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Analysis of Dielectric Attached on Sweep Frequency Microwave Heating Uniformity

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Abstract: Traditional microwave heating faces challenges such as low efficiency and uneven heating, hindering its industrial application. Sweep frequency microwave heating is an effective way to improve uniformity. Larger cavity sizes result in better heating uniformity due to the generation of more resonant modes. However, in industrial applications, large cavities occupy significant space, making them less flexible and limiting their usability. This paper introduces a method to enhance sweep frequency microwave heating uniformity by adding a dielectric substance to cavity walls. First, the impact of increasing cavity size on the uniformity of sweep frequency microwave heating was studied, with the theoretical analysis showing that filling the cavity with dielectric materials can be equivalent to enlarging the cavity size. Subsequently, a multiphysics simulation model for sweep frequency microwave heating was established to analyze the effects of dielectric substance thickness and permittivity on heating uniformity. A high-efficiency, high-uniformity microwave multimode cavity was designed, and the accuracy of the simulation model was validated through experiments. Finally, the effects of sweep frequency range and load variations on the heating performance were analyzed. This method effectively addresses the uniformity issues in industrial microwave heating and aids in promoting the application of microwave energy in industry.

Keywords: multimode cavity; microwave heating; sweep frequency; dielectric attached; heating uniformity

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1. Introduction

In recent decades, microwaves have been extensively employed as an efficient and clean energy source in various fields, including thermal engineering, chemical reactions, food processing, medical treatments, and material synthesis [1–5]. Compared to conventional heating methods, microwave heating is distinguished by its rapid heating, precise control, and the ability to heat materials volumetrically. These attributes result in higher heating efficiency, reduced processing times, and the elimination of contamination, making it an environmentally sustainable option [6]. However, simultaneously achieving high heating uniformity and optimal energy utilization efficiency remains a significant challenge. The primary reason for this is the intrinsic tendency of microwaves to generate non-uniform electric fields within the materials being heated, leading to suboptimal heating uniformity [7–9].

The uniformity of microwave heating is crucial across multiple aspects. Uniform heating ensures the quality of food and products, preventing issues like uneven heating or undercooking, thus guaranteeing food safety and taste [10]. Additionally, uniform heating enhances energy efficiency by reducing energy wastage and contributes to maintaining equipment safety, preventing thermal runaway and equipment damage [11]. In industrial production, maintaining uniform heating ensures process consistency, reduces defect rates, improves production efficiency, and extends equipment lifespan, thereby lowering maintenance costs [12]. Beyond these traditional applications, the ability to precisely control and distribute microwave energy could lead to innovative use cases. For example, uniform heating can enable more effective sterilization and decontamination processes, which would be valuable for medical and biohazard applications [13]. Many teams have conducted research on how to improve the microwave energy efficiency and heating uniformity. Frequency selection technology utilizes two orthogonally polarized antennas installed within the cavity for feeding, analyzing heating efficiency at different frequencies, and selecting the optimal frequency point to ensure uniform heating [14]. Dual-port phase-shifting adjusts the phase difference between the two feeding ports, effectively controlling temperature distribution inside the heated object, optimizing heating uniformity and efficiency [15]. Stirrers or rotating turntables placed inside the microwave heating cavity alter the microwave field distribution, significantly improving heating uniformity [16]. Variable-frequency microwave sources dynamically adjust frequency and power based on real-time feedback, enhancing heating uniformity and efficiency during operation [17]. Intermittent heating adjusts heating and pause intervals adaptively to prevent localized overheating, further ensuring temperature uniformity [18]. Lastly, employing properly designed microwave ceramics, multimode cavities, and optimized antenna layouts inside the microwave oven effectively improve microwave field distribution, thereby enhancing overall heating uniformity [19]. For the industrial technique, it is very common to use the fluidized beds and conveyor systems for improving microwave heating uniformity [20,21], and hybrid heating approaches, which combine microwaves with other heating sources, such as convection or radiation, have also shown promise in enhancing heating efficiency and uniformity [22,23].

It is generally considered that the sweep frequency method can greatly improve the heating uniformity, and many methods are applied to optimize the effect of the sweep frequency heating. Bows et al. proposed that multiple discrete frequency points be under unified use to improve the heating uniformity [24]. In their study, eight discrete frequencies between 2400 MHz and 6200 MHz were chosen to verify the feasibility of the method [25]. Antonio investigated a two-dimensional computer model of the variable frequency microwave technique and found that a more even temperature distribution could be achieved by using a sweep rate that varies as the inverse of the frequency squared [26]. Frequency sweep heating can improve the uniformity of the heating, but the improvement of uniformity is restricted. A large bandwidth may generate more patterns [27], but the cost of a large bandwidth is pricy, and many frequency bands are useless. Operating at a large bandwidth faces multiple challenges and limitations. First, the cost of equipment is high. When the frequency sweep range is extensive, the input and output circuits of amplifiers must handle a broader range of frequencies, necessitating wideband power dividers and combiners, which significantly increase the complexity and cost of circuit design [28,29]. Second, the ISM (industrial, scientific, and medical) frequency bands also limit bandwidth. Operation within these bands is regulated to prevent interference with other devices and applications, and this consideration has been incorporated into our study [30]. Additionally, waveguides have a cutoff frequency, below which the wavelengths are not useful and cannot effectively propagate signals [28].

More patterns can also be produced with a cavity of larger size. However, a larger cavity takes up more space. Therefore, it is crucial for sweep frequency heating to increase the heating uniformity without changing the volume of the cavity.

