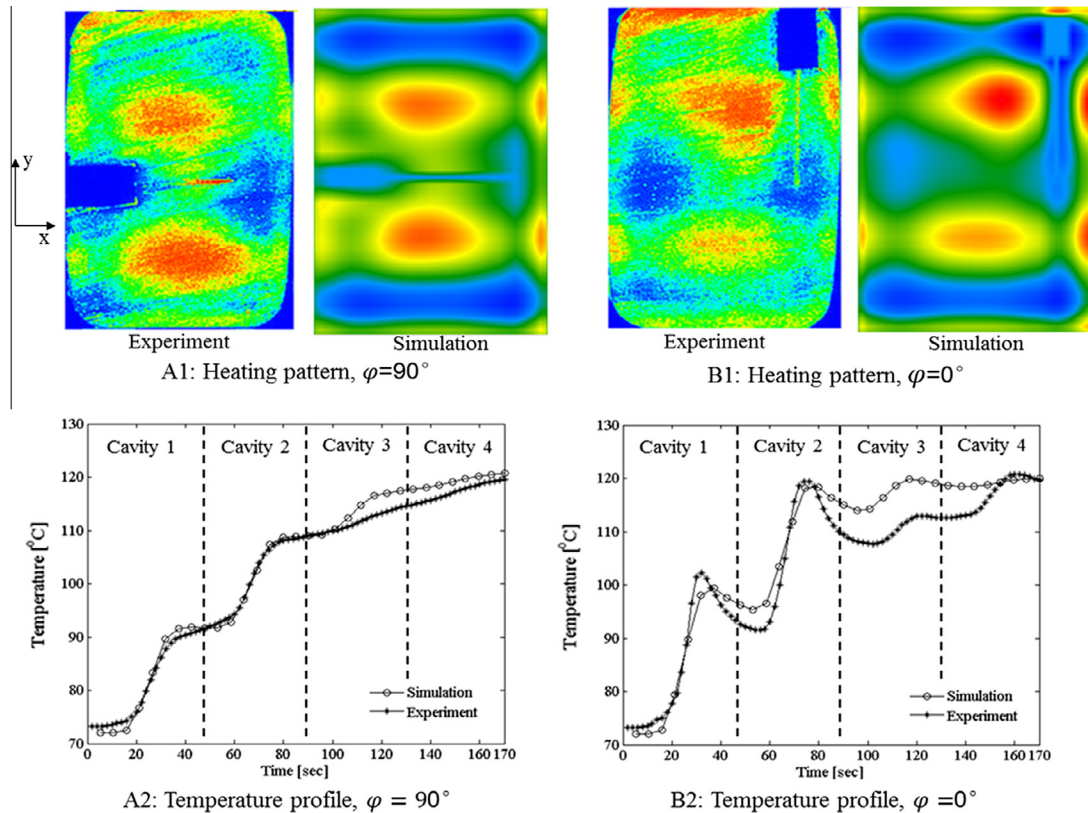


Fig. 4. Validation results of heating pattern and temperature profile through experimental tests of whey protein gels processed by a four cavities microwave heating system. Metallic sensors were embedded in the whey protein gel model food with an orientation angle of $\varphi = 90^\circ$ and 0° . Heating pattern results were obtained at the exit of the fourth cavity. Temperature profiles were the results of temperature history at the probe tips through the four microwave heating cavities. A1 & A2: experiment and simulation results of heating patterns and temperature profiles for the metallic sensor at an orientation angle of $\varphi = 90^\circ$, respectively. B1 & B2: experiment and simulation results of heating patterns and temperature profiles for the metallic sensor at an orientation angle of $\varphi = 0^\circ$, respectively, (modified from Luan et al., 2013).

