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Heating performance of microwave ovens powered by magnetron and solid-state generators

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ABSTRACT

Magnetrons are the most common microwave power sources. However, variation of output frequencies of magnetrons makes heating patterns of foods in multi-mode microwave cavities random and unpredictable. It is desirable to find effective alternatives, such as solid-state microwave generators. Here, we compared the frequency spectra of magnetrons and solid-state generators to evaluate their influence on the heating performance of microwave ovens. Results showed that the spectrum (i.e., peak frequency and bandwidth) of microwaves from the magnetron varied depending on the food and food position and varied considerably between individual ovens of the same model. In contrast, the solid-state microwave generator provided microwaves not only at exactly the set frequency but also within a narrow band, regardless of food loads. That is, solid-state generators had better spectral quality than that from magnetrons. As a result, solid-state generators would provide predictable and stable heating patterns of foods that cannot be achieved with magnetrons. Therefore, solid-state generators create new opportunities in designing next-generation microwave systems with high heating performance.

Industrial relevance: Heating patterns of foods in magnetron-powered multi-mode cavities are random and unpredictable, limiting the use of microwave heating to address food safety issues. Solid-state microwave generators have the potential to overcome this drawback by providing better spectral quality than magnetrons, as shown in this study. In addition, the methodology developed in this work to measure the frequency spectrum of microwave generators is helpful in improving the accuracy of computer simulations. This study provides fundamental information and useful guidance to the food industry on designing and mathematically modelling solid-state powered microwave heating systems.

1. Introduction

Microwave heating is an effective means to deliver heat to foods (Atuonwu & Tassou, 2018; Buffler, 1993; Zhou & Wang, 2019). Since the first invention of a microwave heating device by Percy Spencer in 1947, microwave ovens have been increasingly used at home and in the food industry (Atuonwu & Tassou, 2018; Tang, 2015). In the United States, a limited number of microwave frequencies and bandwidths, such as 915 ± 13 MHz, 2450 ± 50 MHz, and 5800 ± 75 MHz, are allocated by the Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) applications to avoid interference with communications (Buffler, 1993; Tang, 2015).

Magnetrons are the most common microwave generators. However, magnetrons do not consistently generate microwaves at a controlled monochromatic frequency, but rather over a wide band (Chan & Reader, 2000; Collins, 1948; Metaxas & Meredith, 1983). For example, based on data collected over a 1-year time window, Resurrenccion et al. (2015) reported that four different 915 MHz magnetrons had varying frequency spectra over the range from 900 MHz to 920 MHz, depending on the generator's age and power settings. Recent studies reported that magnetrons nominally rated for 2450 MHz in domestic microwave ovens produced a microwave spectrum with substantial power spread over a maximum 70 MHz range, depending on food locations and food types (Celuch, Gwarek, & Olszewska-Placha, 2020; Luan, Wang, Tang, & Jain, 2017).

The operating frequency of a magnetron depends on many factors, including the power supply (i.e., anode voltage and current), structure of the anode cavities, magnetic field produced by the permanent magnets,

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load impedance, temperature, and age (Collins, 1948; Metaxas, 1996; Metaxas & Meredith, 1983; Gerling & Fournier, 1991). A variation in any of those factors could cause a change in the output frequency of magnetrons. The variation of microwave frequencies makes it extremely difficult to predict and control cold and hot spot's locations (heating patterns) in food products, limiting the use of microwave heating for pathogen control (Tang, 2015).

The newly developed solid-state microwave generators hold the potential to overcome this limitation. Solid-state microwave generators can precisely control operating frequency (Atuonwu & Tassou, 2018; Yang, Fathy, Morgan, & Chen, 2022). Additionally, according to manufacturers, such as Radio Frequency Hybrid Integrated Circuit (RFHIC Corp., Anyang, South Korea), Next eXPerience (NXP Corp., Eindhoven, Netherlands), and MKS Instruments Inc. (Andover, MA, USA), microwaves produced by solid-state microwave generators are within a very narrow frequency band. However, this has not been verified with respect to microwave heating of foods. Thus, there is a need to systematically study the spectral quality of solid-state generators in microwave cavities loaded with foods, in comparison with magnetrons.

However, there has been a lack of reported methods to accurately measure the spectrum of microwave generators. Luan et al. (2017) attempted to measure microwaves leaking from domestic microwave ovens by using a frequency spectrum analyzer. Twenty snapshots of the microwave spectra taken over 1 min were superimposed. Several pronounced frequencies were observed, but no dominant (peak) frequency could be recognized. With the lack of accurate data on operating microwave frequencies, it has been difficult to mathematically model the microwave heating of foods with good prediction results. For example, Luan et al. (2017) developed a simulation model to show that computer simulation using any of the four different frequencies (2430, 2440, 2450 and 2460 MHz) did not match with the thermal images taken from the heated samples in domestic ovens. Pitchai, Chen, Birla, Jones, and Subbiah (2016) reported that a computer model using 2450 MHz did not fit with experimental temperature data of foods heated in household microwave ovens. Thus, it is necessary to develop a measurement method for the microwave spectrum, not only to improve computer simulation accuracy but also to better understand the performance of solid-state microwave generators.

The overall goal of this study was to develop a new strategy to study the performance of microwave cavities powered by magnetron and solid-state generators. The specific objectives were to: 1) develop an accurate method to measure frequency spectra; 2) compare the spectral quality of magnetron versus solid-state generators; and 3) develop a computer simulation to visualize the influence of frequency spectra on heating patterns of foods in microwave cavities.

