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Numerical study of initially frozen rice congee with thin film resonators package in microwave domestic oven

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Abstract

Packaging plays a crucial role in microwave processing of foods. However, the characteristics of frozen food and the resonance package are not well understood and inadequate. In this work, the approach is mainly based on a coupled electric-thermal model. The numerical model of the microwave heating of frozen rice congee with resonance package is developed using COMSOL Multiphysics 4.4 software to examine the effects of metal film as a resonator and the port power position on heating patterns and rates in domestic microwave oven. The simulation model food of stationary is placed in the center of the domestic microwave oven. The sample is heated from the room temperature for 60 s, 800 W, and 2.45 GHz. The dielectric properties are measured as a function of the temperature and the thermal properties are calculated from chemical composition of frozen rice congee. In order to validate the results of simulation, a series of experiments were performed with three replicates at each case. The temperature is recorded using fiber-optic sensors and thermal imaging camera. The results show good agreement with simulated results. The difference in results is found by 5–10%. The results in this work indicate that the temperature of frozen food after subjected to microwave is highest in case no metal film on package for both top and side port power. Further investigation showed that the metal film area on package affects heating uniformity. The top port power increases more than 25% of sample temperature.

Practical Applications

The popularity of microwave ovens has led food producers to develop a new generation of microwave heating products. Many products can be heated and served in their packages. However, the big problem in the microwave heating of food is nonuniform heating. The metal microwaveable packaging is developed as one solution of how to overcome this problem. The reason is that the metal film can change the electric distribution pattern because of changing heating profile. This work examines the effects of metal film area and port power position on heating uniformity and thawing time in microwave process. The application of this work can be used to optimize the port position and food package modification to achieve more uniform heating.

1 | INTRODUCTION

Frozen foods can be a convenient and inexpensive way to combine all healthy foods group. It includes whole grains, fruits, vegetables, protein, and dairy products. In addition to a time saving, frozen foods also help reducing food waste. For this reason, a frozen food has become a good way for preparing the meals. The frozen foods are available in a variety of product layouts such as single-component, multicomponent, and multicompartment meals. However, that product has to be thawed before consumption and the rapid heating can offer by the domestic microwave oven.

The quick microwave heating may enhance the high energy efficiency and offer improvements in product quality. However, microwave heating could produce the nonuniform heating inside the food that could reach burned and frozen zones. The factors that can affect the nonuniform heating characteristics of microwave materials are food geometry, thermal and dielectric properties, as well as process parameters such as operating frequency, power, and time. From the point of improving the heating uniformity of microwave ovens, it may be possible to control nonuniform heating during the microwave heating of frozen foods by using an active package that contains a metal film. A novel package contains metal foils or strips which modify the microwave field and result in a more uniform heating or browning of a food product. These have been used in some microwaveable food products for more than 20 years. There are many patents and research related to microwaveable foods improvements, such as Risman (2009), Albert, Salvador, and Fiszman (2012), Acevedo, Usón, and Uche (2015), Vargas, Pantoya, Saed, and Weeks (2016), Sadeghi, Hamdami, Shahedi, and Rafe (2016), and F. Chen, Warning, Datta, and Chen (2017). Various research approaches include both experimental and numerical analysis. A computer-based simulation of microwave heating is an effective tool that offers insights into microwave interactions with food components and packages. It can help to save the amount of time in food product development. Many researchers have attempted to develop susceptor-assisted microwave heat transfer models. For example, Pitchai, Birla, Raj, Subbiah, and Jones (2011) developed modeling of susceptor-assisted microwave heating in domestic ovens using radio frequency and heat transfer modules of COMSOL Multiphysics 4.2. They used two different approaches as domain discretization and transient boundary condition for investigating. It was found that the transient boundary condition approach was to be better considering the computational time in domain discretization method. F. Chen et al. (2017) studied a coupled electromagnetic and thermal model of food-susceptor heating process. The model was validated by heating a frozen pie in a package with a rotating turntable. It was shown that increasing the heat flux at the interface, a susceptor causes the food to absorb nearly three times as much energy initially, with the rate decreasing as the material thaws. A surprising relationship found was the heating effectiveness of a susceptor increases when combined with rotation. These results provide a significant first step toward food design.

From above, many previous studies have explored heat and mass transfer in microwave processing, but the area of Asia frozen food has not been explored in depth. Therefore, to fulfill the knowledge in this field, this study aims to determine changes in the heating patterns and rates in microwave process of the frozen rice congee and its package. The rice congee is a traditional food in Asia. It is served most often as a meal on its own, especially for people who are ill. This work studied the effects of metal film area (as resonator/shielding) and port power position (top and side of oven) on the electric field distribution and the temperature profile. Data analysis was performed with the software COMSOL Multiphysics 4.4. The validity of the projected heating pattern needed to then be assessed by comparison with experimental measurement in the domestic microwave oven. This result will help food product developers design frozen food products to minimize energy use and food safety concerns. Thus, this work is a quality improvement. In addition, this will be a useful data for government regulatory agency implementation on industries application and most importantly for consumers.

2 | MATERIALS AND METHODS

The approach for investigating the microwave heating of a frozen food is mainly based on mathematical modeling. Also, the numerical model can be validated by comparing the numerical results with the experimental results.

2.1 | Sample properties

Samples were frozen rice congee and obtained from the convenience store (7-Eleven) in Thailand as seen in Figure 1. Samples were stored in the freezer at below -18°C for at least 24 hr before testing. The sample properties including dielectric and thermal properties were taken from research of Klinbun and Rattanadecho (2017). From their findings, the dielectric properties of rice congee were measured

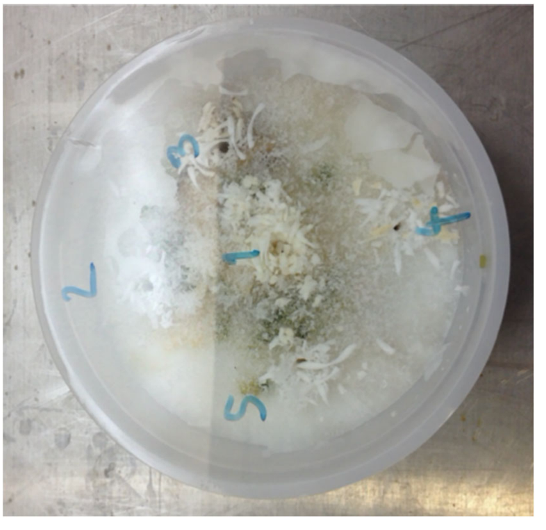


FIGURE 1 The frozen rice congee

dielectric constant and dielectric loss factor as a function of temperature from −18 to 80°C. In addition, they used dielectric properties data to calculate power reflected, power transmitted, dielectric loss tangent (tan δ), and penetration depth.