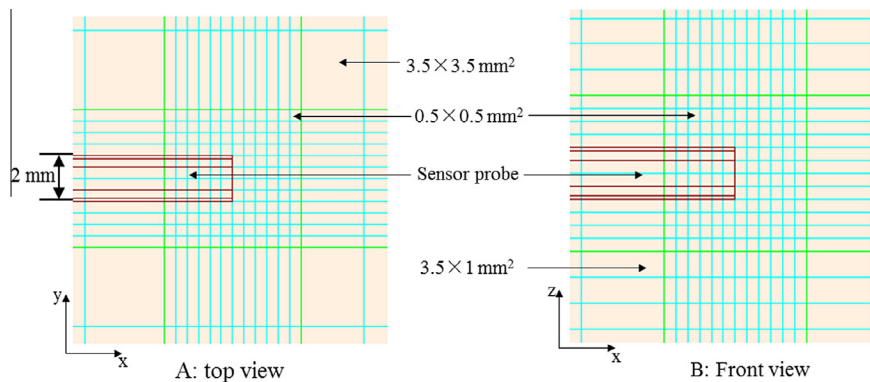


Fig. 5. FDTD cell sizes at the probe tip area of a metallic temperature sensor at the orientation angle of $\varphi = 90^\circ$.

time–temperature profile had ten elements matching ten moving positions. A separated Matlab (Mathworks Inc., MA, USA) script was programed to read the temperature data file and perform the calculation. The same operation was done for the simulation of a control run that was without a sensor to obtain the comparison temperature profile. At each moving position, the temperature difference between the objective run with sensor and the control run was the temperature alteration created by a metallic temperature sensor. A temperature difference profile was obtained by collecting the ten temperature alterations at the corresponding moving positions.

3. Results and discussion

3.1. Influence of orientation angle and tip geometry of metallic probes on heating pattern and temperature alterations

The metallic sensors with three different probe tip geometries were simulated at the two particular orientation angles ($\varphi = 0^\circ$ and 90°) to study the influence of tip geometries on heating patterns and temperature alterations at the original power setting of 6 kW. A general orientation angle of $\varphi = 45^\circ$ was also studied for the sphere probe tip to reveal the performance of the metallic sen-

sor in a general orientation. The best orientation angle was selected by comparing the heating pattern and temperature alteration results. The heating pattern results are shown in Fig. 6. Compared with the heating pattern without sensor (Fig. 6D), a mobile temperature sensor did not change the general cold and hot spot distribution when it was placed at orientation angles of $\varphi = 0^\circ$ or 90° . This result was consistent with the validated model (Fig. 4). Similar heating patterns were observed for different tip geometries when the sensors were placed at the same orientation angle such as the results in Fig. 6A1, B1 and C1. A distorted heating pattern was observed near the base part of the sensor when it was placed at the orientation of $\varphi = 45^\circ$ (Fig. 6B3). However, this local distortion did not affect the temperature distribution at the probe tip zone. There was obvious local overheating at the probe tip zone when the sensor had an orientation angle of $\varphi = 0^\circ$ (Fig. 6A1, B1, and C1) and 45° (Fig. 6B3). This local overheating was displayed by the simulation model with finer mesh size at the probe tip zone. However, no such overheating was observed at the same domain of the metallic sensors with the orientation angle of $\varphi = 90^\circ$. Temperature difference profiles were calculated for the sensors with different tip geometries and orientation angles. These temperature alterations varied with moving positions are shown in Fig. 7. All the values of the alterations were above zero which indicated that the metallic sensor created a higher temperature at the probe tip zone. Electric field distortion and enhancement at the probe tip zone caused these higher temperature zones (Pert et al., 2001; Egorov et al., 2006; Luan et al., 2013). With the same orientation angle ($\varphi = 0^\circ$ or 90°), temperature alterations of different sensor probe geometries had no significant difference. The temperature alterations were reduced by changing the orientation angle from 0° to 45° and 90° . The orientation angle of $\varphi = 90^\circ$ was the best orientation angle for the metallic sensor which was directly perpendicular to the dominant electric field component (y direction). The best orientation angle limited the temperature alterations within a range of 0.6°C when the sensor in food moved through the 6 kW microwave heating cavity.

