Frequency Distribution in Domestic Microwave Ovens and Its Influence on Heating Pattern

Donglei Luan, Yifen Wang, Juming Tang, and Deepali Jain

Abstract: In this study, snapshots of operating frequency profiles of domestic microwave ovens were collected to reveal the extent of microwave frequency variations under different operation conditions. A computer simulation model was developed based on the finite difference time domain method to analyze the influence of the shifting frequency on heating patterns of foods in a microwave oven. The results showed that the operating frequencies of empty and loaded domestic microwave ovens varied widely even among ovens of the same model purchased on the same date. Each microwave oven had its unique characteristic operating frequencies, which were also affected by the location and shape of the load. The simulated heating patterns of a gellan gel model food when heated on a rotary plate agreed well with the experimental results, which supported the reliability of the developed simulation model. Simulation indicated that the heating patterns of a stationary model food load changed with the varying operating frequency. However, the heating pattern of a rotary model food load was not sensitive to microwave frequencies due to the severe edge heating overshadowing the effects of the frequency variations.

Keywords: computer simulation, frequency distribution, heating pattern, microwave oven, operating frequency

Practical Application: The research work revealed the large frequency variations among domestic microwave ovens. The heating patterns of rotary solid model food loads were not sensitive to varying operating frequencies compared with those of stationary loads. This information should provide guidelines for product development in designing appropriate cooking instructions to ensure food safety.

Introduction

Domestic microwave ovens are popular household appliances worldwide. However, a major drawback is nonuniform heating of foods (Vadivambal and Jayas 2010) caused by an uneven electric field distribution (Plaza–Gonzalez and others 2004). Nonhomogenous distribution of temperature in the food can cause problems in terms of microbial safety and quality (Awuah and others 2007). Uneven electric field distribution happens when high and low intensity electric fields are present at the nodes and anti–nodes of the standing waves, respectively. Several standing wave patterns may coexist within a domestic microwave oven; each pattern is referred to as a resonant mode corresponding to a unique frequency within the frequency range of the oven magnetron (2450 ± 50 MHz). Hence, the chamber of a domestic microwave oven is called a multimode heating cavity. In a multimode cavity, the frequencies corresponding to different resonant modes are clustered close to each other; a small frequency shift from the magnetron may result in a totally different electric field distribution and heating pattern of food (Chan and Reader 2000; Dibben 2001).

The operating frequency within a microwave oven is determined by 2 parameters: the design of the magnetron and the output impedance from the oven and the load (Ghammaz and others 2003). The frequency of microwaves emitted by a magnetron may shift as its ages (Cooper 2009; Resurreccion and others 2015), possibly caused by a reduction in the field of the permanent magnet (Decareau 1985). A change in the cathode–anode voltage during operation may also affect the frequency of emitted microwaves. In addition, during microwave heating the dielectric properties of the food load change with temperature, which changes the impedance of the load, causing a shift of the microwave frequency in the cavity. Although the frequency shifting within multimode microwave ovens has been a well-known phenomenon, the variation and distribution patterns of the operating frequencies have not been systematically studied and reported. However, the operating frequency of microwave ovens is a fundamental factor that influences heating pattern and uniformity of food load during microwave heating.

Most of the previous studies that related to heating uniformity in domestic microwave ovens focused on the influences of food shape (Chamchong and Datta 1996; Zhang and Datta 2005), position (Funawatashi and Suzuki 2003), size (Vilayannur and others 1998), and dielectric properties of foods (Peyre and others 1997; Zhang and Datta 2000). Other studies reported heating uniformity improvements made by using different mode stirrers (Plaza–Gonzalez and others 2004; Geogre and Bergman 2006), turntable (Geedipalli and others 2007), and feed designs (Kubota and Kashiwa 1997). Few studies paid attention to the influence of microwave frequency on heating patterns of foods. Birla and others (2010) reported a computer simulation study on the effect of magnetron frequency on heating pattern in a domestic microwave oven with an input frequency from the magnetron that varied from 2.44 to 2.48 GHz. However, the measurement of the frequency was only one snapshot which cannot completely reveal the possible frequency

variations during operation. Furthermore, only 3 frequencies (2.42, 2.46, and 2.52 GHz) were selected to perform the computer simulation runs. Although the simulated heating pattern at 2.46 GHz was closest to experimental result, none of the simulated heating patterns obtained from the selected frequencies matched well with the experimental result. Pitchai and others (2012) developed a simulation model for microwave heating in a domestic microwave oven. Three frequencies, 2.450, 2.455, and 2.458 GHz, were used in the simulation model to study their influences on heating pattern. Results showed that the simulated heating pattern at 2.450 GHz closely matched with the experimental profile. However, only simulation study was performed to show the possible resonant frequency in the microwave oven. There were no systematical frequency measurements in those 2 previous studies.

The objectives of this study were: (1) to measure operating frequencies of domestic microwave ovens with and without loads; and (2) to study the effect of variations in operating frequency on heating patterns of stationary and rotary model food loads using computer simulation. Revealing the frequency variation and its influence on heating patterns of stationary and rotary food load would help to explain heating pattern formation and explore methods to ensure microbial safety of microwave cooked meals.

Materials and Methods

Frequency measurement

A TM-2650 spectrum analyzer and an AN-301 antenna (B&K Precision, Yorba Linda, Calif., U.S.A.) were used to measure operating frequencies of domestic microwave ovens. For each measurement, the antenna of the TM-2650 spectrum analyzer was placed 5 cm away from the door of a microwave oven to detect the leaked microwaves. The spectrum analyzer was set to have a central frequency of 2450 MHz with a span of 100 MHz. The microwave signals at the frequencies from 2400 to 2500 MHz were recorded every 0.4 MHz, that is, there were 251 data points for each measured frequency profile. Since the instantaneous operating frequency of a domestic microwave oven constantly changed with time, it was impossible to obtain all the changing frequencies. Thus, snapshots of the frequency profile were taken every 2 to 3 s through 1 min operating time to collect samples of the operating frequency.