2. Material and methods

2.1. Microwave oven

A microwave oven with a 345 mm × 305 mm × 225 mm cavity was modified from a commercial domestic microwave oven (NN-SD681S, Panasonic Co., Tokyo, Japan) (Fig. 1). The turntable was removed to study stationary samples in the microwave oven. The microwave cavity was powered by two independent microwave generators: a GaN-based solid-state microwave generator (RIU58800–20, RFHIC Co., Anyang, South Korea), and a magnetron (2M261, Panasonic Co., Tokyo, Japan). The solid-state generator produced nominal 5.8 GHz microwaves that propagated to the microwave cavity through a rectangular waveguide (Zhou, Zhang, Tang, Tang, & Takhar, 2022; entry port: 40 mm × 20 mm), whereas the 2.4 GHz magnetron was connected to the cavity through a wedge-shape waveguide (Luan et al., 2017; entry port: 90 mm × 30 mm). It has been well-documented (through experiments and computer simulation) in the literature that the position of the exit for the waveguide from the magneton influences three-dimensional standing wave patterns in a microwave cavity (Chan & Reader, 2000). The effect

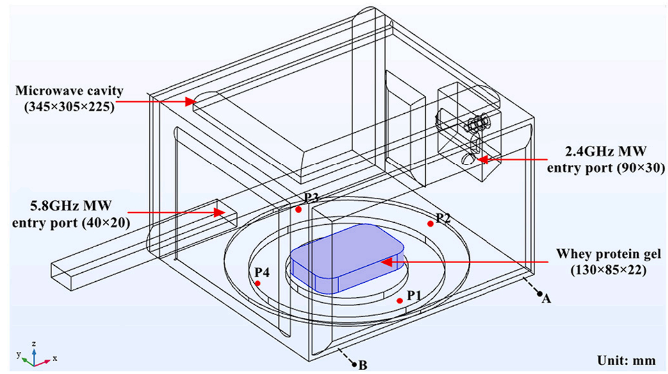


Fig. 1. Schematic diagram of microwave (MW) oven. It includes a MW cavity, two MW entry ports (2.4 GHz microwaves emitted by a magnetron and 5.8 GHz microwaves emitted by a solid-state generator), model food (whey protein gel), four food positions (P1, P2, P3, P4), and two positions of the spectrum analyzer antenna (A, B).

of the positions of generators was, therefore, not considered in our study.

Another magnetron-powered domestic oven of the same model (NN-SD681S, Panasonic Co., Tokyo, Japan) purchased from the same manufacturer at the same time was used to find potential spectra variations between individual ovens. It was named oven #2 to differentiate it from the first oven (oven #1).

2.2. Frequency spectrum

2.2.1. Radiation leakage from microwave ovens

A spectrum analyzer (SPA-6G, LATNEX, Toronto, Canada) was used to measure microwave leakage from the ovens. A small amount of microwaves can leak from microwave ovens, but the emission should be well under 5 mW/cm^2 measured 5 cm from ovens, according to a U.S. Federal standard (21 CFR 1030.10) (Buffler, 1993). This power is far below the level known to pose a hazard to consumers, but high enough to be detected by the SPA-6 G spectrum analyzer which had the minimum measurable power of 1×10^{-7} mW/m^2.

Microwaves are emitted by the generator and propagate to the metal cavity loaded with foods. Microwaves leaking from the oven can be considered the superposition of waves associated with phenomena that include: 1) unhindered propagation through the cavity; 2) attenuated propagation through the food load; 3) reflection from the food load; and 4) reflection from metal cavity walls (Sadiku, 2018). According to Maxwell's equations (Sadiku, 2018; Tang, 2015), the frequency of these waves will remain the same for oven/food systems containing linear electromagnetic properties. Thus, the frequency of microwaves emitted by the generator and/or absorbed by the food can be determined by measuring microwaves leaking from the oven.

2.2.2. Spectra in the frequency domain

A typical frequency spectrum of microwave signals is an *x*-*y* plot in which the *x*-axis represents frequency, and the *y*-axis represents signal amplitude in unit dBm (decibel-milliwatts) (Celuch et al., 2020; Gerling & Fournier, 1991). To compare the frequency spectra of the magnetron and solid-state generators, the spectrum analyzer equipped with a dual-band dipole antenna (AW402DWW, Data Alliance Inc., Nogales, AZ, USA) was set to a center frequency of 2450 MHz with a span of 100 MHz (i.e., 2400–2500 MHz), and a center frequency of 5800 MHz with a span of 200 MHz (i.e., 5700–5900 MHz), respectively. To obtain a sufficiently large number of snapshots, the spectrum analyzer was set to measure signals 5 times per second. This sweep rate was 10 times faster than that used in the study by Luan et al. (2017). To evaluate the influence of antenna positions on the frequency profile, the measurements were conducted at two different positions (A and B, as shown in Fig. 1). Both were placed 5 cm from the microwave oven.

2.2.3. Post-processing of spectra

A maximum of 300 snapshots of frequency spectra were measured from the spectrum analyzer during the 60 s of microwave heating. The frequency spectra were averaged over the selected number of snapshots (i.e., 20, 50, 100, 200 and 300).

To reduce the influence of background noise, the conversion of units of power from dBm to watt is given by Werner (2020) as:

$$P(W) = 10^{\frac{P(dBm)-30}{10}} \tag{1}$$

where $P(dBm)$ is the signal power in dBm measured by the spectrum analyzer, and $P(W)$ is the power in watt.

2.3. Effects of foods on frequency spectrum

To study the influence of foods on the microwave spectrum, three representative food loads, i.e., water (tap water and distilled water), vegetable oil, and model food (whey protein gel, WPG) were used. Distilled water was collected from a purification system (Milli-Q, Millipore Co., Billerica, MA, USA), and tap water was collected in our laboratory at Washington State University (WSU) in Pullman, WA, USA. Soybean oil (Great value ™, Walmart, Pullman, WA, USA) was purchased from a local Walmart store. The WPG was prepared from 75.4% distilled water, 0.3% salt, 0.2% D-ribose, 18.9% whey protein concentrate (WPC 392), and 5.2% whey protein isolate (WP 895-I) following the procedures described in Resurreccion et al. (2015). A 1000 ml of water or oil was loaded in a 1-L cylindrical glass beaker, while 300 g of WPG was loaded in a 10.5 oz. polypropylene tray. The food loads were placed at the center of the oven base and heated separately for 60 s. During microwave heating, the frequency spectra were continuously measured by the spectrum analyzer. The microwave heating tests were conducted separately by using the magnetron or solid-state generator.