The temperature alterations increased first and then decreased with the moving position numbers. This trend can be explained by

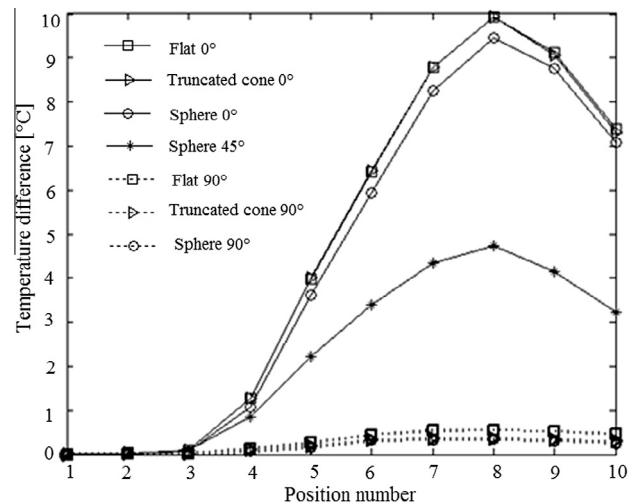


Fig. 7. Temperature difference profiles for different sensor conditions in 6 kW microwave heating cavity. Probe diameter = 2 mm.

the electric field distribution in the microwave heating cavity that the highest electric field intensity arose at the middle of the cavity. The results showed that higher electric field intensity at the center of the microwave heating cavity amplified the temperature alteration. Likewise, higher microwave power may also amplify the temperature alteration to a high level although the sensor was at the best orientation.

3.2. Influence of power setting on heating pattern and temperature alteration

Simulation runs with higher power settings of 12 kW and 24 kW were carried out for three different metallic sensor tip geometries with the best orientation angle ($\varphi = 90^\circ$). The comparison runs without sensor were also carried out with these two power settings. The overall heating time within each simulation

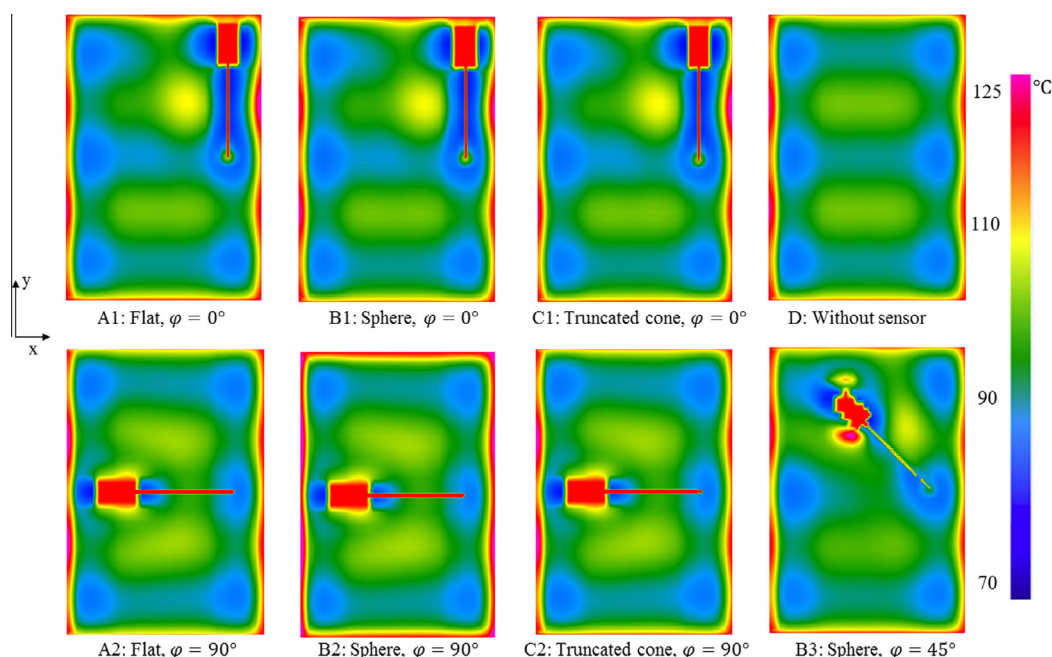


Fig. 6. Heating patterns in the food samples with different sensor conditions at the exit of a 6 kW microwave heating cavity. The sensors with different probe tip geometries were placed at the same location with different orientation angles. Probe diameter = 2 mm.