This paper innovatively proposes a method to further enhance the uniformity of sweep frequency microwave heating by adding a dielectric substance to the cavity walls. In Section 2, it is theoretically revealed that the addition of dielectric materials in the cavity can improve the uniformity of sweep frequency heating. A simulation model of sweep frequency microwave heating based on the finite element method (FEM) is constructed, and the methods for experiments and testing are provided. Section 3 analyzes the factors affecting sweep frequency microwave heating, including the dielectric constant and thickness of the dielectric substance, sweep frequency bandwidth, and the dielectric constant, shape, and size of the load.

2. Methodology

2.1. Multiphysics Simulation

The simulation model of sweep frequency microwave heating consisted of a WR340 waveguides and one multimode cavity, as shown in Figure 1. Microwaves were fed through the WR340 waveguide with the dimension of 86.4 mm × 43.2 mm. The inner wall of the cavity was lined with a 20 mm thick layer of Al_2O_3 ceramic. The heated sample was a cuboid potato block on the center bottom of the cavity. The model was built in the multiphysics software COMSOL Multiphysics (6.2, COMSOL Inc., Stockholm, Sweden).

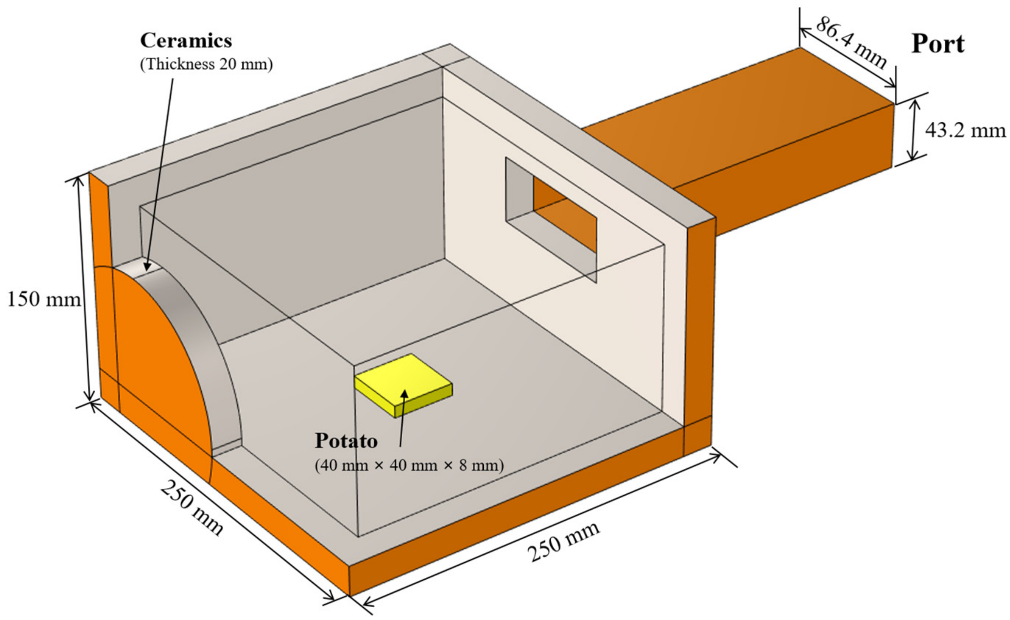

Figure 1. Geometry of the 3D simulation model.

The potato samples used in this study were obtained from a Walmart supermarket in Chengdu. A fixed plastic mold was used to cut the potatoes into the desired size to ensure consistency of the processed potato pieces.

2.2. Governing Equations

The simulation of the model is coupled with the electromagnetic field and the heat transfer. To calculate the electromagnetic field, Maxwell's equation is used [31–33]:

$$\begin{array}{c} \nabla \times \vec{H} = \vec{J} + \varepsilon \frac{\partial \vec{E}}{\partial t} \\ \nabla \times \vec{E} = -\frac{\partial B}{\partial t} \\ \nabla \cdot \vec{B} = 0 \\ \nabla \cdot \vec{D} = \rho_e \end{array}, \tag{1}$$

where $\vec{H}$ is magnetic field intensity, $\vec{J}$ is ampere density, $\vec{E}$ is the electric field strength, t is time, $\vec{B}$ is magnetic induction intensity, $\vec{D}$ is electric displacement vector, and ρ_e is electric charge density. Wave equation of electric field can thus be derived from Equation (1) and be written as Helmholtz equation [32]:

$$\begin{array}{c}\nabla \times \mu_r^{-1}(\nabla \times \vec{E}) - k_0{}^2(\varepsilon_r\varepsilon_0 - \frac{j\sigma}{\omega})\vec{E} = 0 \\ k_0 = \omega\sqrt{\varepsilon_0\mu_r}\end{array}, \tag{2}$$

where the relative permeability, electric field, and wave number are expressed in μ_r, $\vec{E}$, and k_0, respectively. The relative permittivity is expressed in ε_r, the angular frequency is expressed in ω, σ is the electrical conductivity, and ε_0 and μ_0 are the permittivity and permeability of vacuum, respectively.