In this study, the operating frequencies of microwave ovens in 2 different models were investigated. Four ovens in the same model (Westbend, Model EM915AJW-P2, WI, U.S.A.) were purchased at the same time (July 2014) from the same store, they were used to study frequency variations among individual ovens. Another microwave oven (Panasonic, Model NN-SD681S, Tokyo, Janpan),
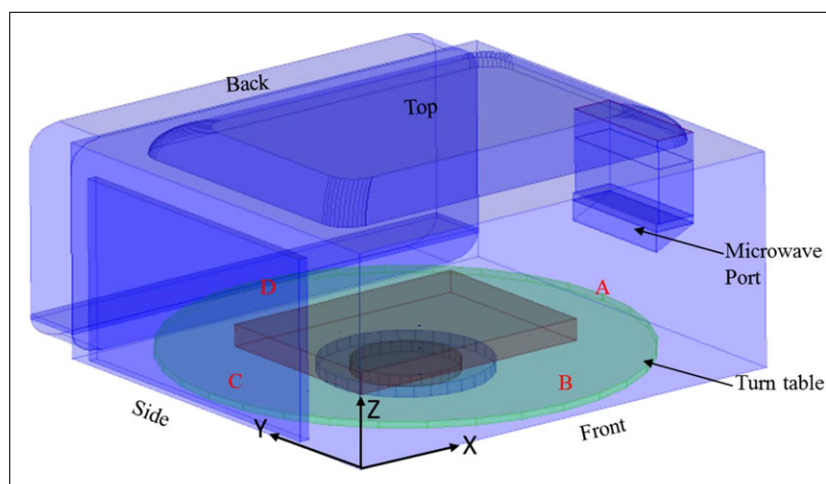
Figure 1–Schematic diagram of a domestic microwave oven (NN-SD681S, Panasonic, Tokyo, Japan), and the locations (A to D) to place the stationary loads during heating experiments.
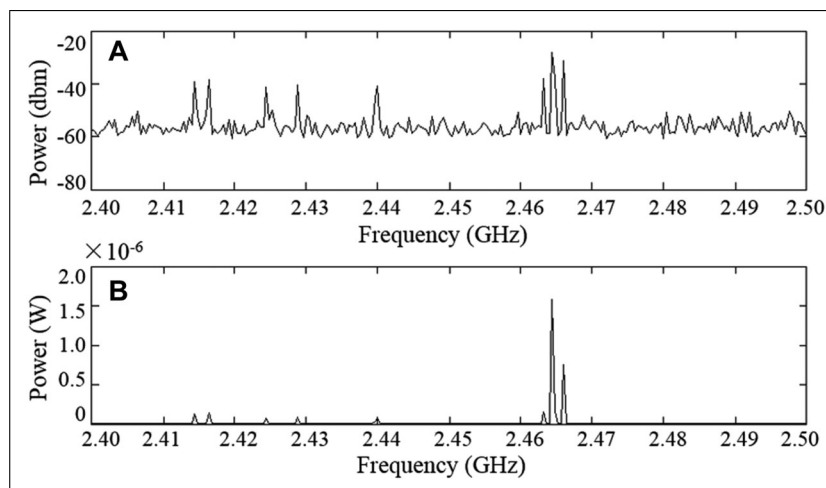

Figure 2–Operating frequency distribution of an empty domestic microwave oven using 2 power units, decibel (dbm, A) and watt (W, B).

newly bought, was used to study the frequency variation affected by load conditions.

Heating pattern validation

A model food made out of gellan gel was used to obtain the experimental heating patterns in a domestic microwave oven for comparison with simulated results. The model food was in a rectangular shape with a dimension of 184 × 134 × 23 mm³ and weighed 567 g (that is, 20 oz). The gellan gel model food was prepared according to Zhang and others (2015).

The model food was placed in the center of the Panasonic NN-SD681S domestic oven, as shown in Figure 1, and heated from room temperature for 60 s. Snapshots of the frequency profiles were taken during the heating process. A thermal camera (Therma-CAM™ Researcher 2001, FLIR Systems, Portland, Oreg., U.S.A.) was used to capture the temperature distribution of the gellan gel at surface, middle, and bottom layers immediately after microwave heating for stationary and rotary modes (rotation

speed of 6 rpm). To capture the temperature distribution at the middle layer, the model food was cut into 2 pieces before heating, and placed together as a whole food.