run was reduced accordingly to 19.5 s and 9.75 s, respectively, so that the cold spot temperature reached the same proximity value as for lower microwave power heating. The heating patterns for 24 kW power setting are shown in Fig. 8. Compared with power setting of 6 kW (Fig. 6), four times power setting did not change the general heating patterns. Results proved that the heating pattern in a MATS system was stable regardless power settings. However, the overheating in y direction near the sensor surface was more obvious for high microwave power settings. The reason was that the existence of metallic sensor cut off the continuity of electric field component in y direction and led to field enhancement at the metallic surface. Heat dispersion within a short time was not adequate to ease the local overheating intensified by high microwave powers.

Analyses of the electric field component in the middle layer (z direction) of the microwave heating cavity could help to verify this electric field enhancement effect. Two identical microwave heating cavities were built in one simulation run to analyze the distribution of electric field components. Food samples with and without sensor (sphere tip) were placed at the center of each cavity. Combined in one simulation run, the electric fields within the two cavities had the same phase. A snapshot of electric field component distributions at the middle layer of z direction is shown in Fig. 9. The right side cavity was the control without sensor. It was clear that the dominant component of the overall electric field intensity (E) was in y direction (E_y). The electric components in x (E_x) and z (E_z) directions were close to zero. Electric field enhancement was observed near the sensor surface in y direction which was reflected on the heating patterns (Fig. 8).

The influences of probe tip geometries and power settings on the temperature difference profiles are shown in Fig. 10. The temperature alterations were amplified by increasing the microwave power setting for each type of probe tip geometry. However, the sphere probe tip had the lowest sensitivity to the increased powers. It was reasonable that electric field enhancement was very intensive at sharp edges (Bouwkamp, 1946). The smooth surface of the sphere tip helped to reduce this type of enhancement. The sensor with the truncated cone tip had lower temperature alteration and displayed less sensitivity to power settings compared with the flat tip sensor which also proved that the probe tip with smoother surface is better.

The amplification effect of high power setting on temperature alterations could be used in arranging the microwave power distribution of multi-cavity microwave heating systems. A proper arrangement for microwave power distribution could reduce the influence of temperature alterations on the development of a thermal process to meet the academic desired microbial inactivation. For a microwave heating system with two or more cavities along

the moving direction of food packages, a decreasing power setting is desirable to make the larger temperature alteration arise at the first cavity or first few cavities where food temperatures were at a low level. The temperature alterations at a low temperature level had limited influence on evaluation values of microbial inactivation due to the relationship between time–temperature profile and the thermal inactivation of microorganisms (Holdsworth, 1985).

The simulation model was also used to study the influence of heat dissipation on temperature alterations caused by the presence of mobile probe after the food pouches moving out of microwave heating cavities into the holding zone. In the holding zone the microwave power was set to zero, only heat transfer was considered, and the circulating water temperature was set as 125 °C. The temperature difference profiles during microwave heating and holding processes for two sensor tips (flat and sphere) at three microwave power settings are shown in Fig. 11. In the holding section, the temperature alterations decreased gradually with holding time. At 10 s after the food pouch moved to the holding section, the temperature alterations caused by the flat sensor in 6, 12 and 24 kW microwave heating process decreased to 0.36, 0.47 and 0.61 °C, respectively. For the sphere sensor, the corresponding temperature alterations were reduced to 0.15, 0.27 and 0.33 °C, respectively. These results indicate that lower power setting of the last few microwave heating cavities could reduce the effect of temperature alterations to an acceptable level within a very short holding time. For example, if a 6 kW microwave power setting was used for the last microwave cavity connected to the holding section, the 0.15 °C alteration over a holding temperature of 121.1 °C at the cold spot would only led to an overestimated value of 0.21 min (i.e. 12.6 s) to a $F_0 = 6$ min (thermal lethality to *Clostridium botulinum* at constant temperature of 121.1 °C) when using a probe with spherical tip.