For the thermal properties, such as thermal conductivity (k), specific heat (C_p), and density (ρ) that were calculated using the Choi and Okos equations (Choi & Okos, 1986) based on composition and temperature. The nutrition facts label showed the nutrients in sample, including moisture 89.7%; fat 0.5%; protein 1.9%; carbohydrate 7.1%; fiber <0.5%, and ash 0.81%.

Their models are following:

$$C_p = \sum_{i=1}^{n} C_{pi} X_i \tag{1}$$

where X_i is the fraction of the ith component, n is the total number of components in a food, and C_{pi} is the specific heat of the ith component.

$$k = \sum_{i=1}^{n} k_i Y_i \tag{2}$$

where a food material is n components, k_i is the thermal conductivity of the ith component, Y_i is the volume fraction of the ith component, obtained as follows:

$$Y_i = \frac{X_i/\rho_i}{\sum_{i=1}^{n} (X_i/\rho_i)} \tag{3}$$

where X_i is the weight fraction and ρ_i is the density (kg/m^3) of the ith component.

Figure 2 shows a strong correlation between thermal properties (C_p, k, ρ) and temperature from −18 to 80°C. In Figure 2a, the correlation between density (ρ) and temperature indicates the maximum density (1,035 kg/m^3) at 0°C. This decrease in density from 0 to 80°C is certainly because the density of water decreases with increasing temperature. The initial density is 960 kg/m^3 at −18°C and 1,011 kg/m^3 at 80°C. Figure 2b shows a trend different from that observed in the thermal properties. It shows an increase in thermal conductivity (k) with increasing temperature. The maximum k value is high in the frozen stage from −18 to 0°C because the ice fraction as a function of

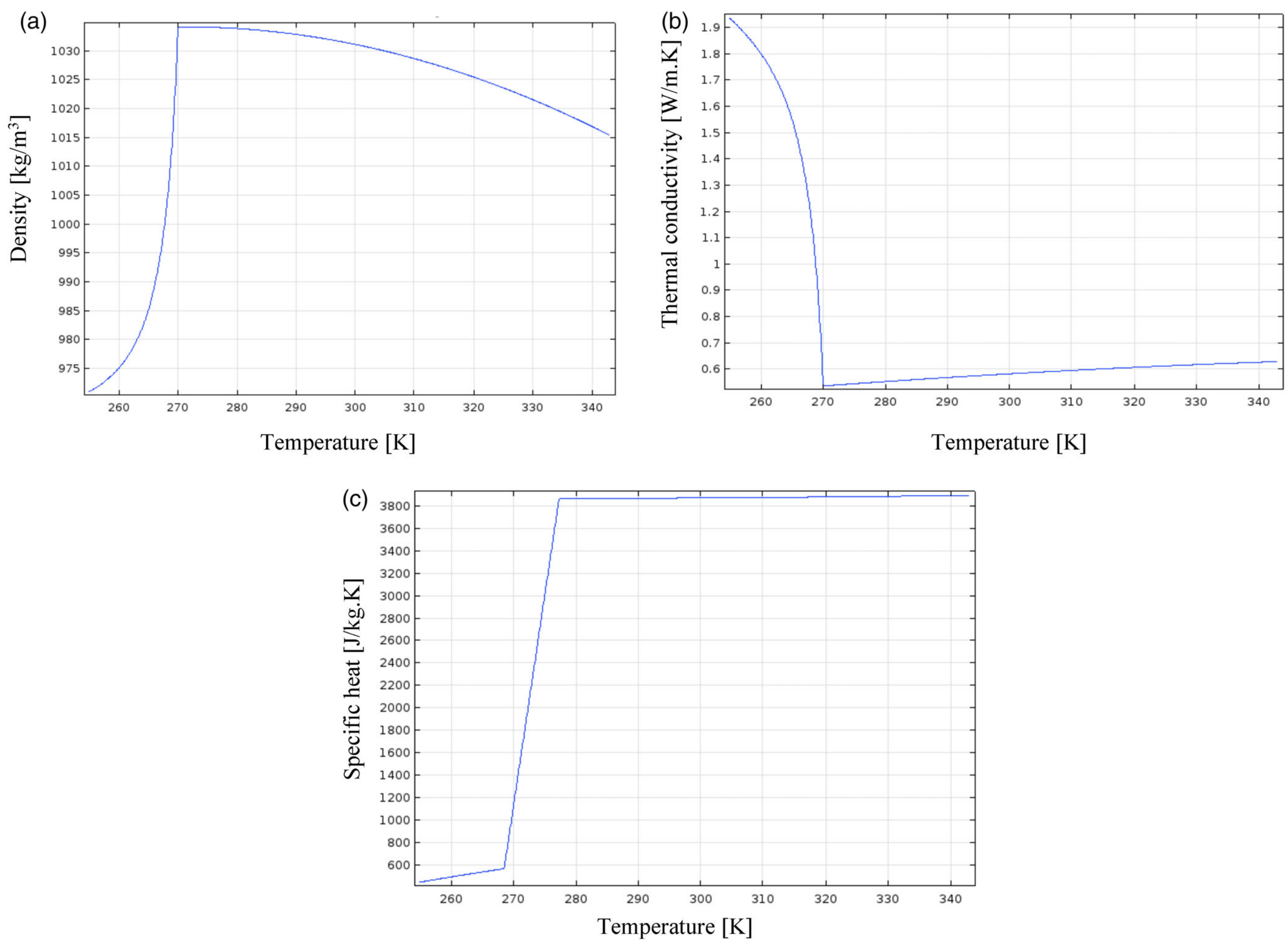


FIGURE 2 Thermal properties of sample as a function of temperature from −18 to 80°C (a) density, (b) thermal conductivity, and (c) specific heat

temperature. This k value is similarly reported by many previous researchers such as Delgado, Gallo, Piante, and Rubiolo (1997), Mohamed (2009), Zhang, Li, and He (2011), Bornhorst, Sarkar, and Singh (2014), and J. Chen et al. (2013). Finally, Figure 2c shows a clear trend of increasing the specific heat (C_p) of the frozen rice congee as a function of temperature from −18 to 80°C. The specific heat increases sharply in the thawed state from 0 to 10°C due to the phase change in the water content. It is 2.96 and 3.90 kJ/kgK at 0 and 10°C, respectively. After that, the specific heat is slightly increased from 0 to 80°C.