To study the influence of food positions on the microwave spectrum, a glass beaker containing 1000 ml of distilled water was placed at four positions (~P1, P2, P3 and P4 in Fig. 1) and heated by microwaves for 60 s. The microwave heating tests were conducted separately by using the magnetron or solid-state generator.

For the above tests, the microwave oven was set idle for 60 mins to allow the generators to return to room temperature (22 ± 3 °C) before the start of a new test.

2.4. Computer simulation

2.4.1. Geometric model

A 3-dimensional computer simulation based on the finite element method was developed to visualize the influence of varying microwave frequencies on the heating patterns of foods. The frequency variations considered in this study were in varying narrow bands measured from magnetrons or can be controlled by solid-state microwave generators.

The computer simulation was built in commercial software, COMSOL Multiphysics 5.5 (COMSOL Inc., Boston, MA, USA). Fig. 1 shows the geometry and dimensions of the microwave cavity, the entry ports of microwaves, and the model food in the COMSOL geometric model.

2.4.2. Governing equations and boundary conditions

The EM fields in the microwave oven are governed by Maxwell's equations (Sadiku, 2018):

$$\nabla \cdot \overrightarrow{E} = 0 \tag{2}$$

$$\nabla \cdot \overrightarrow{H} = 0 \tag{3}$$

$$\nabla \times \overrightarrow{E} = -\mu \frac{\partial \overrightarrow{H}}{\partial t} \tag{4}$$

$$\nabla \times \overrightarrow{H} = \tilde{\varepsilon} \frac{\partial \overrightarrow{E}}{\partial t} \tag{5}$$

where $\overrightarrow{E}$ is the electric field intensity (V/m), $\overrightarrow{H}$ the is magnetic field intensity (A/m), $\tilde{\varepsilon}$ is complex permittivity $\tilde{\varepsilon} = \varepsilon_0\tilde{\varepsilon}_r = \varepsilon_0(\varepsilon_r' - j\varepsilon''_r)$, ε_0 is the permittivity of free space, ε_r' is the dielectric constant, ε''_r is the loss factor, and μ is permeability. Dissipation due to conductivity is included in $\tilde{\varepsilon}$. Eq. (2)–(5) were solved under the assumption that the EM fields are time harmonic (i.e., vary sinusoidally in time) (Sadiku, 2018). The simulation region contained no free volume charge density, and the metal walls and waveguide surfaces were assumed to be perfect electric conductors (PECs) (Sadiku, 2018).

Microwave radiation was absorbed by the food, and the dissipated portion of the electromagnetic energy was converted to thermal energy (Tang, 2015):

$$Q = 2\pi\varepsilon_0\varepsilon''_r f\left|\overrightarrow{E}\right|^2 \tag{6}$$

where Q is dissipated electromagnetic power density (W/m^3), ε''_r is the loss factor of the food, f is the microwave frequency (Hz). Thus Q represents an electromagnetic power sink, but also it represents a thermal power source.

As a result, the temperature of the model food increased (Birla & Pitchai, 2017):

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \bullet (k\nabla T) + Q \tag{7}$$

where T is the temperature (°C), ρ is the density (kg/m^3), C_p is the specific heat (J/kg·K), and k is the thermal conductivity (W/m·K) of the model food.

Some of the heat was lost to the air due to natural convection:

$$-k\frac{\partial T}{\partial \overrightarrow{n}} = h(T - T_{air}) \tag{8}$$

where T_{air} is the air temperature in the cavity (°C), and h is the convection coefficient (W/m^2·K). h was assumed to be 20 W/m^2·K for the

Table 1
Physical properties of materials used in COMSOL computer simulations.

	Temperature (°C)	Dielectric properties ($\varepsilon_r'-j\varepsilon_r''$)		Specific heat (C_p, J/kg·K)	Thermal conductivity (k, W/m·K)
		2.4 GHz	5.8 GHz		
Whey protein gel[a]	4	52.7 – j15.3	44.4 – j21.2	2846	0.50
	20	51.6 – j14.2	44.9 – j19.1	2950	0.53
	40	50.4 – j13.6	45.7 – j16.2	3025	0.57
	60	48.9 – j13.9	45.3 – j14.3	3150	0.58
	80	46.8 – j14.8	43.8 – j13.2	3410	0.60
Air[b]	20	1	1	–	–
Metal[b]	20	1	1	–	–

[a] from Resurreccion et al. (2015).
[b] from Sadiku (2018).

natural convection inside the microwave cavity (Birla & Pitchai, 2017; Pitchai et al., 2016). Table 1 shows physical properties of model foods and other materials used in the COMSOL Multiphysics software program.

The following assumptions were made in simplifying the computer simulation:

1. The surrounding air was at a uniform and constant temperature (T_{air} = 25 °C).
2. The plastic tray made from polypropylene was microwave transparent due to its considerably small loss factor ($\varepsilon''_r = 0.003$) (Pitchai et al., 2016).
3. Heat conduction from the food to the plastic tray was negligible.
4. The water evaporation from the food surface was negligible.
5. Heat transfer by thermal radiation was negligible.

The mesh size of air and foods followed the general rule of 10 cells per wavelength (Birla & Pitchai, 2017; Chan & Reader, 2000; Luan et al., 2017), and a convergence study (data not shown) as a function of mesh size was conducted to ensure accurate approximation and avoid unnecessary use of computer memory. The COMSOL simulation models consisted of 268,285 elements for the 2.4 GHz magnetron-powered microwave oven, and 1,432,339 elements for the 5.8 GHz solid-state-powered microwave oven, respectively. The COMSOL computer simulations were run on a U.S. Micro commercial workstation (Intel i7-6700K CPU @ 4.0 GHz, 64 GB RAM, Window 10 64-bit system) for 60 s microwave heating. The total computation times were 8 min 16 s, and 19 min 2 s for simulating microwave heating in the magnetron oven and solid-state oven, respectively.

2.4.3. Microwave power and excitation

Due to the lack of power measurement devices in consumer microwave ovens, an approximation for magnetron power input was determined by the IMPI 2-L test (Buffler, 1993). The measured value of 960 W was set for the magnetron input power in the COMSOL model. The forward and reflected microwave powers were monitored by a power meter built in the solid-state generator (Zhou et al., 2022). Based on the measurement (800 W forward power and 90 W reflected power), the input power of the solid-state generator was set as 710 W in the computer model.