3.3. Influence of probe diameter on temperature alteration

The flat probe tip which was most sensitive to microwave power settings was chosen to study the influence of probe diameter on temperature alterations. Fig. 12 shows the temperature difference profiles obtained from the simulation with power setting of 24 kW for flat probe tips with different diameters (1 mm and 2 mm) and probe orientation angle of $\varphi = 90^\circ$. The temperature alteration caused by electric field enhancement decreased from more than 1.1 °C to less than 0.2 °C by reducing the probe diameter from 2 mm to 1 mm. The temperature alteration of 0.2 °C in the 24 kW microwave heating cavity even for the worst tip design (flat tip) considered in this study was comparable to the accuracy of

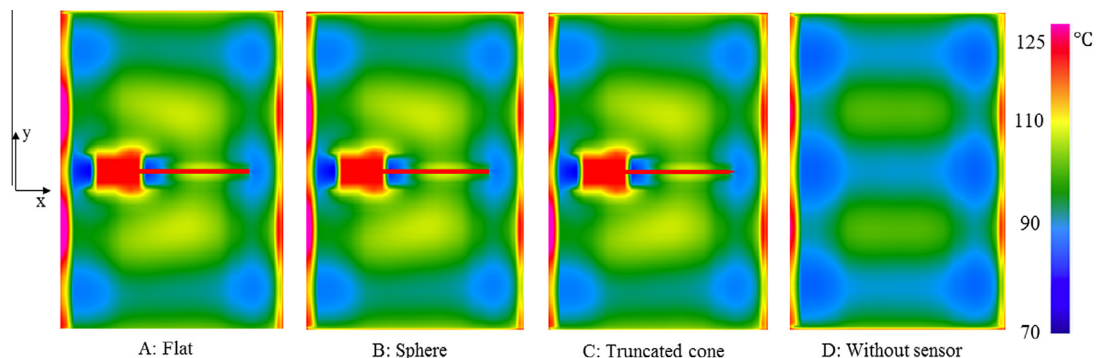


Fig. 8. Heating patterns in food samples without sensor and with three different probe tips (orientation angle of $\varphi = 90^\circ$) at the exit of the 24 kW microwave heating cavity. A: flat, B: sphere, C: truncated cone, D: without sensor. Probe diameter = 2 mm.