For this model, a metal film (food grade aluminum foil) was wrapped on package to understand microwave interaction with resonator package and food material. The dielectric and thermal properties of metal film was held constant because heating sample temperature below the critical temperature.

2.2 | Geometric model

Figure 3a shows the model of microwave heating system of frozen rice congee with resonance package is developed using COMSOL Multiphysics 4.4 software (COMSOL Inc., Boston, MA). The microwave oven was domestic oven Model no: R222; Sharp Cooperation. The frozen sample was placed on turntable at center of oven. The microwave system was operated 800 W, frequency of 2.45 GHz, and 60 s. Figure 3b is frozen rice congee inside the resonator package. The metal film as resonator is wrapped on food package. The metal film is used to modify the electric field patterns and eliminate the hot areas.

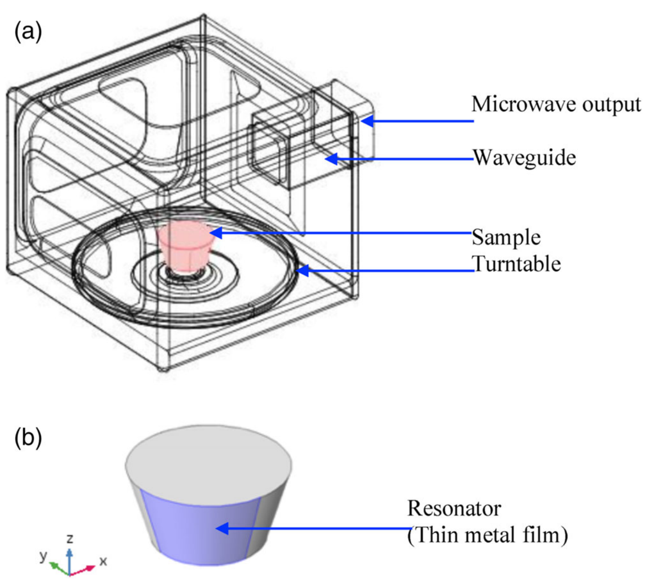


FIGURE 3 Geometrics of (a) domestic microwave oven and (b) frozen food with resonator

2.3 | Mathematical modeling

This work is done by a three-dimensional electromagnetic-thermal analysis. The following assumptions are made in the analysis of electromagnetic and heat transfer.

1. The wall of the oven is a perfect electrical conductor.
2. The magnetron power source is 800 W, at a frequency of 2.45 GHz and TE_{10} mode.
3. The heat transfer is occurred only in sample.
4. The sample is assumed to be a homogeneous isotropic material.
5. The mass and momentum transfer of moisture are negligible.

2.3.1 | Governing equations

The electromagnetic field distribution ($\vec{E}$) inside the microwave cavity and within sample is solved according to set of Maxwell's equations. The combined waveform of Maxwell's equation is expressed as (COMSOL 4.4):

$$\nabla \times \mu_r^{-1}\left(\nabla \times \vec{E}\right) - \left(\frac{2\pi f}{c}\right)^2 (\varepsilon_r - j\varepsilon'')\,\vec{E} = 0 \tag{4}$$

where f is the frequency in 2.45 GHz, c is the speed of light in 3×10^8 m/s, $\varepsilon_r = \varepsilon/\varepsilon_0$, μ_r are relative dielectric constant, and permeability of the medium, respectively.

Dielectric properties of foods are important parameters that influence the interaction between microwaves and food materials. When phase changes process occurs during the process such as thawing, the dielectric properties change significantly and are critical input parameters to the microwave heating model. In this study, the dielectric properties of frozen food are temperature dependent, which is defined as:

$$\varepsilon(T) = \varepsilon'(T) - j\,\varepsilon''(T) \tag{5}$$

where the real component is the dielectric constant (ε') and the imaginary component is the dielectric loss factor (ε''), and $j = \sqrt{-1}$.

From Equation (4), the solution $\vec{E}$ is the electric field vector inside the cavity and sample. During the microwave heating process, the electromagnetic energy penetrated in the material and is converted into thermal energy. It is proportional to the dielectric loss factor (ε''), square of electric field strength $\left(\vec{E}\right)$, and the frequency of the wave (f). The electromagnetic power loss density (Q) is governed by:

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

where ε_0 is the free space permittivity, 8.854×10^{-12} F/m.

The dissipated electromagnetic power loss density (Q) is a heat source term in frozen food and governed by Fourier's heat transfer equation.

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + Q - \lambda_e \dot{I} \tag{7}$$

where ρ is the density (kg/m^3), C_p is the specific heat capacity at constant pressure (J/kg°C), k is the thermal conductivity (W/m°C), and T is the transient temperature (°C).

$$\lambda_e \dot{I} = \begin{cases} 0 \; T < 100^\circ\mathrm{C} \\ Q \; T \geq 100^\circ\mathrm{C} \end{cases} \tag{8}$$

where λ_e is the latent heat of vaporization and $\dot{I}$ is the rate of water evaporation. Equation (8) is assumed no evaporation for temperature below 100°C and evaporation for temperature above 100°C. The latent heat of fusion of frozen congee is 295.26 kJ/kg. However, this model used a simple model but it has been widely used for microwave heating studies (F. Chen et al., 2017).

2.3.2 | Boundary and initial conditions

The incident wave power is 800 W, at frequency of 2.45 GHz and TE_{10} mode. The equations to obtain electric wave (E) and magnetic wave (H), are given by the following equation (Rattanadecho & Klinbun, 2011):

$$E_z = E_{zin} \sin\left(\frac{\pi y}{L_y}\right) \sin(2\pi f t) \tag{9}$$

$$H_y = \frac{E_{zin}}{Z_H} \sin\left(\frac{\pi y}{L_y}\right) \sin(2\pi f t) \tag{10}$$

where E_{zin} is the input value of electric field intensity (V/m), L_y is the length of the rectangular waveguide in the y-direction (m), and Z_H is the wave impedance (Ω).