Computer simulation model

A computer simulation model was developed based on the dimensions of the newly bought domestic microwave oven (Panasonic NN-SD681S). The geometries of the waveguide, port, turntable, top, and side covers were combined in the computer simulation model (Figure 1). The simulation model was built using a commercial software of Quickwave version 7.5 64-bit (QWED, Warsaw, Poland). With an attached Basic Heating Module of QuickWave (QW-BHM), the coupled electromagnetic and heat transfer equations were numerically solved through finite difference time domain method (Luan and others 2013, 2015). The mesh size was set as 8 mm in air and 1 mm in food which follows the rule of 10 cells per wavelength (Rattanadecho 2006) and based on a mesh sensitivity study (data not shown). The dielectric and
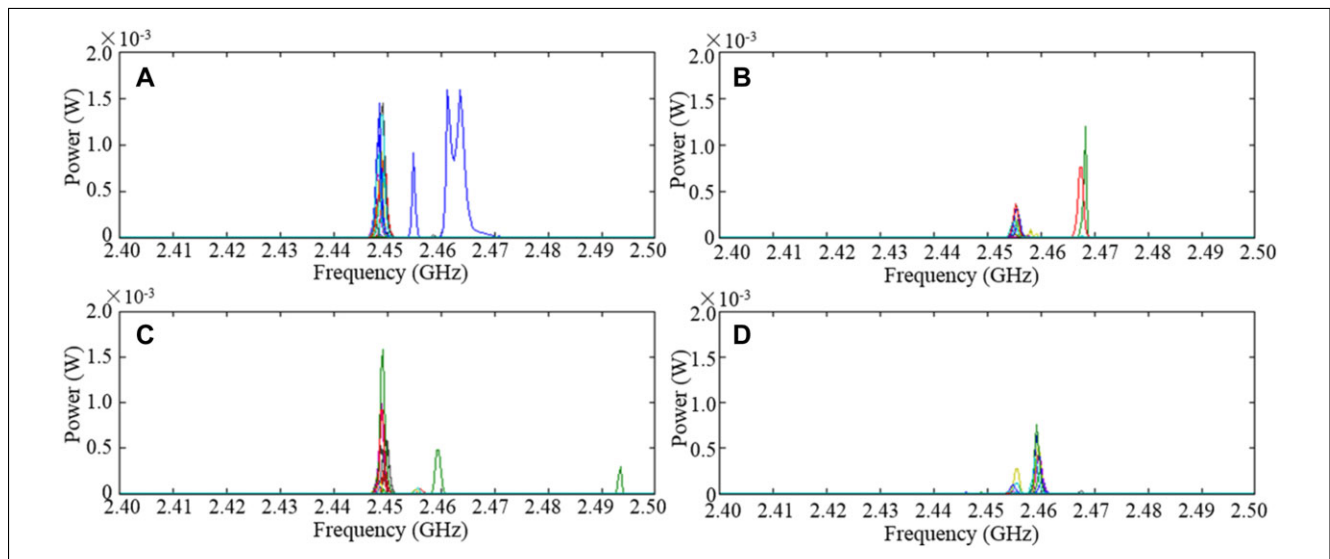

Figure 3–Operating frequency distribution for 4 empty domestic microwave ovens (A, B, C, and D) of the same model. Each graph was the collection of 25 frequency profile snapshots
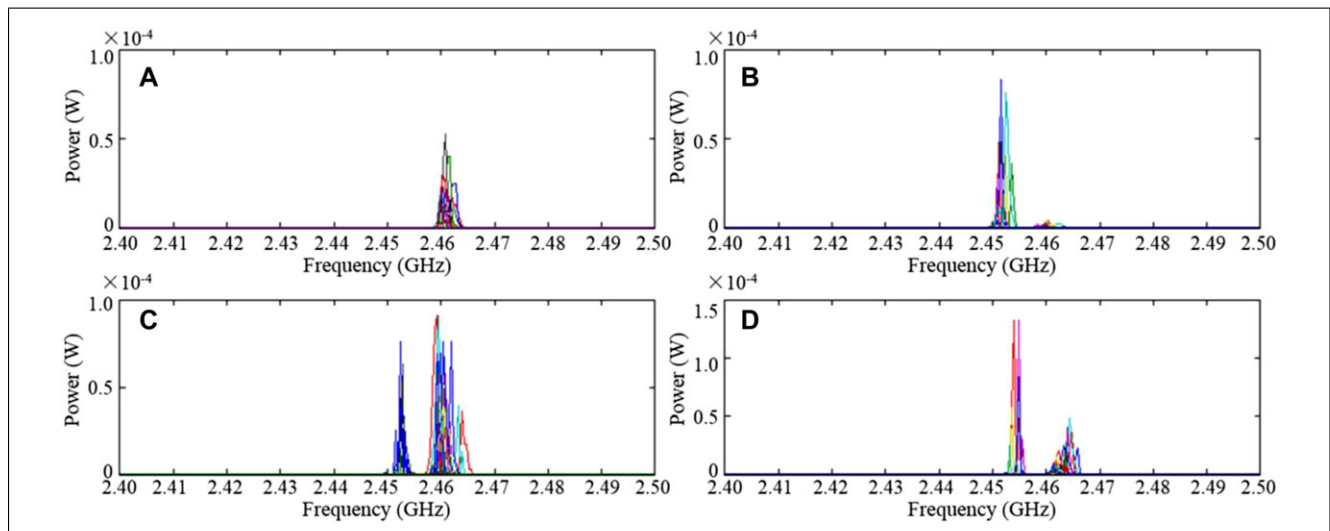

Figure 4–Operating frequency distribution of an empty domestic microwave oven within 4-mo period, A: brand new, B: 2 mo, C: 3 mo, D: 4 mo.

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thermal properties of gellan gel were updated with changing temperatures in the simulation. The data of dielectric properties used in the simulation model were reported in Zhang and others (2015).

Heating tests with rotation of the food were carried out to study the influence of a turntable. A sensitivity study of the rotation angle was performed to balance the simulation time and accuracy, an increment of 30° for rotation angle was selected.

The microwave source was set as TE10 sinusoidal wave at a fixed frequency. The microwave power was set as 800 W, although the actual input power may change with different load condition. The main research interest was to analyze the changes in food heating pattern due to variations of the oven's operating frequency, not the effect of actual power. Any changes in power level of each frequency would only affect the overall temperature magnitude but not the heating pattern.

Results and Discussion

Frequency profile

For each frequency measurement, 25 to 30 snapshots were taken as samples of the overall frequency profiles. Each measured result was the collection of those snapshots of the frequency profile, which were plotted in one graph. The collection of these snapshots showed the probability of occurrence for the operating frequency within the spectral band. It also revealed the variation and distribution of the operating frequencies.