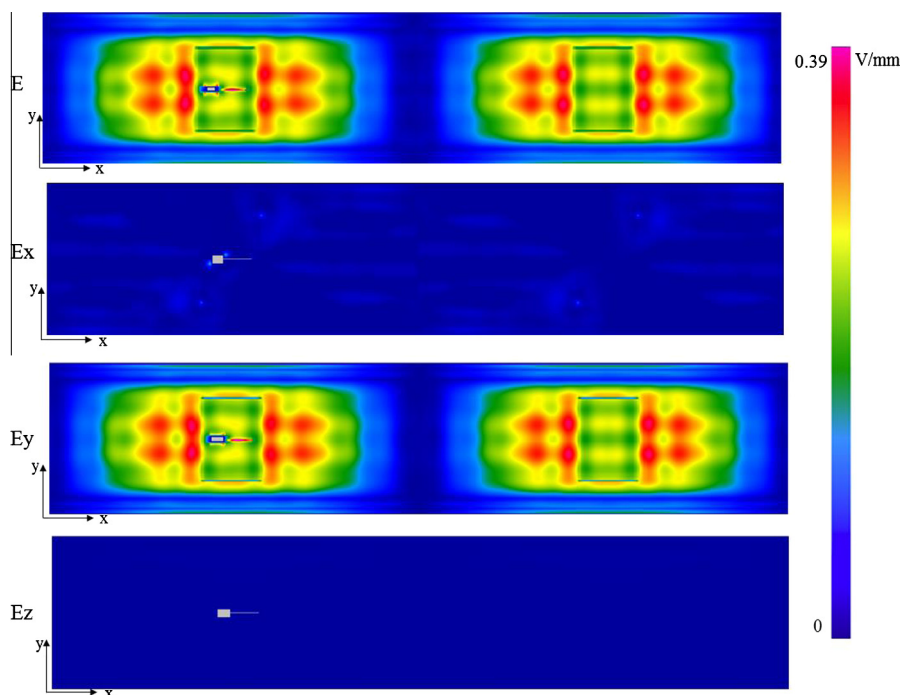


Fig. 9. Snapshot of electric field component distributions in two 24 kW microwave heating cavities. Food samples with sensor (spherical tip, $\varphi = 90^\circ$) and without sensor were placed at the center position of the left and right cavities, respectively.

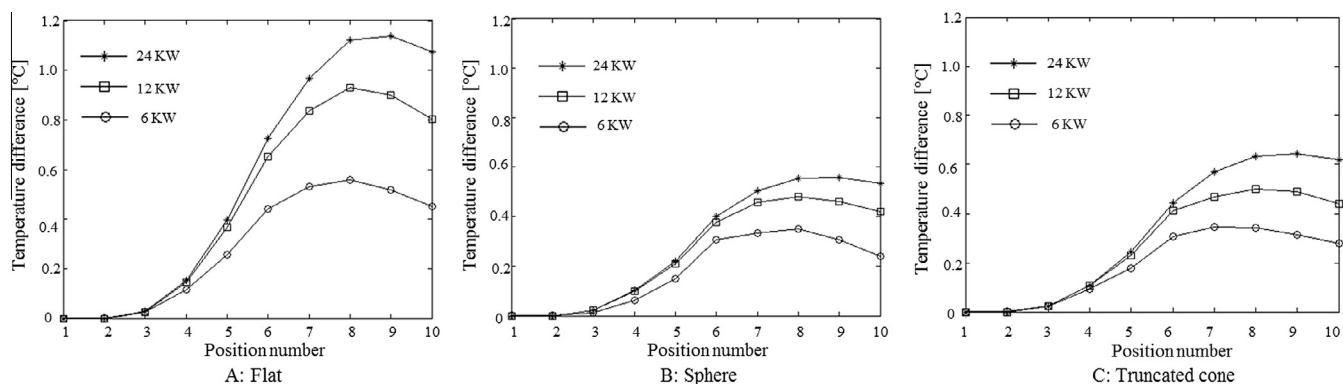


Fig. 10. Temperature difference profiles for the three probe tip geometries at different microwave power settings with the probe orientation angle of $\varphi = 90^\circ$. A: flat, B: sphere, C: truncated cone. Probe diameter = 2 mm.