In Figure 3, the inner wall of the microwave cavity and a thin metal film contained in the package are perfectly conducting wall. The tangential component of the electric field and the normal component of the magnetic field are set to zero on the perfect conducting wall. The package of sample is made from polypropylene, PP. When electromagnetic wave incidents on sample with package, it can be noted that electromagnetic waves reflect at the resonator area and transmit through PP layer. Thus, the interfaces between the sample, PP, and air are set to be the continuity boundary conditions, is given by (Rattanadecho & Klinbun, 2011):

$$E_t = 0, H_n = 0 \tag{11}$$

$$E_t = E'_t, H_t = H'_t$$

$$D_n = D'_n, B_n = B'_n \tag{12}$$

where t and n represent the tangential and normal components, respectively.

Finally, the top surface is exposed to the air.

$$-k\frac{\partial T}{\partial n} = h(T - T_{air}) \tag{13}$$

where the initial temperature of the frozen food average is −18°C, and the coefficient of heat transfer between the food and the air, $h = 20$ W/m^{2}K. The ambient air temperature, $T_{air} = 27$°C.

Table 1 shows the summaries of initial conditions and materials properties applied in the mathematical model.

2.3.3 | Simulation strategy

In this study, multiple meshes were implemented for different domains to ensure the simulation results regardless of meshing. Air domain was assigned with free tetrahedral elements; frozen rice congee was assigned with quadrilateral element. The actual thickness of the metal film was very small (below 1 μm). Thus, the metal film needed to be coarse discretization and in transient boundary condition method.

Equations (4), (6), and (7) were solved using radio frequency and heat transfer modules of COMSOL Multiphysics 4.4. To study the effects of metal film and port power position on heating pattern and rates in, the coupled electromagnetic and heat transfer equations were solved using two segregated steps. The main solution steps were described as follows. In Step 1, a three-dimensional geometric model following the real structure and size of the microwave heating system was built. With this geometric model here, two new models, such as "EM model" and "HT model" were built separately by setting different parameters and boundary conditions in Step 2. The "EM model" was used to estimate the electromagnetic field distribution in the sample and microwave cavity and get the internal heat generations were used in "HT model" for temperature prediction and heat transfer analysis. Thus, in Step 3, the simulation by coupling "EM model" and "HT model" were carried out continuously until a desired heating time was reached. The estimated results could show the change in figures or animation directly. The simulations were performed on a Dell Precision T7500 workstation with an operating memory of 72 GB RAM running on two quad-core Intel Xeon X5570 2.93 GHz frequency processors.

3 | RESULTS AND DISCUSSION

3.1 | Experimental verification

The metal film is chosen to see the model effect of resonator film on heating patterns. The spatial simulated temperature distributions of rice congee obtained are compared with the experimental heating profiles. For experimental study, a frozen rice congee in package was purchased and was kept at temperature average −18°C in a freezer until starting the experimental. The sample was placed in the center

TABLE 1 Summary of initial conditions and material properties applied in the mathematical model

Domain	Properties	Unit	Value
Air	Initial temperature	°C	27
	Dielectric constant (ε')	–	1
	Dielectric loss factor (ε'')	–	0
Glass turntable	Initial temperature	°C	27
	Dielectric constant (ε')	–	4
	Dielectric loss factor (ε'')	–	0
	Density (ρ)		2,050
Frozen rice congee	Initial temperature	°C	−18
	Dielectric constant (ε')	–	Klinbun and Rattanadecho (2017)
	Dielectric loss factor (ε'')	–	
	Specific heat capacity (C_p)	J kg^{-1} K^{-1}	Figure 2
	Density (ρ)	kg/m^3	
	Thermal conductivity, (k)		
Food–air	Heat transfer coefficient (h)	W m^{-2} K^{-1}	20

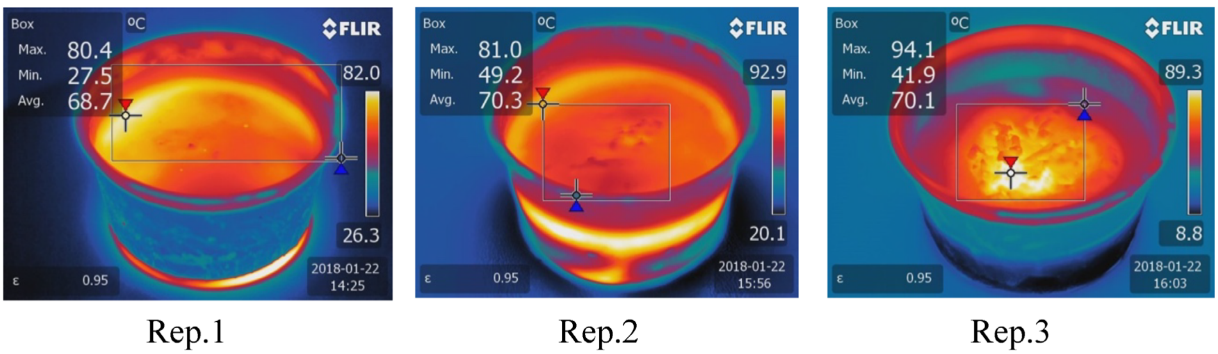


FIGURE 4 Thermal image of frozen rice congee with package and resonator after subjected to microwave power 800 W, 2.45 GHz for 300 s

of the oven and was subjected to microwave power for 800 W, 2.45 GHz during 300 s while the food was stationary on the glass turntable. A metal film (food grade aluminum foil) was cut to size of package and wrap on outside the package as seen in Figure 3b. The optical fiber temperature sensors (four-channel reflex signal conditioner, accuracy ±0.8°C, Neoptix Inc., Quebec, Canada) recorded four different points inside the sample. Then, we took the thermal image immediately after finished heating using IR camera (SC640, accuracy ±2°C, 640 × 480 pixels, FLIR Systems, Boston, MA). The experiment was repeated for three times to obtain the temperature results.