The electromagnetic power loss is Q_e, which can be gained from the computed electric field by Equation (2), and then, the temperature of the heated object can be calculated by the heat transfer equation [34,35]:

$$\begin{array}{c}\rho_0 C_p \frac{\partial T}{\partial t} - k\nabla^2 T = Q \\ Q_e = \frac{1}{2}\omega\varepsilon_0\varepsilon''\left|\vec{E}\right|^2 \\ Q_e = Q\end{array}, \tag{3}$$

where the imaginary part of the relative permittivity is expressed in ε'', the material density is expressed in ρ_0, and the material heat capacity is expressed in C_p. T is the temperature, Q is the heat source, and k is the thermal conductivity.

2.3. Input Parameters

In the simulation model, the frequency range of the microwave is from 2.41 GHz to 2.49 GHz, and the input power of the microwave is 200 W, operating in the TE_{10} mode. The initial temperature of the potato is 293.15 K, and there is no gas convection within the cavity, so the boundary of the potato is set as thermally insulated. Furthermore, since the average temperature of potatoes change in a very small range (293.15 K ~ approximately 323.15 K), the influence of temperature and frequency on the dielectric constant of the potato is ignored in the calculations. The relevant input parameters of the simulation are shown in Table 1.

Table 1. Related input parameters.

Property	Domain	Value	Reference
Relative permittivity	Air	1	Build in COMSOL
	Potato	57–17j	[35]
	PTFE	2.3	Build in COMSOL
	Al_2O_3 Ceramics	9.9	[36]
	ZrO_2 Ceramics	20	[37]
Relative permeability	All	1	Build in COMSOL
Heat conductivity	Potato	0.648	[35]
Density	Potato	1050	[35]
Heat capacity	Potato	3640	[35]
Dielectric loss tangent	Potato	0.298	[35]

2.4. Methods to Increase the Mode Number in Cavity

The relationship between mode number and cavity size can be proven by the intrinsic frequency formula of rectangular resonator. For rectangular resonators, the intrinsic frequency is given by the following formula [38]:

$$f_{mnp} = \frac{c}{2}\sqrt{(\frac{m}{a})^2 + (\frac{n}{b})^2 + (\frac{p}{d})^2}. \tag{4}$$

Among them, f_{mnp} is intrinsic frequency, c is the speed of light, (m, n, p) is a model index, and (a, b, d) is the cavity length, width, and height. From this formula, it can be seen that the number of modes is directly related to the dimensions of the cavity (a, b, d). When the size of the cavity enlarged, more resonant modes can exist.

Generally, the wavelength can be expressed by the following [39]:

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{\omega\sqrt{\mu\varepsilon}}. \tag{5}$$

The relationship between λ_0 and λ_g can be derived [39]:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}}. \tag{6}$$

From the above equations, it can be seen that the wavelength of the microwave in the cavity is influenced by the relative dielectric constant of the material. When dielectric material is added to the cavity, it indirectly enlarges the size of the cavity, allowing it to accommodate more electromagnetic modes. Therefore, using sweep frequency heating in a cavity with a dielectric substance can produce more modes, thereby improving the uniformity of microwave heating.

The microwave energy conversion efficiency at different frequencies is assessed by measuring the incident and reflected power, while the uniformity of microwave heating is evaluated using the coefficient of temperature variation (COV). The COV is calculated as the standard deviation of the temperature rise at each position of the sample divided by the average temperature rise at each position, which can be expressed as follows [40]:

$$COV = \sqrt{\frac{\sum_{i=1}^{n}(T_i - T_a)}{n}} / (T_a - T_0), \tag{7}$$

where the point temperature of the selected region is expressed in T_i, the average temperature is expressed in T_a, the total number of points is n, and the initial average temperature is expressed in T_0.

A larger cavity size will contain more resonant modes, similar to using a dielectric substance, which can benefit the uniformity of microwave heating. We analyzed the uniformity of sweep frequency heating in the cavity without a dielectric substance at different enlargement factors, with the simulation results shown in Table 2. In the simulation, the microwave power was set to 200 W, the frequency range was set from 2410 to 2490 MHz, the volume of the heated potato was 40 mm × 40 mm × 8 mm, and the heating time was 10 s. The size of the cavity was enlarged 1.25 times, 1.5 times, 1.75 times, and 2 times. It is worth noting in the enlarging detail that the dimensions of the multimode cavity, including its length, width, and height, were scaled up, while the waveguide dimensions and its distance from the bottom edge of the multimode cavity were maintained constant.

Table 2. Simulated heating results for different cavity size.

Cavity Enlargement	Average Temperature	COV
1	307.74	0.627
1.25	308.69	0.571
1.5	311.71	0.493
1.75	307.99	0.396
2	310.50	0.436

By comparing the COV of different cavity size, the temperature distribution of the sweep frequency heating was more uniform, but the heating efficiency was not necessarily higher when the cavity size was larger, which can be seen in Table 2. However, it is necessary to notice that when the cavity was enlarged by a factor of 2, the COV actually rebounded. That is because the relationship between COV and the cavity size is not strictly monotonic reducing but a reducing trend.

2.5. Mesh Analysis

The computational accuracy of a model based on the finite element analysis method is directly related to the quality of the mesh. The finite element mesh divides the geometric model into many small domains according to the physical field's characteristics. Polynomial functions are defined in each unit to approximate the physical field's constraint equations, which are then solved iteratively. As the mesh is refined, the minimum solution area becomes smaller, and the results become closer to the true solution. The solution's accuracy is also related to material properties. In electromagnetic calculations, the mesh division criteria must satisfy the following equation, and this equation is also applicable to FEM [41]:

$$l < \frac{\lambda}{6\sqrt{\varepsilon'}} \tag{8}$$

where λ is the wavelength in vacuum, the mesh size with the best convergence rate and calculation accuracy can be obtained through this method because the optimal mesh size in the electromagnetic problem is related to the relative dielectric constant of the material and the wavelength of the electromagnetic wave-free space. According to Figure 2, both the mesh division of the cavity and the load have been found to satisfy Equation (7) very well.