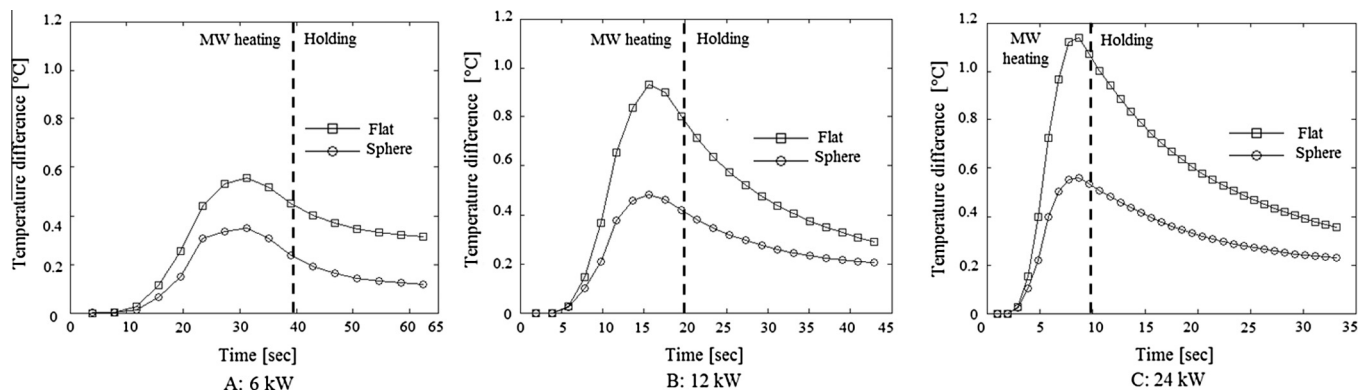


Fig. 11. Temperature difference profiles during microwave (MW) heating and holding processes for flat and sphere tips with the probe orientation angle of $\varphi = 90^\circ$ at three microwave power settings. A: 6 kW, B: 12 kW, C: 24 kW. Probe diameter = 2 mm.

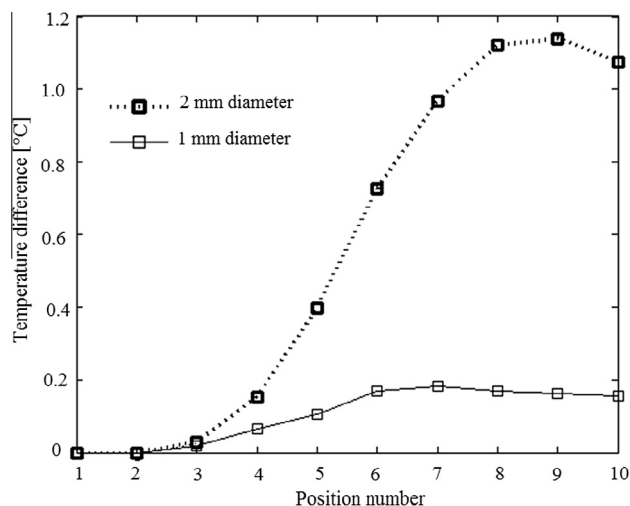


Fig. 12. Temperature difference profiles during microwave (MW) heating process for flat tips with different probe diameters of 1 mm and 2 mm at an orientation angle of $\varphi = 90^\circ$ and 24 kW microwave power setting.

RTD (Wang et al., 2003). It was acceptable in commercial thermal processing development.

4. Conclusion

Computer simulation results revealed that a higher temperature zone was created at the metallic temperature sensor tip which could cause erroneous temperature readings. These temperature alterations were caused by electric field distortion and enhancement at the probe tip. The temperature alterations were reduced by orienting the sensor probe perpendicular to the dominant electric field component.

At a low microwave power setting of 6 kW for a 915 MHz single mode cavity, there was no significant difference among the temperature alterations of the probes with different tip geometries; however, the temperature alterations were amplified by higher microwave power settings.

Among the three probe tip geometries, the sphere tip with the smoothest surface had the lowest sensitivity to microwave power settings. For the worst case of flat probe tip, which caused the highest temperature alteration, the temperature alteration could be greatly reduced by decreasing the probe diameter from 2 mm to 1 mm. It was suggested that the design of spherical probe tip and thinner probe diameter should improve the accuracy of metallic temperature sensors applied in high microwave power environment.

For a multi-cavity microwave heating system, a decreasing power distribution of the heating cavities along the package moving direction is recommended. This arrangement could reduce the propagating errors from the time–temperature profiles to the estimation of desired microbial inactivation level in designing microwave thermal processes. The dominant electric field component within microwave heating cavity is in y direction which is the same as the electric field in a waveguide. It implies that in MATS system, the general mode of microwaves does not change when they propagate from waveguide to the heating cavity.

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