Figure 4 shows the thermal image of the sample for 300 s of the microwave heating process. As can be seen in Figure 4, the average temperature of the sample is 70°C. The maximum temperature is higher than 80°C and occurs on the side without wrapping metal foil. However, the minimum temperature is about 30°C that happens in the area with a metal foil wrapped on the outside. These results show a significant relationship between a resonator (metal film) and electromagnetic waves distribution.

In Figure 5, the average simulation temperatures are compared with the experimental data. It shows that the simulated temperatures are lower than the experimental temperatures. These numerical results differ slightly from measurement and can be explained by setting all parameters in calculation. However, it can be noted that the calculated transient temperatures are the same trend with the experiment results. Thus, this model is validated by the results.

3.2 | Effect of a metal film as a resonator

The metal film on the microwaveable package is an important factor in deciding the amount of power absorbed and the heating pattern in the food. This topic explains the effect of a metal film on the average temperature and nonuniformity of sample. The metal film (food grade aluminum foil) is wrapped on the outside of the sample package with different locations and areas. In early works, they have studied on conductance properties considered it to be shielding when the conductance value was more than 0.1 s. For this study, the electrical conductance value of the thin metal film set of 1 s. The metal film will be a shield or resonator. Figure 6 shows a relationship between the average temperature of the sample and the heating time under various

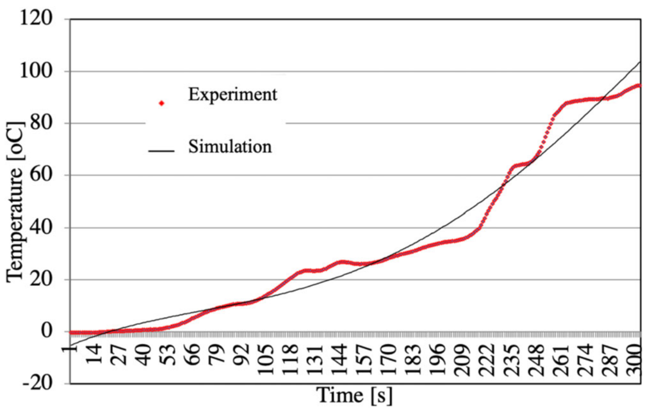


FIGURE 5 Comparison of average temperature results between the simulation and experimental

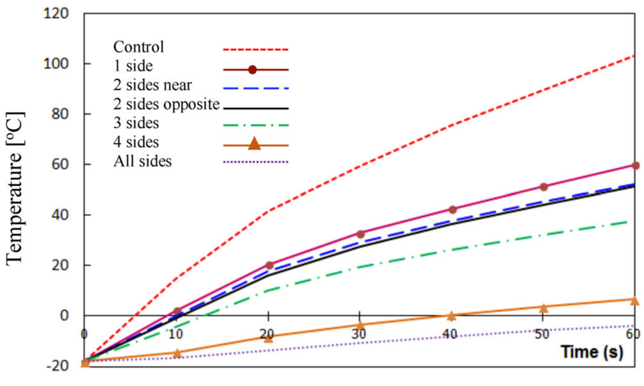


FIGURE 6 The average calculated temperature inside the sample during microwave heating for 60 s at various resonator areas: case of side port

area sizes and the different locations of a metal film. Interestingly, the results reveal the decreasing average temperature with increasing area of the metal film. No substantial differences are found between the case of metal film near two sides (dash line) and the case of metal film opposite two sides (line). These results confirm again in Table 2.

Table 2 summarized the simulation results of power absorption or resistive loss, the temperature distribution inside the frozen rice congee, and the electric field distribution inside the microwave oven at heating time 60 s. First, the power source that produced an electric field in TE_{10} mode is located on the side of the cavity. Then, the electromagnetic wave propagates through the rectangular waveguide. The dominant electric field component within the microwave cavity controls the heating pattern in the food packages. From Table 2, it can be noted that the phase of standing wave within the microwave cavity is the same for all cases. The peak of the electric field happened at the center of the cavity. The maximum temperature is found in the control case (no metal film) and is occurred at the edge of the sample. Conversely, the minimum temperature is shown in the case of wrapped metal film around package (five sides/around). The temperature increases from -18 to -12°C for 60 s. Furthermore, the nonuniformity is likely caused by the effect of the metal film. As detailed in Table 2, the power absorption inside the sample is found uniformly in the case of control and the case of a metal film on opposite two sides. The correlation between the power absorption and the temperature distribution inside the sample indicates the metal film will be a resonator or shielding. The temperature is low at the wrapping metal film area due to the reflection. These results extend our knowledge on reflector type of microwave package. It is important and necessary to know about the properties of the resonator or shield packages that affect microwave heating process. Microwave heating is nonuniformity heating. Thus, the resonator can use in a location that food is heated rapidly and is placed on hot spots to adjust the electric field pattern and eliminated these hot areas.

3.3 | Effect of port power position

This topic plays a crucial role in the effect of port power position on average temperature and nonuniformity of the sample. The port power positions, is located on the side and the top of the cavity, are investigated. Figure 7 shows the simulated distribution of the overall electric distribution (norm of the electric field) and its E_z component within the microwave heating system. They are snapshots of the side views (*x-y* plane) at the middle layer of *z* direction. In Figure 7, the overall electric field distribution is clearly presented as wave crests and troughs. Furthermore, the electric field intensity (E_z) is the dominant electric field component at the middle of the microwave cavity. The electric field distribution in case the top port power position is similar to that in the cavity with side port power position. Electric field distribution determines the heating pattern of the food loads. However, the presence of food may also affect the electric field distribution.

Figure 8 reveals a significant difference between the effect of a metal film and the position of magnetron port. The electrical conductance value set of 1 s. As can be seen in Figure 8, the average temperature of the sample is maximum in the case of control (no metal film), one side, two sides near, two sides opposite, four sides around, and three sides, respectively. The sample temperature in the case of one side of metal film is closed to the control case. Interestingly, the results displays the food samples in a package wrapped with four side metal films are at a higher temperature than that the samples in a package wrapped with three side metal films after the microwave heating process. Because when the wave is emitted from the waveguide, it enters the sample directly and the metal film at the package will trap it. In addition, it is found that the metal film on the bottom of the package would reflect the incident waves, so the temperature of the food in case of around (package is completely covered with metal film) is less than the temperature of the food in a package wrapped with four side metal film.