The excitation mode for microwaves should be selected based on the dimension of the waveguide (Sadiku, 2018). The lowest mode (or dominant mode) for the 5.8 GHz microwaves from the solid-state generator was TE_{10} mode, while the TE_{20} mode was set as the excitation mode for the 2.4 GHz microwaves emitted by the magnetron.

2.4.4. Experimental validation

The computer simulations were validated by measuring temperature distributions of the model food using thermal imaging. The model food was conditioned in a refrigerator at 4.0 ± 0.1 °C for 12 h. Three-hundred grams of the WPG (model food) was horizontally cut into two pieces with equal thickness and then packed together in a 10.5 oz. polypropylene tray (130 mm × 85 mm × 22 mm), prior to microwave heating.

The WPG was placed at the center of the oven base (Fig. 1) and heated for 60 s by using the magnetron or solid-state generator separately. After microwave heating, spatial temperature distributions of surface, middle and bottom layers of the WPG were immediately captured by an infrared thermal camera (SC-3000, FLIR Systems, Portland, OR., USA) with an accuracy of ±2 °C.

Heating patterns are caused by standing microwave waves in microwave ovens. The intensities of temperature variations change with heating time, but the locations of the cold and hot spots remain the same as long as the standing wave patterns do not change (Birla & Pitchai, 2017; Buffler, 1993; Luan et al., 2017). Thus, we used 1 min (60 s) for all the tests.

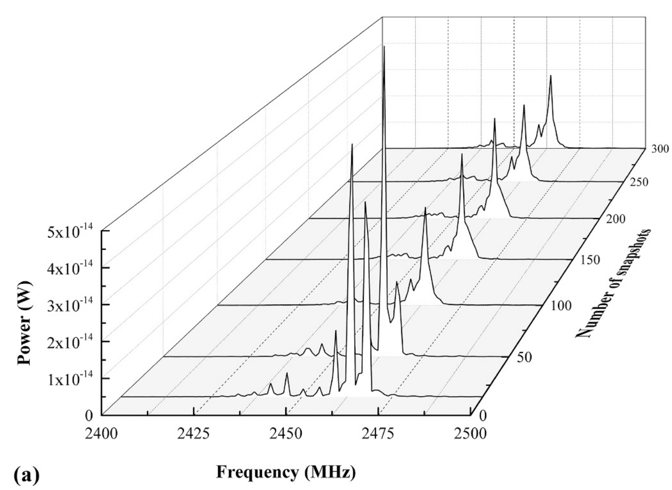
3. Results and discussion

3.1. Measurement of frequency spectrum

3.1.1. Effects of snapshot number

The influence of snapshots on the measured frequency spectra of the magnetron-based microwave oven was studied (Fig. 2). Varying microwave frequencies were observed when the snapshots were less than 50. This might be due to the unsteady operation of the magnetron at the beginning of microwave heating (Buffler, 1993; Metaxas & Meredith, 1983). However, the spectrum curves became more stable and smoother as the number of snapshots increased. A dominant peak frequency was easily distinguished when the snapshots were more than 100. For example, based on the results of 300 snapshots, the peak frequency of the magnetron-powered microwave oven was 2464 MHz for the water load and 2437 MHz for the oil load, respectively (Fig. 2). These frequencies remained stable throughout the rest of the microwave heating period.

Data analysis usually requires an adequate size of samples to estimate the population. Snapshots of less than 50 were not enough to reveal the true features of the frequency spectrum. This explains why a highly unpredictable distribution of microwave frequencies in domestic ovens was reported by Luan et al. (2017) in which only 25 or 30 snapshots were taken. Therefore, we suggest that a sufficiently large number of snapshots (at least 100) should be collected to accurately measure the



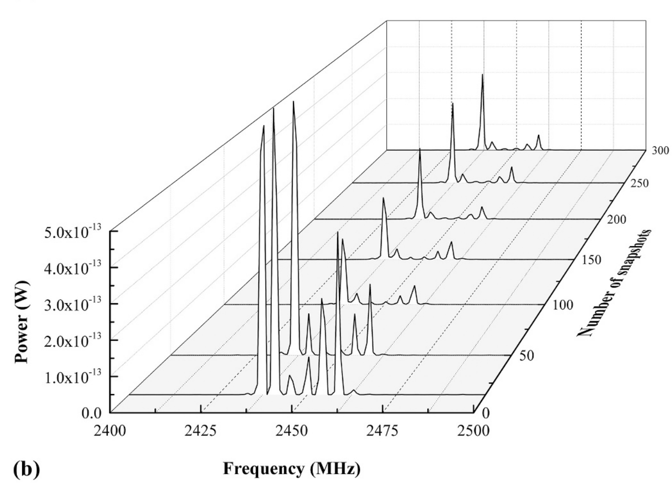


Fig. 2. Measured spectra of magnetron-powered microwave oven loaded with (a) 1000 ml-distilled-water and (b) 1000 ml-oil. Each curve was an average of a selected number of snapshots (20, 50, 100, 150, 200, 250, or 300) during a 60 s microwave heating (n = 3).

microwave frequency spectra.

3.1.2. Effects of probe position

The frequency spectrum of the magnetron was measured when the spectrum analyzer was placed at two different positions (Fig. 3). The peak frequency and occupied frequency bandwidth (containing 99% of the total power) of the spectra remained the same at different measurement positions, which means that the location of the antenna did not influence the measured data for the frequency spectrum.

It should be noted that amplitudes of microwave signals were different when the antenna was placed at different positions. The higher strength of the leaked microwaves was always associated with position A (Fig. 3). One reason for this is the antenna-to-magnetron distance. The leaked microwave power increases as the inverse square of the distance from the microwave source (Buffler, 1993; Chan & Reader, 2000). Position A was closer to the magnetron than position B, so more microwave flux was received at position A. In addition, the difference in the amplitude might be caused by non-uniform gaps between the microwave door and oven front panel. The microwave radiation leaked from the door seals, but the gap variation may happen due to the manufacturing tolerances or any minor deformation of the door, latch or hinges during transportation or operation (Buffler, 1993).