In microwave communication, dbm (decibel to milliwatt) was the usually used power unit during measurement of signals. The raw measured data in this study was also in the unit of dbm. To clearly show the frequency distribution, the power unit was converted to watt by Eq. 1 (Joseph and others 2001), where P(dbm) is the power unit of dbm and P(W) is the power unit of watt.

$$P(dbm) = 30 + 10\log_{10}(P(W)) \qquad (1)$$

$$P(W) = 10^{-8}10^{\frac{P(dbm)}{10}} \qquad (2)$$

A typical snapshot of frequency profile in 2 different units is shown in Figure 2. In the unit of watt, the background signals were removed and the frequency distribution was clearer than the
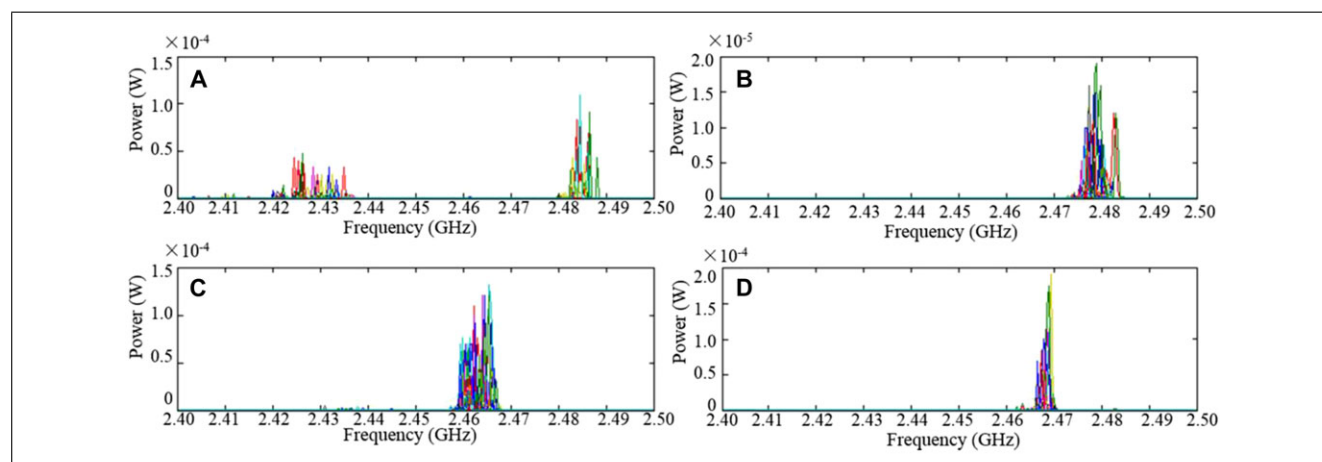

Figure 5–Operating frequency distribution (30 frequency snapshots) of a domestic microwave oven with 500 mL water load in beaker at 4 different stationary locations, A, B, C, and D as shown in Figure 1.
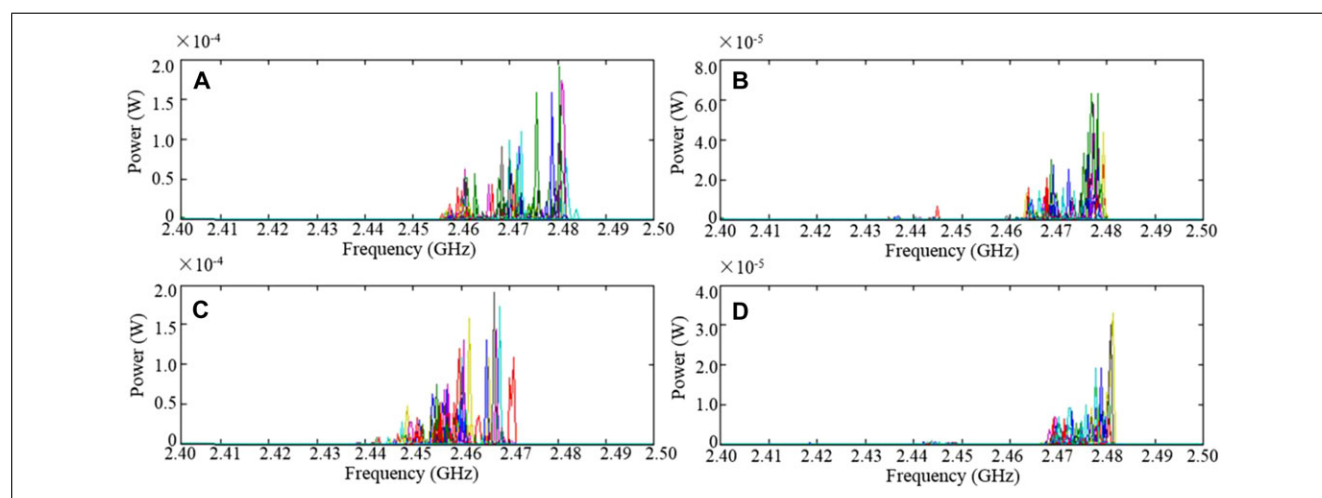

Figure 6–Operating frequency distribution (30 frequency snapshots) of 500 mL tap water load within a food tray (with a basal area of 184 × 134 mm²) at 4 stationary locations shown in Figure 1.

one in unit of dbm. Thus the unit of watt was used in the results of frequency profiles presented in the rest of the paper.