Figure 9 shows a comparison of the average temperature of food with various metal film areas on the package between two types of microwave systems. The port power is located on top (upper port) or side (side port) of the oven. The microwave power is 800 W,

TABLE 2 Simulates the results of the power absorption, electric field distribution, and temperature during 60 s of microwave heating process

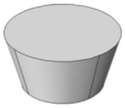
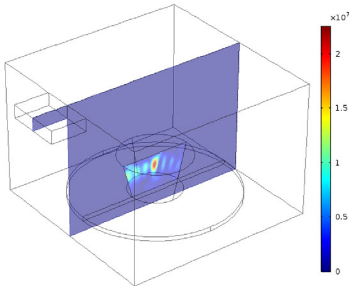
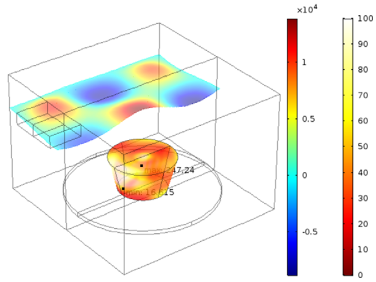
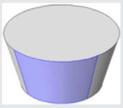
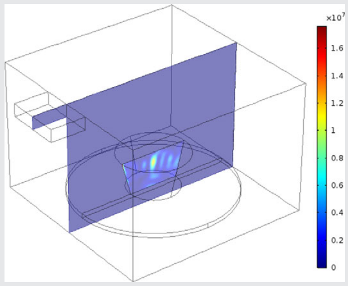
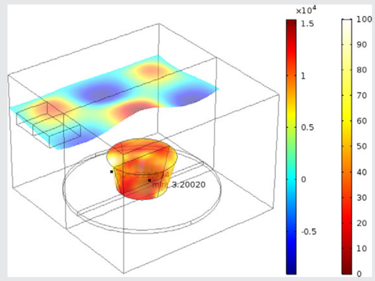
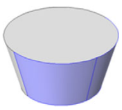
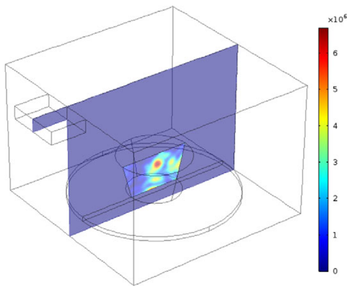
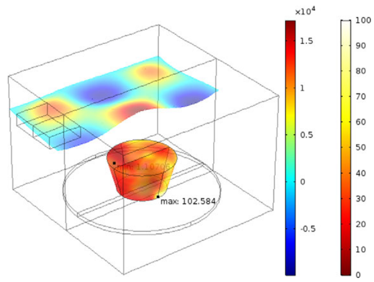
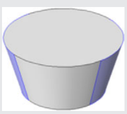
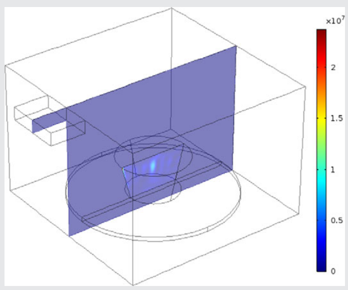
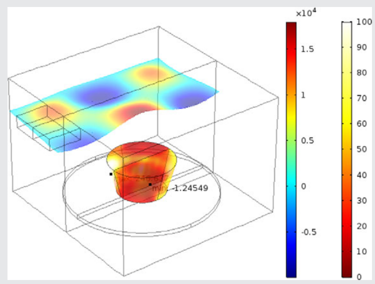
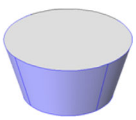
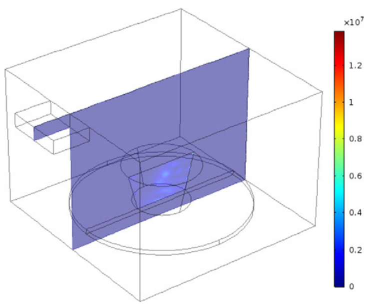
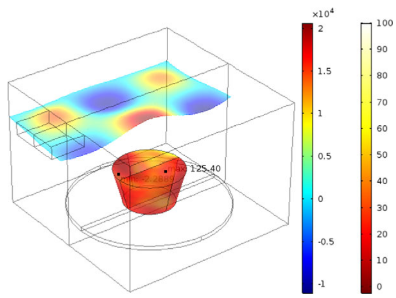
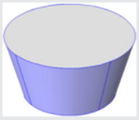
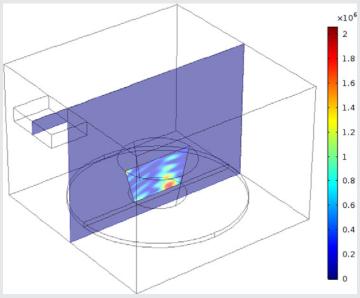
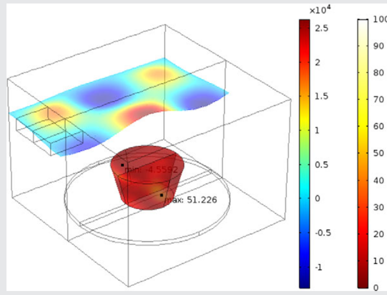
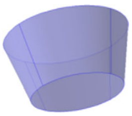
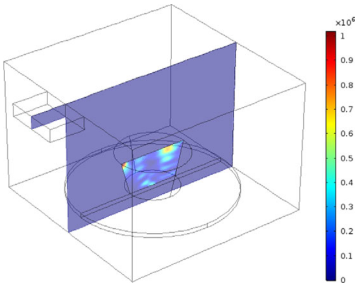
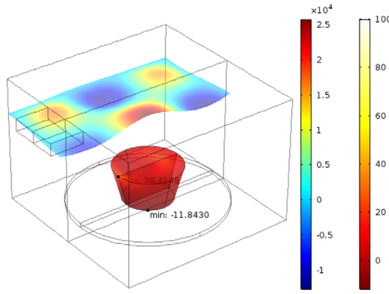
Case	Power absorption (W/m3)	Electric field distribution (V/m) and temperature contour (°C)
 Control (no metal film)		
 One side		
 Near two sides		
 Opposite two sides		
 Three sides		

TABLE 2 (Continued)