3.2. Spectral quality of magnetron and solid-state generator

The frequency spectra of the magnetron and the solid-state microwave generator were compared (Figs. 4 and 5). The spectra of the solid-state generator were measured when the generator was controlled at one of three different frequencies (5725, 5800 and 5875 MHz).

As can be seen in Fig. 4, the magnetron did not provide microwaves exactly at 2450 MHz but rather over a varying band depending on the food loads (for example, between 2430 and 2465 MHz for oil, between 2460 and 2470 for tap water). The peak frequencies of microwaves also varied with the food position; a maximum 20-MHz change was observed at different load positions in the cavity (Fig. 5a).

The variation of the microwave spectra due to variations of loads were caused by the corresponding changes of the impedances of the loaded cavity (Collins, 1948; Metaxas, 1996; Metaxas & Meredith, 1983). The nominal frequency specifically refers to a matched load condition (in the case of domestic microwave ovens, the nominal frequency of the magnetron is 2450 MHz). However, the impedance of the cavity changes when loaded with different foods, resulting in impedance mismatching between the magnetron and the loaded cavity (Metaxas, 1996). Dielectric properties of foods are one of the most important

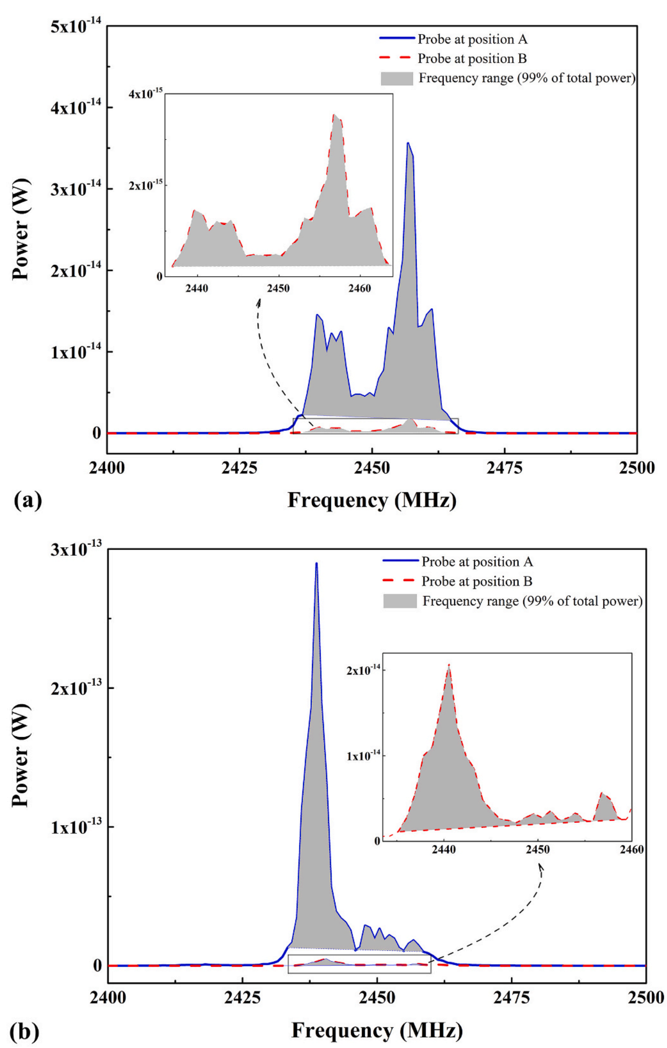


Fig. 3. Measured spectra of magnetron-powered microwave oven loaded with (a) 1000 ml-distilled-water and (b) 1000 ml-oil at two antenna positions (A and B in Fig. 1). Each curve was an average of 300 snapshots during 60 s heating (n = 3).

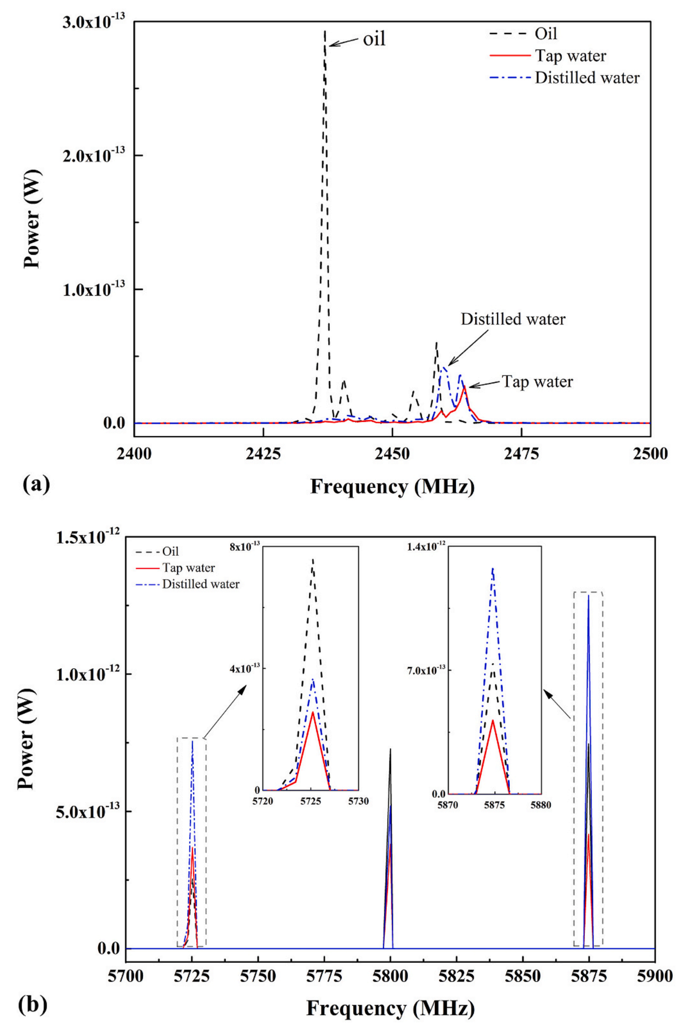


Fig. 4. Influences of food loads on measured spectra of microwave ovens powered by (a) magnetron and (b) solid-state generator. Loads were placed at the center of the cavity base. Each curve was an average of 300 snapshots measured at antenna positions A (n = 3). The spectra for the solid-state generator corresponded to three different set frequencies: 5725, 5800 and 5875 MHz.