Frequency difference among individual ovens

The operating frequencies of 4 empty ovens in the same model (Westbend, Model EM915AJW-P2) were measured within 30 min. Each measurement included 25 snapshots of the frequency profile. A replication measurement was performed within 2 d. Good repeatability was observed between the 2 measurements in terms of frequency distribution. The measured frequency results for these 4 microwave ovens are summarized in Figure 3. Although there were no 2 identical snapshots of the frequency profiles in each measurement, the collection of these snapshots demonstrated a unique frequency distribution and variation pattern for each of the 4 microwave ovens. Results showed that the operating frequencies of these microwave ovens clustered at several frequency bands. The number and position of these frequency bands were different among the 4 empty microwave ovens. The frequency variation of those microwave ovens spreaded over from 5 (Figure 3D) to 40 MHz (Figure 3C). Operating frequencies of the microwave oven A and C clustered at 2.45 GHz with few additional frequencies with

low occurrence probability. For the microwave oven B and D, 2 frequency clusters were observed at 2.455, 2.468 GHz and 2.455, 2.460 GHz, respectively. These results indicated that the operating frequencies of a domestic microwave oven were constantly changing with time and the varying frequencies accumulated at different frequency bands; each individual oven had unique characteristic operating frequencies.

Frequency shift over time

Figure 4 shows the operating frequencies distribution of an empty domestic microwave oven (Panasonic NN-SD681S) measured over a period of 4 mo after it was purchased from a local store. The measurements were performed every 10 d. These measured results were similar but not identical to each other, and poor similarity between 2 adjacent results was observed during 4-mo period. The operating frequencies of the brand new oven clustered around 2.46 GHz (Figure 4A). However, after it was used for 2 mo, a new frequency cluster appeared around 2.45 GHz. The observed changes in operating frequencies may be partially attributed to aging. This shift in frequency may also be due to random variations.
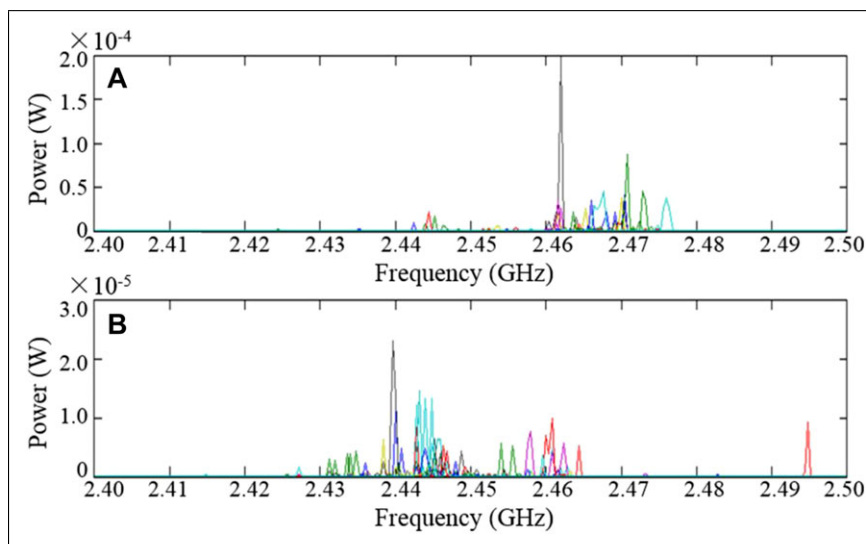

Figure 7–Operating frequency distribution (25 frequency snapshots) of 500 mL tap water load filled in a beaker (A) and food tray with a basal area of 184 × 134 mm^2 (B). The beaker and food tray were placed at the center of the turntable with a speed of 6 rpm.
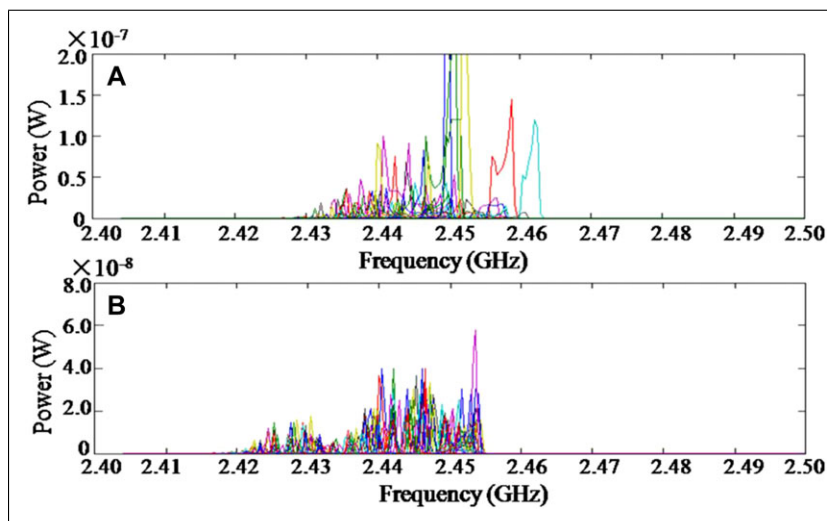

Figure 8–Operating frequency distribution (30 frequency snapshots) of gellan model food heated at stationary (A) and rotary (B) conditions.

Frequency shift caused by load shape and location

A 500 mL tap water load in a beaker (cylinder shape, 51 mm in diameter) was used to study the influence of load location on the operating frequencies. The turntable was removed from the microwave oven and the beaker was placed at 4 locations as shown in Figure 1 (that is, A, B, C, and D, close to the 4 sides of the oven wall). For each measurement, the tap water was heated from room temperature for 1 min, and 30 frequency snapshots were taken. There was a time interval of 30 min before next measurement for cooling down the magnetron. Repeated measurements were carried out next day. The results of repetition agreed well qualitatively with the 1st measurements. These results are summarized in Figure 5.