Case	Power absorption (W/m3)	Electric field distribution (V/m) and temperature contour (°C)
 Four sides		
 Five sides/around		

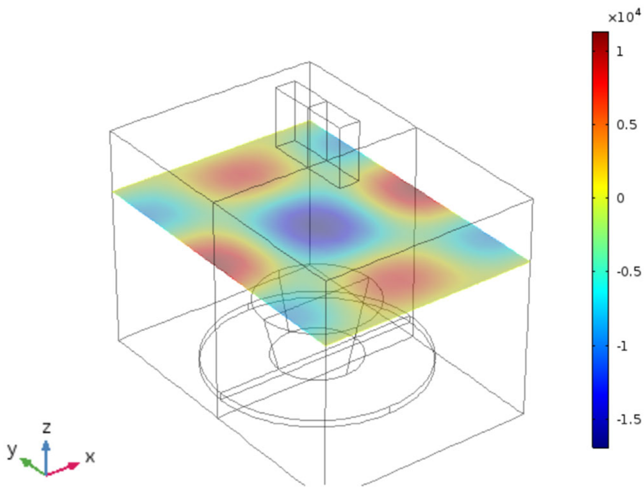


FIGURE 7 The snapshots of electric field distribution at middle layer in z direction of the microwave heating cavity with upper port position

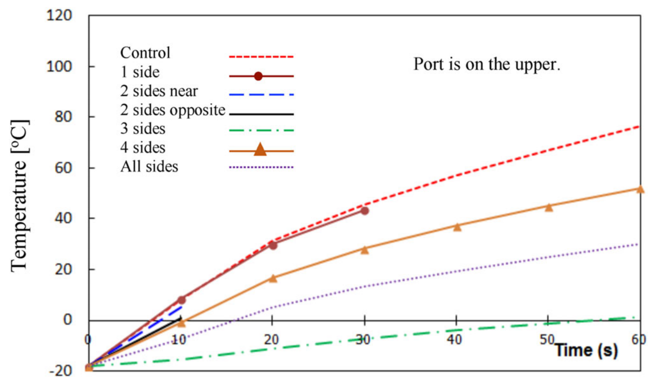


FIGURE 8 The average calculated temperature inside the sample during microwave heating for 60 s at various resonator areas: case of upper port

frequency of 2.45 GHz, and the heating time is 60 s. From Figure 9 for the package case of control, two sides opposite, and three side metal films, it is found that the average temperature of the food in case side port is higher than the average temperature of the food in case upper port. While the package case of one side, two sides near, four sides, and wrapped around with metal film, the average temperature of the food in case upper port is higher than the average temperature of the food in case side port. These results emphasize the importance of appropriate packages for a microwave system.

The simulation results are presented in Table 3; these results show a significant relationship between the power absorption and the

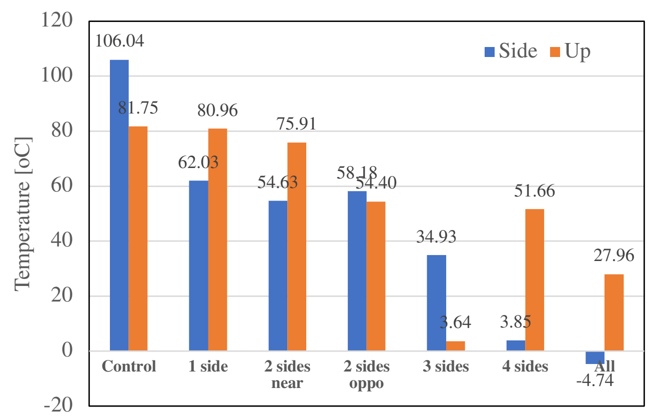


FIGURE 9 The average temperature comparison by waveguide position at various resonator areas after microwave heating process for 60 s

TABLE 3 Simulates the results of the power absorption, electric field distribution, and temperature during 60 s of microwave heating process: case of upper port