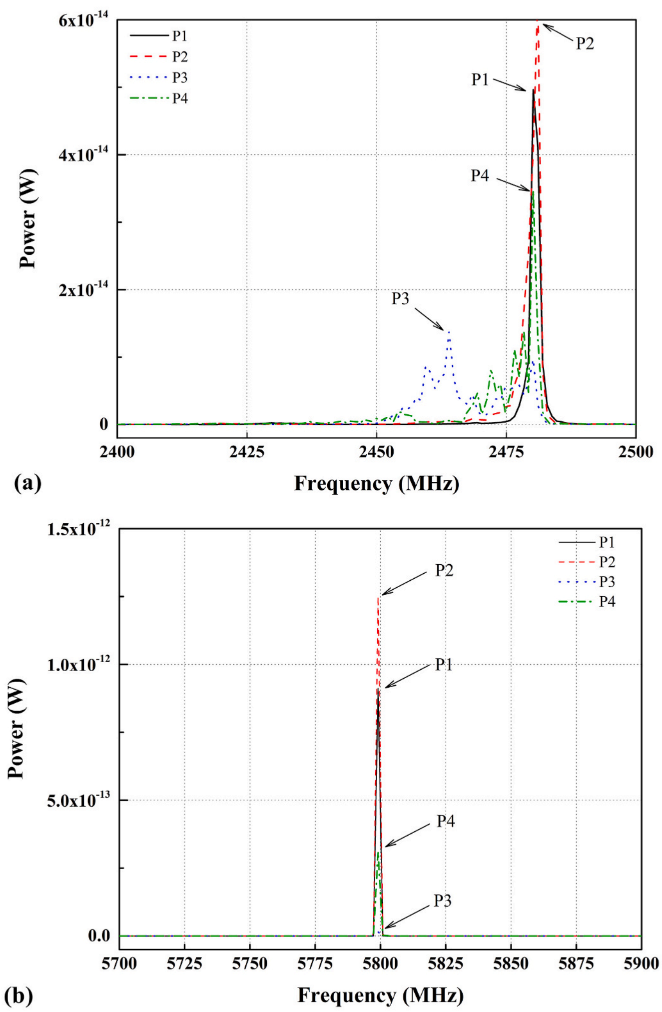


Fig. 5. Influences of load positions (P1, P2, P3, and P4 in Fig. 1) on measured spectra of microwave ovens powered by (a) magnetron and (b) solid-state generator. A 1000 ml-distilled-water load was used. Each curve was an average of 300 snapshots (n = 3).

factors influencing the impedance of the food-loaded cavity (Metaxas, 1996). Distilled water has dielectric properties of 78.1 – 9.3j (Gezahegn et al., 2021), while soybean oil has dielectric properties of 2.5 – 0.14j (Tang, 2015) (25 °C, 2450 MHz). The difference in the impedance of the loaded cavity changes the equilibrium condition of the magnetron, which consequently changes the frequency of oscillation (Metaxas & Meredith, 1983). It is interesting to note that the microwave frequency of the cavity loaded with tap water was very close to that loaded with distilled water (Fig. 4a), probably because distilled water and tap water have very similar dielectric properties at 2.4 GHz (Gezahegn et al., 2021). The load position also influences the impedance of the loaded microwave cavity.

In contrast, for the microwave oven powered by the solid-state generator, the measured peak frequencies matched exactly with the set frequencies regardless of food loads and load positions (Fig. 4). In addition to the stable spectrum, the solid-state generator provided microwave signals in a very narrow band (less than 2 MHz). For example, 99% of the total microwave power was in the frequency bandwidth of 5799 – 5801 MHz, when the set frequency of the solid-state generator was 5800 MHz (Fig. 5b). The results were consistent when testing with different loads at different positions in the cavity (data not shown).

This stable and narrow frequency bandwidth was majorly due to the working principle of the solid-state power amplifier: a small microwave signal is precisely generated in a tuned electronic circuit, and then amplified by semiconductor (solid-state) transistors (Atuonwu & Tassou, 2018; Werner, 2020). Also, solid-state generators are usually well cooled down by using internal circulators and water cooling, which could be another contributor.

This study shows that the load impedance did not affect the output microwave frequencies of solid-state generators. This is the unique feature of solid-state microwave generators when compared to magnetrons. To study long-term stability and reliability of solid-state generators, tests under the different power supply, output levels, temperature and age are desirable in future studies.

3.3. Simulated and experimental heating patterns

The frequency spectra of two individual magnetron-powered ovens of the same model (i.e., oven #1 and oven #2) were compared (Fig. 6 a & b). Every parameter (e.g., cavity geometry/dimension, food type, food position, and spectrum position) were the same, but the peak frequency of microwaves varied between two individual magnetron ovens. Manufacturing tolerances of magnetrons and ovens might have caused the variation among individual microwave ovens in a single production line, as discussed by Buffler (1993).

The simulated and experimental temperature distributions of the model foods in the two magnetron-powered microwave ovens were compared (Fig. 7). Computer simulations were run at different microwave frequencies, including 2450 MHz and the measured peak frequencies. The simulated heating patterns at the measured peak frequency matched best with the experimental heating patterns. However, the simulations at 2450 MHz did not fit well with the experimental results (Fig. 7). It is, therefore, highly recommended to use measured microwave frequencies instead of 2450 MHz in computer simulations for magnetron-powered microwave ovens.