The operating frequencies were totally different from each other when placing the beaker with 500 mL water at the 4 different locations within the microwave oven. At the location B, C, and D, there was only one frequency cluster with band of 2.473 to 2.482 GHz, 2.460 to 2.468 GHz, and 2.466 to 2.470 GHz, repectively. However, at the location A, the operating frequency clustered at 2 bands of 2.420 to 2.438 GHz and 2.480 to 2.488 GHz, respectively. A possible reason was that the location A was closer to the entry port of the microwaves. In summary, varying locations of the same load resulted in different operating frequencies.

The effect of load shape on operating frequency of the microwave oven was stuided by placing 500 mL tap water in a food tray (with a basal area of 184×134 mm^2) at the 4 locations shown
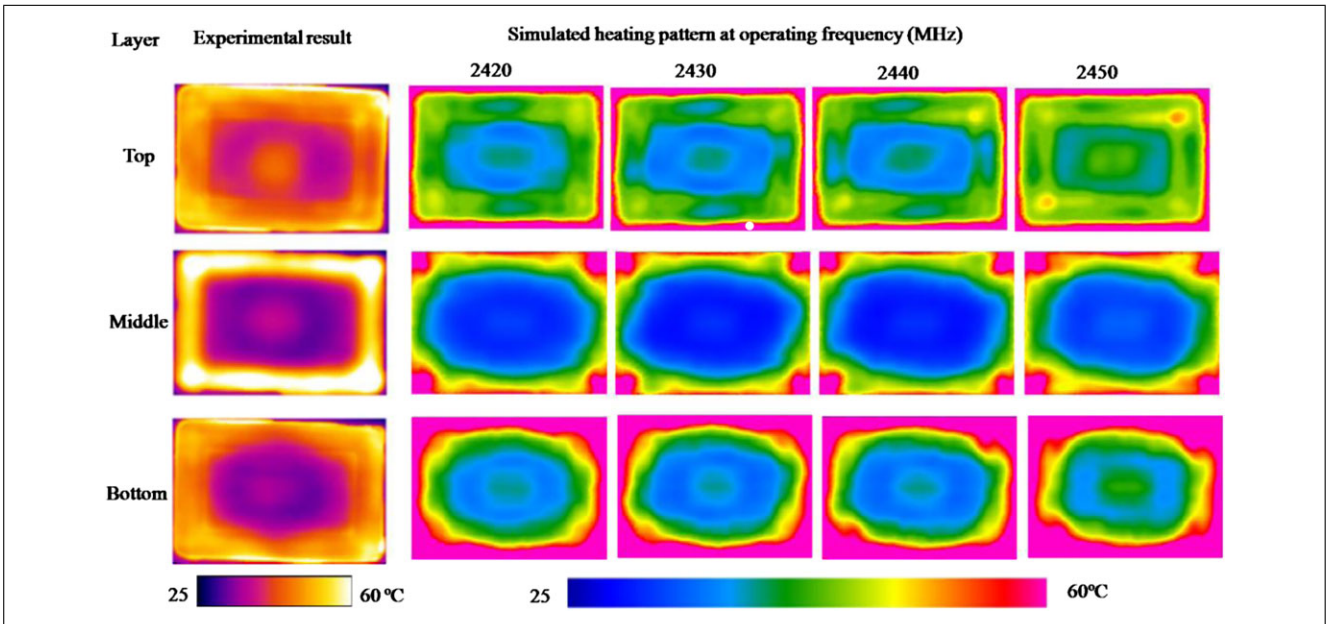

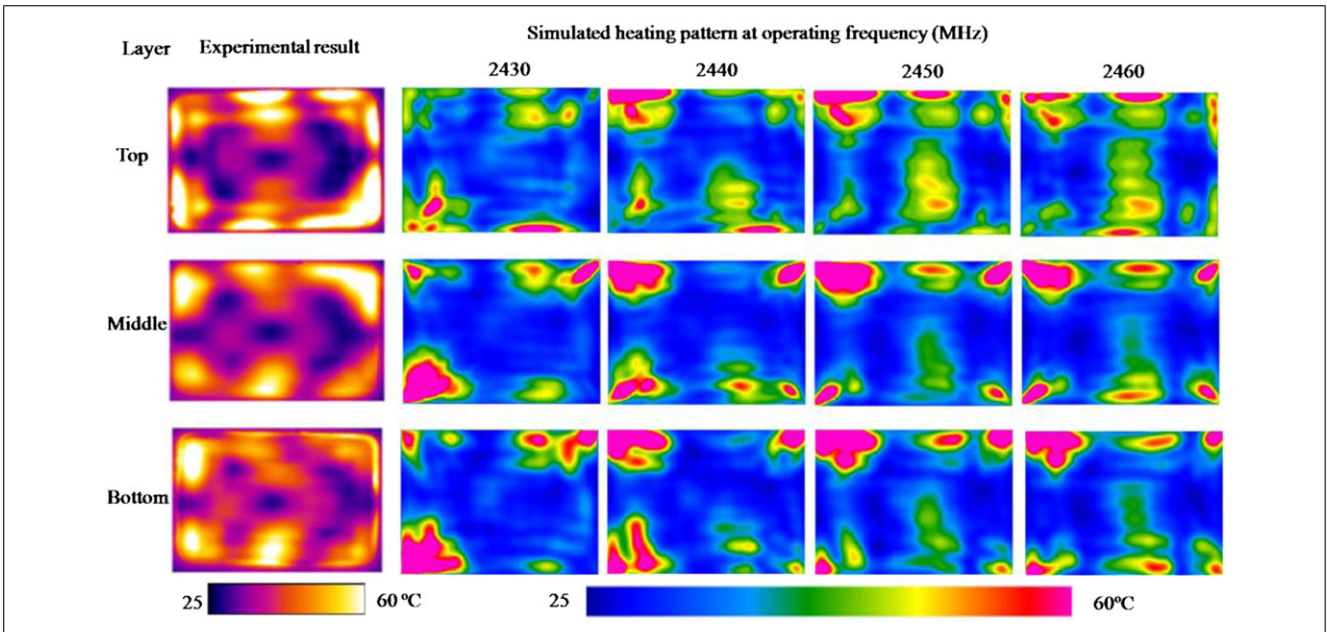Figure 9–Experimental and simulated heating patterns for rotary gellan model food.