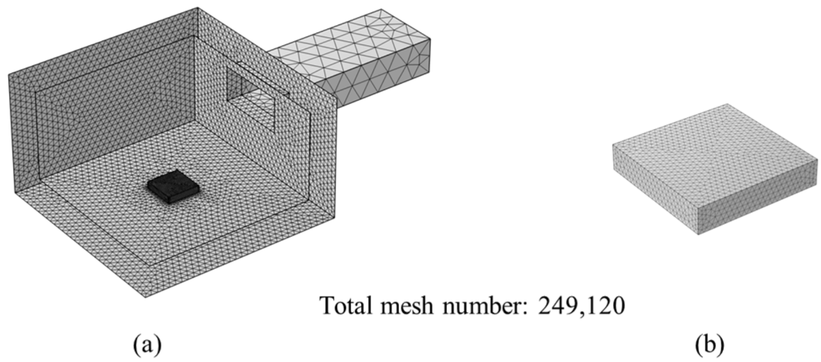

Figure 2. Model meshing: (**a**) the mesh division of the whole multimode cavity; (**b**) the mesh division of the load.

2.6. Experimental Setup

The experimental setup for the microwave sweep frequency heating system is shown in Figure 3. A sweep frequency solid-state source was used to provide the microwave output, with a power of 200 W. The sweep signal had a sweep period of 1 s and a frequency range of 2410 MHz to 2490 MHz, with a frequency step size of 0.1 MHz. A circulator and water load were used to protect the solid-state source from reflected power. A directional coupler and power meter were used to monitor the incident and reflected power of the system. The solid-state source was connected to the microwave waveguide system via a coaxial line. Ceramic substance was attached to the inner walls of the cavity. The sweep frequency output of the solid-state source was controlled using a laptop. The temperature of the upper surface of the potato was measured using a thermal imager, and the power meter was used to evaluate the microwave energy conversion (heating efficiency).

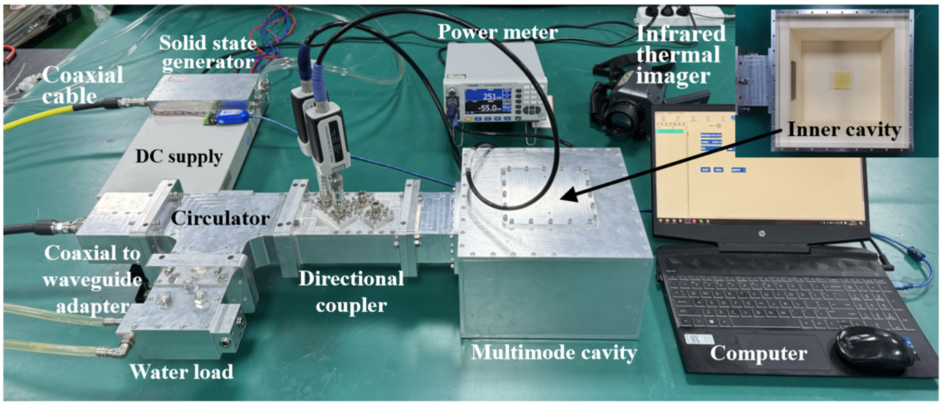

Figure 3. Sweep frequency microwave heating experimental system.

2.7. Material Subsection

In the absence of special instructions, the dielectric substance on the multi-cavity walls was made of 20 mm thick Al_2O_3 ceramic, both in simulation and experiment. The use of aluminum oxide was attributed to its relatively low cost and its prevalence as a common ceramic material.

In the simulation of Section 3.3, other dielectric substances like PTFE and ZrO_2 ceramics were discussed to study the relationship between heating uniformity and permittivity of dielectric substance due to the significant difference in the dielectric constants of these materials compared to Al_2O_3 ceramic.

3. Results and Discussion

3.1. Model Validation

In the experiment, the sweep frequency heating range is from 2410 MHz to 2490 MHz, with a sweep period of 1 s. The microwave input power is 200 W, and the heating time is 10 s. The heated sample is a potato measuring 40 mm $\times$ 40 mm $\times$ 8 mm, placed at the center of the cavity's bottom. Microwave heating experiments were conducted with and without a dielectric substance to verify the accuracy of the simulation model and the effectiveness of the dielectric substance in improving sweep frequency heating efficiency.

The results of sweep frequency microwave heating with and without a dielectric substance are shown in Table 3. It can be observed that under these conditions, the cavity with the dielectric substance demonstrates higher heating uniformity and efficiency. Additionally, we measured the surface temperature distribution of the potato after 10 s of heating using a thermal imager, and the comparison between simulation and experimental results is shown in Figure 4. It is evident that the hotspot shapes and positions on the potato's surface in both experiments and simulations are largely consistent, confirming the accuracy of the multiphysics simulation model. The comparison of microwave energy utilization rates at different frequencies is presented in Figure 5. The simulation results indicate that microwave heating efficiency varies with frequency changes, and the trends in both the experimental and simulation results are generally consistent. Although some deviations exist, they may be attributed to fabrication errors of the cavity and operational errors during the experiment. The lower average temperature of the experiment is caused by the thermal insulation boundaries.