The experimental heating pattern of the model foods heated in oven #1 was totally different from that in oven #2 (Fig. 7). This was because these two commercial microwave ovens of the same model had different peak frequencies and frequency bandwidths, as been seen in Fig. 6 a & b. The temperature distribution in foods in a multi-mode microwave cavity was sensitive to possible differences in the microwave frequency; a 5-MHz change in microwave frequency led to a very different heating pattern in foods (Fig. 7). This once again highlights the difficulties in mathematical modelling of magnetron-powered multi-mode cavities and the need for measurements of actual output frequency when reliable predictive results are required.

Different microwave frequencies led to different temperature rises of the food sample within the same heating time (Fig. 7). Energy coupling between the cavity loaded with foods and the microwave generator depended on the operating frequency of the generator. Similar results have been reported by Yakovlev (2018) and Yang et al. (2022).

For oven #1, the simulation at the measured microwave frequency showed excellent agreement with the experimental heating pattern. However, for oven #2, there was a cold spot at the top edge of the food in the simulation result, but it was not observed in the experimental result. This was because oven #2 had a relatively wider frequency band and more peak frequencies compared to oven #1 (Fig. 6 a & b). For example, oven #2 had two peak frequencies, 2443 MHz and 2464 MHz (Fig. 6b). We hypothesize that the superposition of microwaves at these two frequencies may give us more accurate heating patterns. More investigation to validate our hypothesis is needed to decide the contribution (or weight) of each frequency.

The simulated and experimental heating patterns of the model food matched well when heated at 5800 MHz by the solid-state generator (Fig. 8). The validated model was also used to simulate heating patterns at other frequencies within the ISM range. Simulations show that heating patterns were totally different at different microwave frequencies. However, the three adjacent frequencies (i.e., 5799, 5800 and 5801 MHz) generally produced the same heating pattern of the food (Fig. 8). Recall that the solid-state microwave oven generated microwaves over a

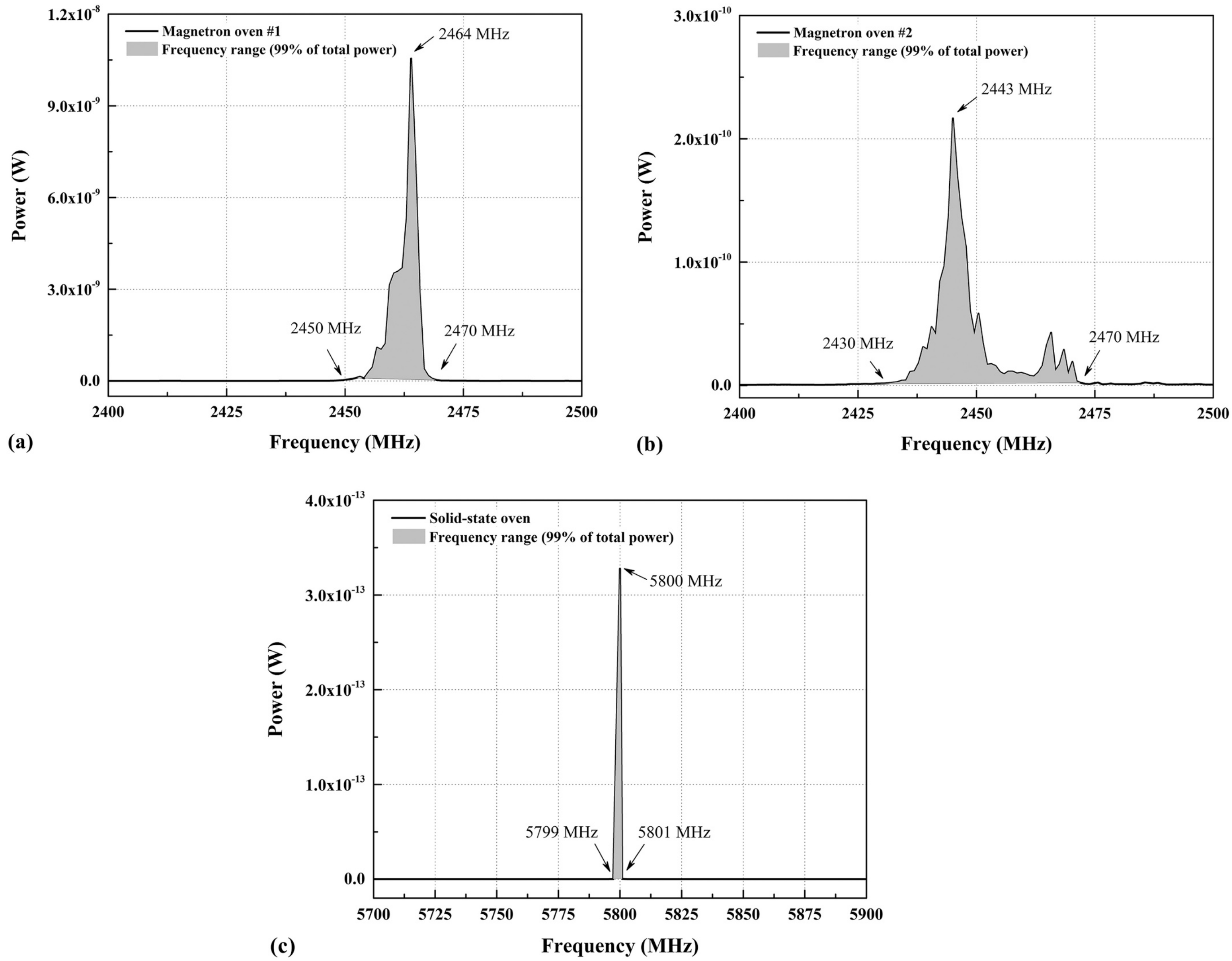


Fig. 6. Measured spectra of two magnetron-powered microwave ovens [(a) oven #1 and (b) oven #2)] of the same model, and (c) solid-state microwave oven loaded with whey protein gel. Each curve was an average of 300 snapshots ($n = 3$).