Figure 10–Experimental and simulated heating patterns for stationary gellan load.

in Figure 1. The measured frequency results are summerized in Figure 6. Again, different frequency distributions were observed for the water in the tray at different locations. Interestingly the frequency distributions were more dispersed when replacing the beaker by food tray, that is, wider frequency distribution bands were observed. At the location A, B, and C, the operating frequency had a wide range more than 20 MHz, that is, 2.55 to 2.480 GHz, 2.460 to 2.480 GHz, and 2.440 to 2.470 GHz, respectively. At the location D, the operating frequency had a range of 10 MHz. Compared with the results of water in the cylindrical beaker, the same amount of water in tray caused a more scattered frequency distribution. Since the dielectric constant of the beaker and the tray are similar and both very low(<4), this type of frequency distribution was attributed to the large basal area of the tray which illustrated that the shape of a food load could also affect the operating frequencies of a domestic microwave oven. Operating frequencies of the microwave oven with rotary loads in these 2 shapes are shown in Figure 7. The beaker and tray with 500 mL tap water were placed at the edge of the truntable (6 rpm) to performe the frequency measurement. Wider frequency distribution ranges were observed for both of these 2 rotary loads compared with the stationary conditions. It was revealed that changing locations of loads bring more scattered frequency distribution

Heating pattern affected by frequency

A model food load of gellan gel ($184 \times 134 \times 23$ mm^3) was heated within the microwave oven at stationary and rotary conditions. The operating frequencies of these 2 operations are summarized in Figure 8. Results showed that operating frequency of the microwave oven with stationary model food had a distribution range from 2.43 to 2.460 GHz. The operating frequencies with rotary model food had a distribution range from 2.42 to 2.45 GHz. Computer simulation runs with monochromatic frequency setting were performed, that is, 2.43, 2.44, 2.45, and 2.46 GHz for stationary model food and 2.42, 2.43, 2.44, and 2.45 GHz for rotary model food.

Figure 9 shows the simulated and experimental heating patterns at 3 layers of the rotary model food. The simulated heating patterns at different frequencies were qualitatively same as each other and they were consistent at the top, middle and bottom layers. Results showed that the hot areas located at edges and corners of the rectangular model food and a cold domain appeared at the inner part. At the center of the model food, there was a local hot spot with relative lower temperature than that of the edges. These heating patterns matched well with the experimental results. It proved that the computer simulation model was reliable in predicting heating patterns.

Figure 10 shows the simulated and experimental heating patterns for stationary model food. Different from the results of rotary model food, the simulated heating patterns changed with shifting frequencies from 2.43 to 2.46 GHz. Theoretically the heating pattern within a multimode domestic microwave oven changed with varying frequencies (Dibben 2001). Thus it would be expected for the heating pattern of the static model food to change at different frequencies. Changing heating patterns at different frequencies were also reported by Birla (2010) at 2.42, 2.46, 2.52 GHz and Pitchai (2012) at 2.45, 2.455, 2.458 GHz. Both of these 2 previous studies utilized cylindrical gellan model food (80 mm in diameter and 50 mm thick), and reported their heating pattern change when frequency shifts were as low as 3 MHz. All these results indicated that within a multimode domestic microwave oven, small frequency shift led to different heating patterns.

The frequency variation displayed different effect on heating patterns of rotary and stationary model food shown in Figure 9 and Figure 10, respectively. In Figure 10, the simulated heating pattern did not match well with the experimental results. A reasonable explanation was that the operating frequency kept changing during microwave heating and the experimental heating pattern was the combined influences of all existing frequencies. However, both the heating patterns obtained from simulation and experiment showed that the hot spots located at edges of the model food. This might have been caused by a large difference between the dielectric constant of food (>40) and air (1) (Tang 2015).

The heating pattern of rotary model food was not sensitive to varying frequencies compared with that of stationary one. The discrete hot spots at the edges of stationary model food changed to continuous edge heating pattern for rotary model food. Because of rotation, each part of the edges had same probability to experience high electric field. As a result, the simulated heating pattern of rotary loads at different single frequencies formed similar heating patterns. In summary, edge heating dominated the heating pattern of rotary food load. Thus, increasing the probability of food to experience the shifting electric field mode, either of using turntable or mode stirrer, could not completely solve the nonuniform heating problem in a multimode microwave heating cavity. Techniques that helping to avoid edge heating (such as metallic package shielding) and conducting electric field to inner part of the load (such as field antenna) are recommended in future studies.

Conclusions

The test results in this study showed that the operating frequencies were different among individual microwave ovens of the same brand. The operating frequency of any given oven in the tests was highly unpredictable; it constantly changed with time within the frequency band from 2400 to 2500 MHz and varied with the location, size, and geometry of the load.

A computer simulation model was developed to study the influence of varying frequencies on heating patterns of rotary and stationary gellan model food. Simulation runs with monochromatic operating frequencies were performed. The simulated heating patterns of rotary model food agreed well with experimental results, which supported the reliability of the developed simulation model in heating pattern prediction.