Table 3. With and without dielectric substance heating simulation results.

Kinds	Average Body Temperature	COV
Without dielectric substance	307.74	0.627
With dielectric substance	319.41	0.37

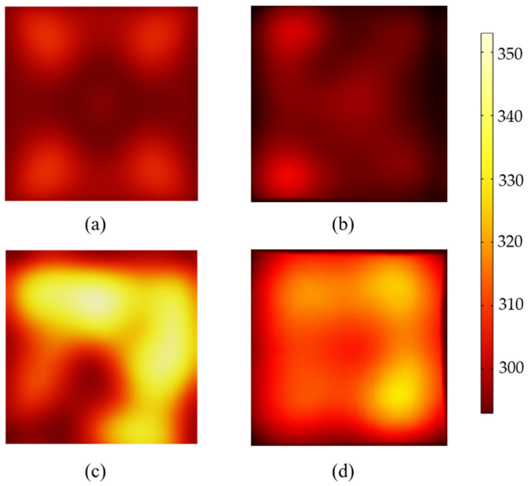

Figure 4. The result comparison of potato surface temperature distribution between simulation and experiment under frequency sweep (unit: K): (**a**) the simulated heating results without a dielectric substance; (**b**) the experimental heating results without a dielectric substance; (**c**) the simulated heating results with a ceramic dielectric substance; and (**d**) the experimental heating results with a ceramic dielectric substance.

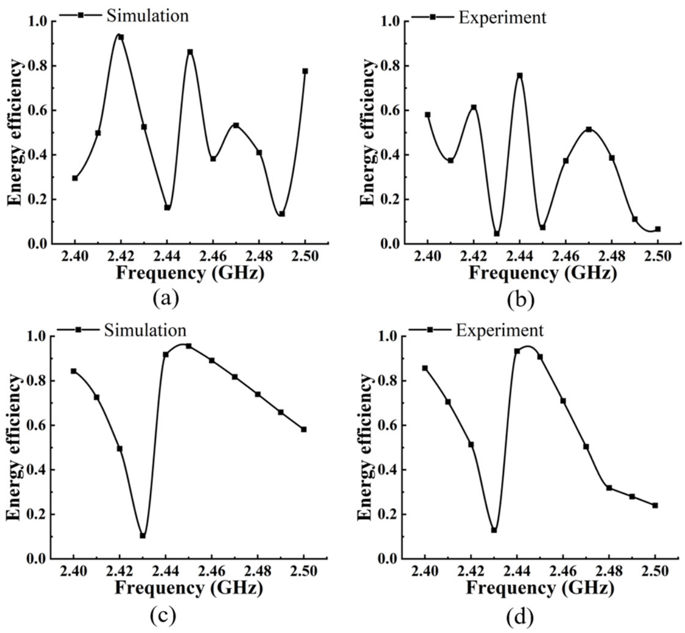

Figure 5. The result comparison of S11 between simulation and experiment under different frequencies: (**a**) the simulated heating results without a dielectric substance; (**b**) the experimental heating results without a dielectric substance; (**c**) the simulated heating results with a ceramic dielectric substance; and (**d**) the experimental heating results with a ceramic dielectric substance.

3.2. Discussion of Electric Field Distribution

The reason for improving heating uniformity by adding a dielectric substance can be found in the electric field distribution within the cavity. The electric field distributions in the multimode cavity with and without a dielectric substance under different frequencies were analyzed, and the simulation results are shown in Figure 6. The results indicate that compared to the case without a dielectric substance, the electric field distribution in the cavity with the dielectric substance is more significantly affected by changes in microwave frequency. The larger the differences in electric field distribution, the better the uniformity of microwave heating it can have.

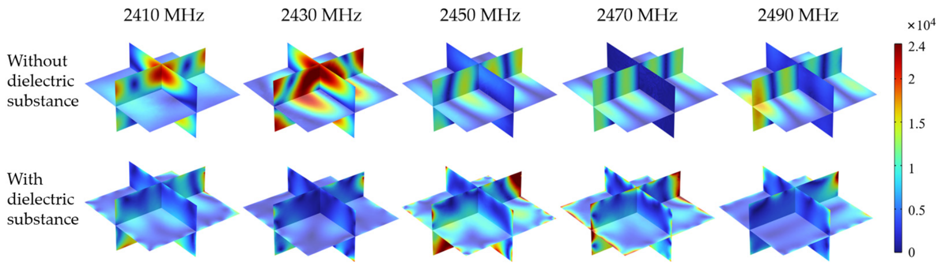

Figure 6. The electric field distribution with or without a dielectric substance in different frequencies.

The electric field distribution inside loads under different frequencies is shown in Figure 7 below. When the load is put in, the uniformity of heating can be reflected by the inner electric field distribution of the load because the position with a strong electric field will be a hot spot, and that hot spot often results in uneven heating.

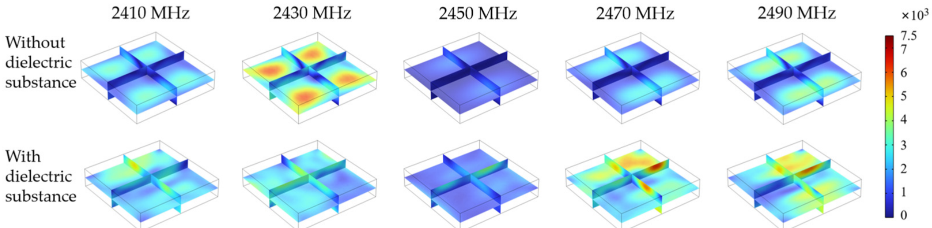

Figure 7. The electric field distribution of potato with or without a dielectric substance in different frequencies.