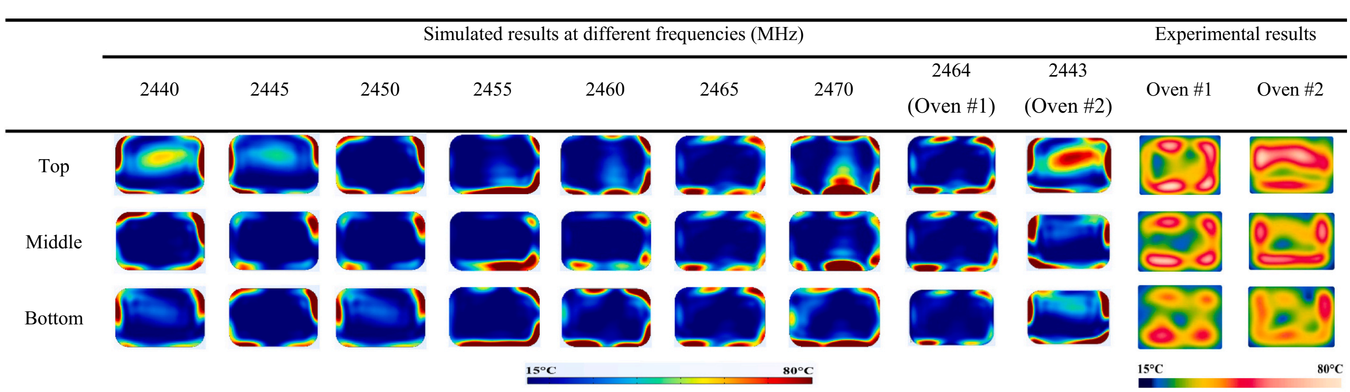


Fig. 7. Experimental and simulated heating patterns of whey protein gel (135 mm × 92 mm × 22 mm) heated in two magnetron-based microwave ovens (#1, #2). The experimental heating patterns of three layers were obtained by a thermal camera. Oven #1 had a measured peak frequency of 2464 MHz, while oven #2 had a measured peak frequency of 2443 MHz (Fig. 6).

very narrow bandwidth (less than 2 MHz) (Fig. 7) and the peak microwave frequency of the solid-state generator was exactly the set frequency regardless of food loads (Figs. 4b; 5b; 6c). Within such a narrow frequency band, the heating patterns of foods would remain the same. This is an important finding that has not been published in the literature. With respect to computer simulations, the set frequency of the solid-state system can be, therefore, directly used with good accuracy no matter what kinds of food loads are heated in the oven. More

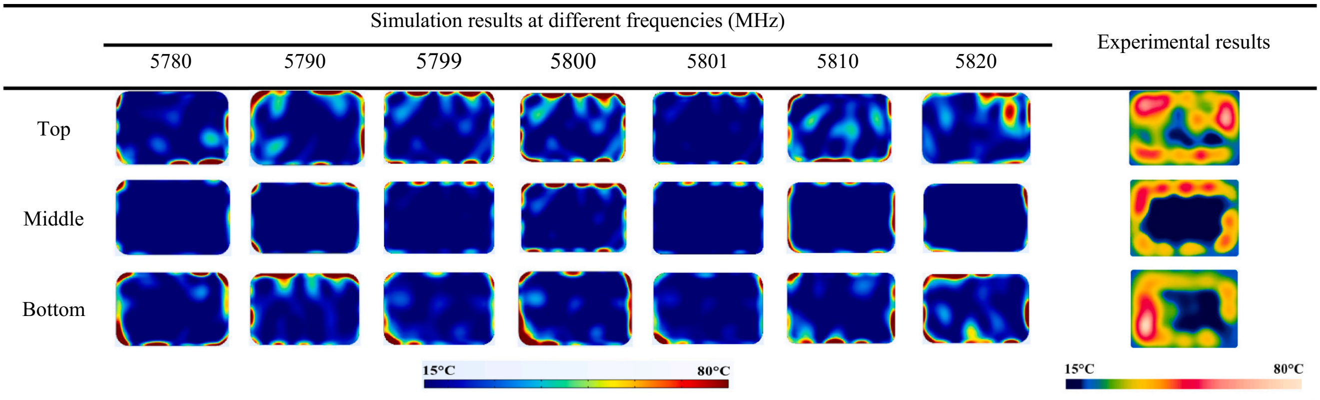


Fig. 8. Experimental and simulated heating patterns of whey protein gel (135 mm × 92 mm × 22 mm) heated in a solid-state powered microwave oven. The experimental heating patterns of three layers were obtained by a thermal camera. The solid-state oven was operating at 5800 MHz (Fig. 6).

importantly, more stable and predictable heating patterns of foods are expected when using solid-state generators, when compared to magnetrons. These should be major advantages of solid-state generators over magnetrons. A systematic study of resonant modes and their corresponding standing wave patterns is needed to further confirm the predictability of heating patterns in foods heated in multi-mode microwave cavities powered by solid-state generators.

Due to the limitation of the available solid-state generators in our laboratory, the frequency of the solid-state microwave generators (5800 MHz) was different from that of the magnetron (2450 MHz) in this work. But we believe that the general principle and engineering fundamentals described above are the same for microwaves at all ISM frequencies allocated by FCC.

4. Conclusion

The spectral quality of the magnetron and solid-state generators were compared. The output frequency of the magnetron in domestic microwave ovens was not exactly 2450 MHz, but rather over a wide band; the peak frequencies varied considerably, depending on the food and food locations. In contrast, the solid-state microwave generator provided microwaves not only at exactly the set frequency but also within a narrow band regardless of foods. That is, it has been validated with microwave heating of foods that solid-state generators had much better spectral quality than magnetrons, with respect to stability and accuracy. As a result, solid-state microwave generators would be able to provide stable and predictable heating patterns (cold and hot spots' locations) of foods that cannot be achieved with magnetrons. This study provides useful and fundamental information beneficial to the research community and the food industry who are interested in the next generation microwave ovens based on solid-state generators.

CRediT authorship contribution statement

Xu Zhou: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Project administration. **Patrick D. Pedrow:** Methodology, Writing – review & editing. **Zhongwei Tang:** Methodology, Writing – review & editing. **Stewart Bohnet:** Writing – review & editing. **Shyam S. Sablani:** Writing – review & editing. **Juming Tang:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

To the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

Data availability

Data will be made available on request.

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