The heating patterns of stationary gellan model food changed with varying frequencies. At each single frequency, the simulated and experimental heating pattern was unique and none of them matched well with the experimental heating pattern since it was the combination effect of all the existing frequencies. However, the simulated and experimental heating patterns of rotary model food load were not sensitive to varying frequencies due to the severe edge heating overshadowing the effects of the frequency variations. Thus, turntable or mode stirrer could not completely solve nonuniform heating problem caused by edge heating. In future work, metallic shielding, field antenna and special oven design are recommended for improving heating uniformity within domestic microwave ovens.

Acknowledgments

Author Contributions

Conception design and principle investigator: Juming Tang; frequency measurement, data analysis, computer simulation model development, drafting the manuscript; model food preparation: Donglei Luan; some of the tests were assisted by Deepali Jain; All authors reviewed the manuscript.

References

Awuaha GB, Ramaswamy HS, Economides A. 2007. Thermal processing and quality: principles and overview. Chem Eng Process 46:584–602.

Birla S, Pitchai K, Subbiah J, Jones D. 2010. Effect of magnetron frequency on heating pattern in domestic oven. International Microwave Power Institute's 44th Annual Symposium, Denver, July 14–16, 2010.

Chamchong M, Datta AK. 1996. Thawing of foods in a microwave oven: II. Effect of load geometry and dielectric properties. J Microwave Powers Electromagnetic Energy 34(1):22–32.

Chan TVCT, Reader HC. 2000. Understanding microwave heating cavities. Boston: Artech House.

Cooper N. 2009. Microwave Oven. In: Lorence MW, Pesheck PS, editors. Development of packaging and products for use in microwave ovens. Boca Raton: CRC Press LLC. p 105–27.

Decareau RV. 1985. Microwaves in the food processing industry. Orlando, FL, USA: Academic Press, Inc.

Dibben D. 2001. Electromagnetics: fundamental aspects and numerical modeling. In: Datta AK, Anantheswaran RC, editors. Handbook of microwave technology for food applications. Boca Raton: CRC press. p 1–28.

Funawatashi Y, Suzuki T. 2003. Numerical analysis of microwave heating of a dielectric. Heat Tran Asian Res 32(3):227–36.

Geedipalli S, Rakesh V, Datta A. 2007. Modeling the heating uniformity contributed by a rotating turntable in microwave ovens. J Food Eng 82(3):359–68.

George J, Bergman R. 2006. Selective Re-Meshing: a new approach to include mode stirring effects in the steady state FDTD simulation of microwave heating cavities. Microw Opt Techn Let 48(6):1179–82.

Ghammaz A, Lefeuvre S, Teissandier N. 2003. Spectral behavior of domestic microwave ovens and its effects on the ism band. Ann Telecommun 58:1178–88.

Joseph C, Steve W, Stephen B. 2001. Understanding telephone electronics. 4th ed. Boston: Newnes Press.

Kubota T, Kashiwa T. 1997. Analysis of electromagnetic fields in a mass-produced microwave oven using finite difference time domain method. J Microwave Powers Electromagnetic Energy 31(3):188–96.

Luan D, Tang J, Pedrow DP, Liu F, Tang Z. 2015. Performance of mobile metallic temperature sensors in high power microwave heating systems. J Food Eng 149:114–22.

Luan D, Tang J, Pedrow DP, Liu F, Tang Z. 2013. Using mobile metallic temperature sensors in continuous microwave assisted sterilization (MATS) systems. J Food Eng 119:552–60.

Peyre F, Datta A, Seyler C. 1997. Influence of the dielectric property on microwave oven heating patterns: application to food materials. J Microwave Power Electromagnetic Energy 32(1):3–15.

Pitchai K, Birla S, Subbiah J, Jones D, Thippareddi, H. 2012. Coupled electromagnetic and heat transfer model for microwave heating in domestic ovens. J Food Eng 112:100–11.

Plaza-Gonzalez P, Monzo-Cabrera J, Catala-Civera JM, Sanchez-Hernandez D. 2004. New approach for the prediction of the electric field distribution in multimode microwave-heating applicators with mode stirrers. IEEE Trans Magn 40(3):1672–78.

Rattanadecho P. 2006. The simulation of microwave heating of wood using a rectangular wave guide: influence of frequency and sample size. Chem Eng Sci 61:4798–4811.

Resurreccion FP, Luan D, Tang J, Liu F, Tang Z, Pedrow PD, Cavalieri R. 2015. Effect of changes in microwave frequency on heating patterns of foods in a microwave assisted thermal sterilization system. J Food Eng 150:99–105.

Tang J. 2015. Unlocking potential of microwave energy for food safety and quality. J Food Sci 80:1776–93.

Vadivambal D, Jayas DS. 2010. Non-uniform temperature distribution during microwave heating of food materials—a review. Food Bioprocess Tech 3:161–71.

Vilayannur RS, Puri VM, Anantheswaran RC. 1998. Size and shape effect on non-uniformity of temperature and moisture distributions in microwave heated food materials: Part II Experimental Validation. J Food Process Eng 21(3):235–48.

Zhang H, Datta AK. 2005. Heating concentrations of microwaves in spherical and cylindrical foods Part Two: in a cavity. Food Bioprod Process 83(C1):14–24.

Zhang H, Datta AK. 2000. Coupled Electromagnetic and termal modeling of microwave oven heating of foods. J Microwave Power Electromagnetic Energy 35(2):71–85.

Zhang W, Luan D, Tang J, Sablani S, Rasco B, Lin H, Liu F. 2015. Dielectric properties and other physical properties of low–acyl gellan gel as relevant to microwave assisted pasteurization process. J Food Eng 149:195–203.