According to this figure, heating with a dielectric substance can always excite a more uniform electric field distribution in the load, which can avoid the formation of hot spots. Therefore, it can lead to more uniform heating by sticking a dielectric substance to the multimode cavity wall.

3.3. Discussion of Dielectric Substance Thickness

To analyze the effect of the thickness and material of the dielectric substance on heating uniformity, heating simulations were performed with different thicknesses and materials of dielectric substances. The dielectric substance included PTFE, Al_2O_3 ceramics, and ZrO_2 ceramics, with thickness varying from 9 mm to 29 mm in 2 mm increments. In the simulation, the microwave sweep frequency range was set from 2410 MHz to 2490 MHz, with a power of 200 W and a heating time of 10 s. A potato measuring 40 mm × 40 mm × 8 mm was used as the heated load, with an initial temperature of 293.15 K. The average temperature and COV results for different dielectric substances are shown in Figure 8.

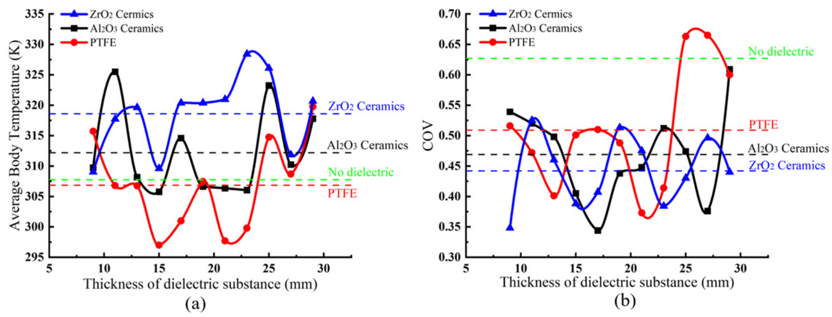

Figure 8. The influence of heating with different thicknesses of different dielectric substances: (**a**) the influence of average temperature and (**b**) the influence of the COV. The horizontal dash line is the average value among all of the dielectric substance.

From the simulation results, it can be observed that the efficiency of microwave heating and the COV of the potato temperature fluctuate periodically with the thickness of the dielectric substance. As the thickness of the dielectric substance increases, the heating efficiency fluctuations gradually increase, while the temperature COV of the potato gradually decreases. By comparing the heating effects of different materials (with different permittivity), it is evident that a higher relative permittivity of the dielectric substance leads to greater microwave heating efficiency and better heating uniformity. The average temperature without a dielectric substance is 307.74 K, which is higher than that with PTFE but lower than that with a ceramic substance. The COV without a dielectric substance is 0.627, significantly higher than in almost all cases with dielectric materials. When using ZrO_2 ceramics with a dielectric constant of 20 as the dielectric substance, the highest temperature rise and lowest COV were observed, and that just corroborates the theory of increasing the cavity electrical size to result in a higher number of resonant modes. Therefore, we can conclude that a higher relative permittivity of the dielectric substance is beneficial for improving heating efficiency and uniformity.

3.4. Discussion of Sweep Frequency Bandwidth

The simulation conducted an analysis of S11 across different frequencies, where S11 represents the return loss, serving as a metric for evaluating the energy reflected back to the microwave source. During the simulation, electromagnetic losses associated with the cavity walls and microwave leakage were neglected; thus, a smaller S11 indicates an enhanced microwave heating efficiency. Figure 9 illustrates the S11 characteristics of the cavity with and without the dielectric substance. It is evident that in the absence of the dielectric substance, the S11 curve exhibits a relatively smooth profile, whereas the presence of the dielectric substance introduces numerous peaks in the S11 response. These results demonstrate that within the multimode cavity incorporating the dielectric substance, the electromagnetic modes experience significant variations with frequency, leading to improved uniformity in heating.

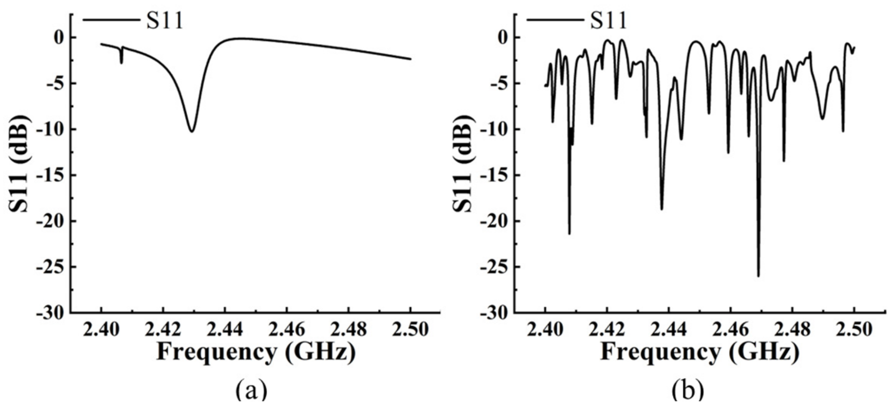

Figure 9. The S11 curve of the multimode cavity with (**a**) or without (**b**) a dielectric substance.

A further analysis on the effect of sweep bandwidth on the cavity filled with a dielectric substance has been performed. Simulations were conducted using sweep bandwidths of 20 MHz, 40 MHz, 60 MHz, 80 MHz, and 100 MHz, as shown in Table 4.

Table 4. COV under different sweep frequency bandwidths.

Sweep Frequency (MHz)	2440–2460	2430–2470	2420–2480	2410–2490	2400–2500
Sweep bandwidth (MHz)	20	40	60	80	100
COV without dielectric	0.675	0.669	0.662	0.627	0.644
COV with dielectric	0.477	0.429	0.482	0.37	0.386

The simulation results clearly demonstrate that regardless of the sweep bandwidth used, the coefficient of variation (COV) is significantly lower when the cavity is filled with the dielectric substance compared to the one without a dielectric substance. This indicates that filling the cavity with a dielectric substance can consistently enhance the uniformity of the heating.

Interestingly, the COV has been found to exhibit a decreasing trend as the sweep bandwidth is increased, especially for the one with a dielectric substance. The lowest COV with a dielectric substance was observed when the sweep bandwidth was set to 80 MHz. Therefore, 2410 MHz to 2490 MHz can be regarded as the optimum sweep frequency in this cavity.

Further on, the inner temperature field of the load under different sweep frequency bandwidths is shown in Figure 10. It is clear to see that heating without a dielectric substance often has a hot spot in the four corners of the load, while the one with a dielectric substance has an inconspicuous hot spot. That means that no matter what the sweep frequency bandwidth is, the heating uniformity can be improved by adding a dielectric substance.

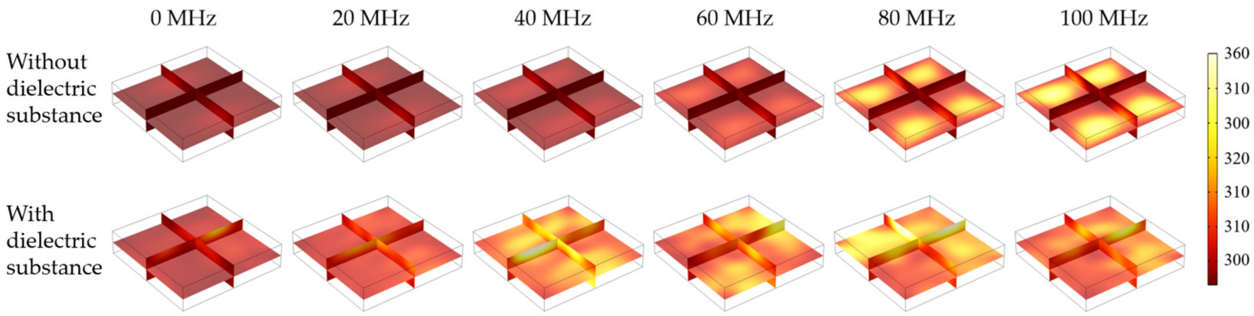

Figure 10. The heating temperature distribution inside loads with or without a dielectric substance under different sweep frequency bandwidths.

3.5. Discussion of Load Shape, Size and Permittivity

Materials with different shapes, different sizes, and different dielectric constants were studied under the above conditions and under the condition without filling the dielectric substance. Cuboids, cylinders, and spheres are used in the simulation. It is worth noting that in this simulation, the position of the load without a dielectric substance is 20 mm higher than the general one without a dielectric substance, which will lead to the load hanging in the air, but that can keep the two groups of loads (with and without a dielectric substance) having the same z-position. The comparison results for the heating efficiency of different loads are shown in Figure 11, while the results for heating uniformity are presented in Figure 12. From the comparison of heating materials of different shapes and dielectric constants, it is obvious that filling the dielectric substances can improve the heating uniformity whatever the shape, the size, and the dielectric constant of materials heated are. It is evident that the cavity with a dielectric substance generally exhibits a smaller COV. Additionally, in the vast majority of cases, the temperature rise in the cavity with the dielectric substance is higher than that in the cavity without it, although there are a few exceptions when the size of the load changes. Therefore, it can be concluded that using a dielectric substance during sweep frequency microwave heating can improve heating uniformity and efficiency, but it does not necessarily lead to an increase in heating efficiency. This simulation proves that other materials with different dielectric constants and shapes can also be heated more uniformly by the proposed methods.

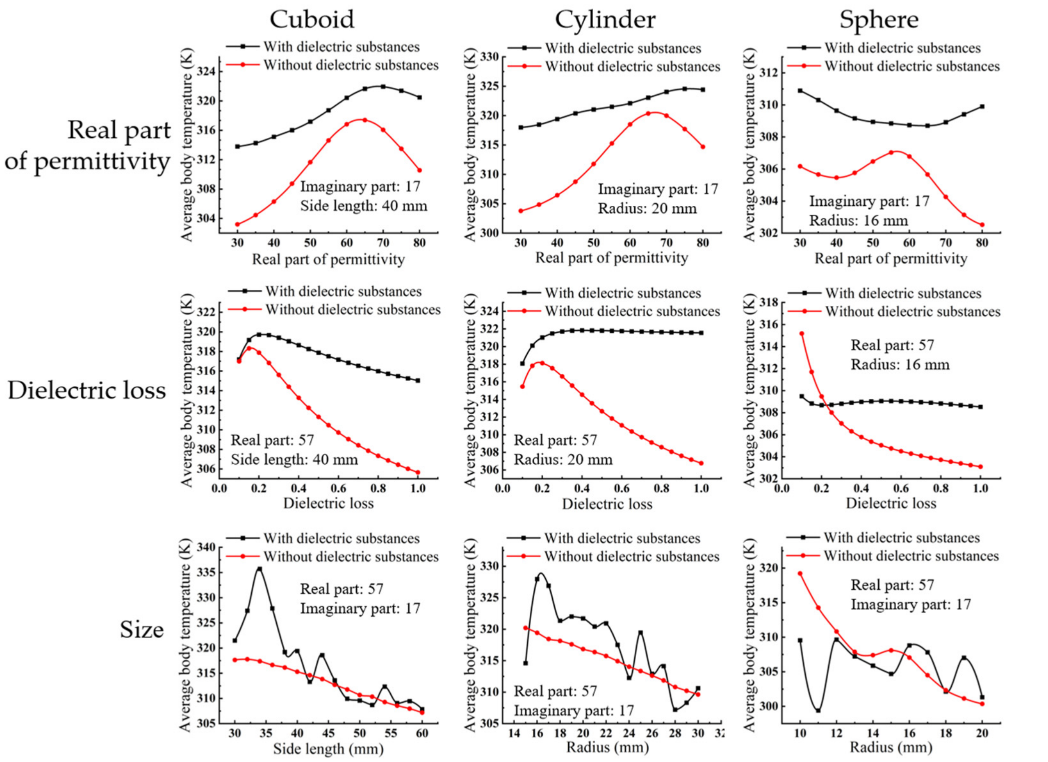

Figure 11. The influence of the load property on the average temperature.

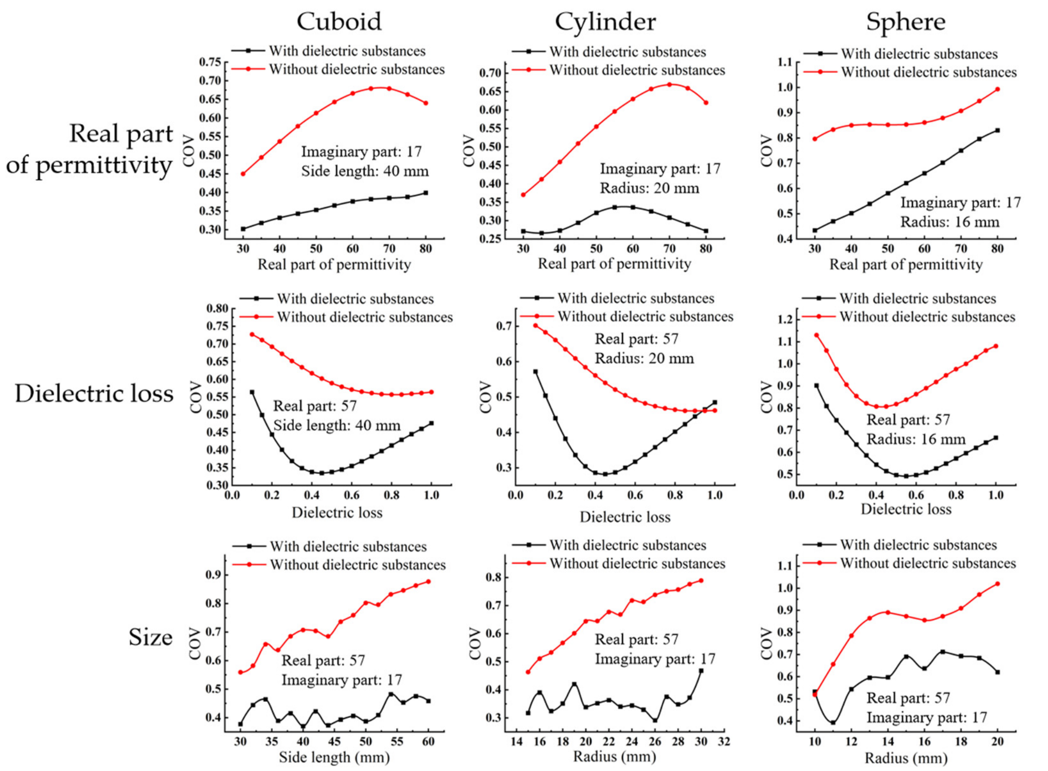

Figure 12. The influence of the load property on the COV.

4. Conclusions

This paper proposes a novel method to improve the uniformity of sweep frequency microwave heating by applying a dielectric substance to the inner walls of the cavity. The theoretical derivation demonstrates the effectiveness of the dielectric substance in enhancing heating uniformity. A multiphysics simulation model for microwave sweep frequency heating has been established, and an experimental system for sweep heating with a dielectric substance cavity has been constructed. The experimental results are consistent with the simulation results, showing that the average temperature of the load with the dielectric substance is 11.67 K higher, and the COV is reduced by 0.26 compared to without the substance, thereby validating the effectiveness of the method and the reliability of the simulation model. Furthermore, we analyzed the impact of the material type and thickness of the dielectric substance on heating performance, finding that a higher dielectric constant significantly improves both heating efficiency and uniformity. Additionally, the method's effectiveness has been verified across various loads with different dielectric constants, shapes, and volumes, demonstrating its wide applicability. This study will help address the challenges of microwave heating uniformity in industrial production and promote the application of microwave energy in industrial processes.

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