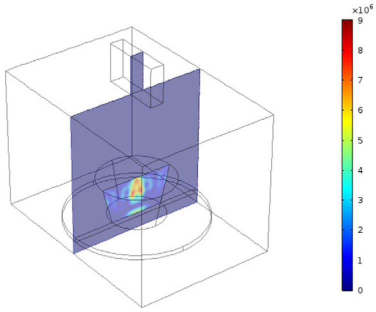
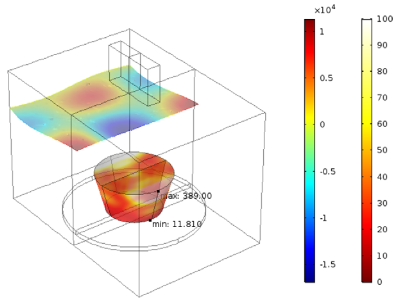
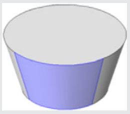
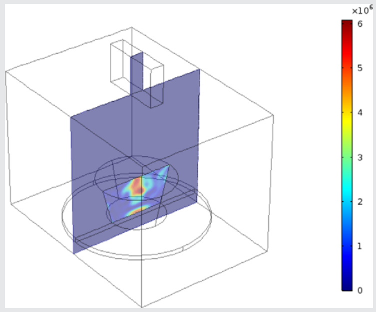
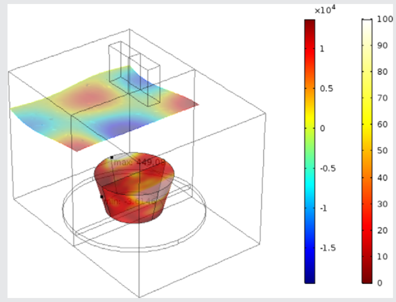
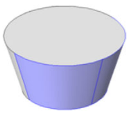
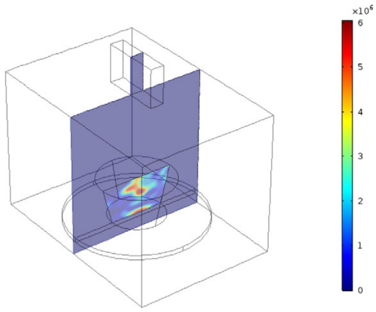
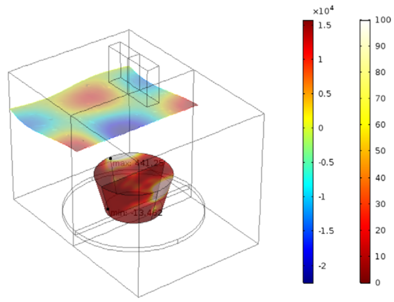
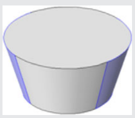
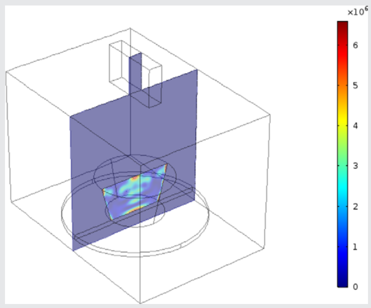
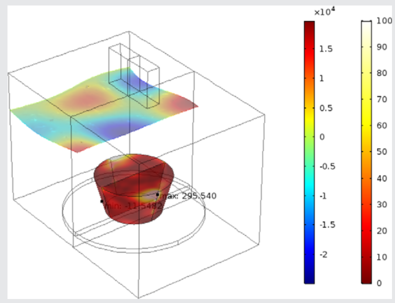
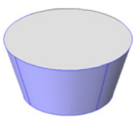
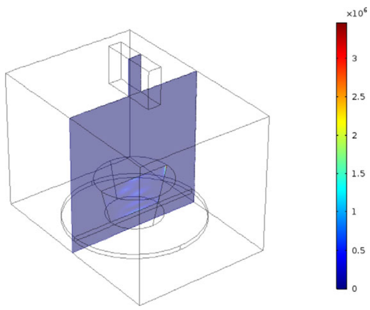
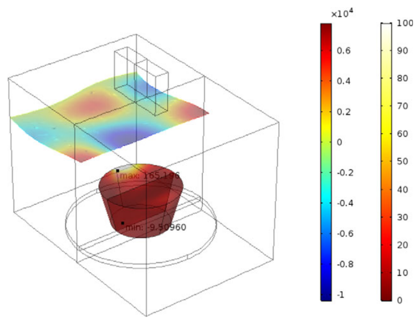
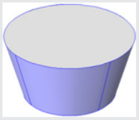
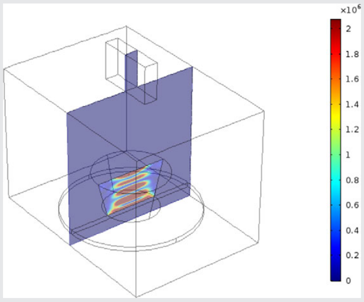
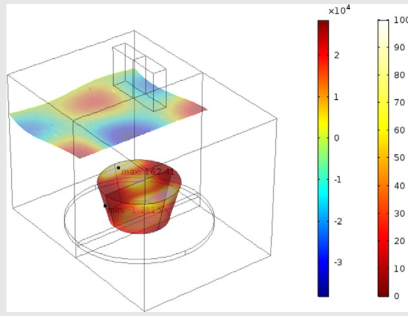
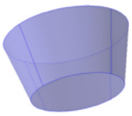
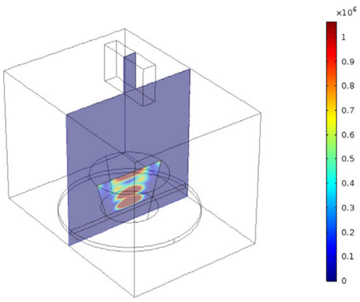
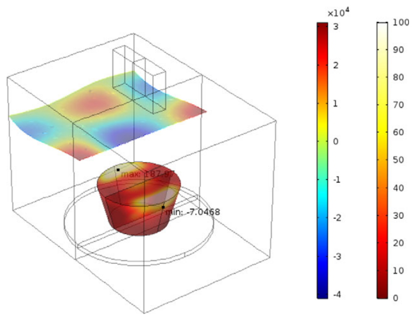
Case	Power absorption (W/m3)	Electric field distribution (V/m) and temperature contour (°C)
 Control (no metal film)		
 One side		
 Near two sides		
 Opposite two sides		
 Three sides		

TABLE 3 (Continued)

Case	Power absorption (W/m3)	Electric field distribution (V/m) and temperature contour (°C)
 Four sides		
 Five sides/around		

temperature contour. The density of microwave power absorbed is related to the electric field and temperature distribution within the sample. Therefore, the sample with high-density power absorption will have high temperature. From Table 3, it can be noted that the incident wave from the waveguide will go directly into the food and reflect from the food with the cavity. Then, the microwave reverts to the food in any direction because the container/package does not have a metal film as a resonator (case of control). As a result, the temperature of the food is rising rapidly and quite uniformly. While the sample food in package with a metal film acting as a resonator occurs physical phenomena following. The metal film will trap the transmitted waves and prevent the reflected wave from entering the sample. For example, the power absorbed value in case of four side metal films is higher than the case of three side metal films. Because the metal film at all sides of package protected the transmitted wave, as results in the wave cannot escape. A surprising relationship is found that a metal film at the bottom of the package reflected the transmitted wave. Thus, the average temperature of food contained in the package (case around) is lower than that of the case four side metal films. This work can be helpful in the knowledge of packaging design with a metal film/resonator suitable for microwave heating systems.

4 | CONCLUSIONS

The electromagnetic wave, heat, and mass transfer model was developed to simulate a frozen rice congee with a metal film package in the microwave heating process. The effects of the metal film as a resonator and port power position were studied. The area of a metal film on the package of frozen congee was separated to five sides (four sides + one side bottom) while the port position was considered at side and top of microwave cavity. The model was validated with experimental measurements. The simulated temperature profile obtained from the food package with one side metal film, side port position, frequency of 2.45 GHz, power of 800 W, heating time 300 s. It was found to be in good agreement with the experimental spatial temperature profile. The average error values ranged from 5 to 10%. The results of this study indicated that the metal film as a resonator did affect the temperature distribution inside the food. The average temperature of the food was low in the area that contacted with of the resonator because the shielding effect. In addition, the average temperature of the food was high for the case of control (no metal film) for both side and upper port position. The validated model was a useful tool to obtain various metal film packages, and port positions of power for improving heating uniformity for both food safety and quality.

5 | RECOMMENDATION FOR FUTURE WORK

Future studies on microwave heating of frozen food with the metal film package are recommended to as follows:

1. This model was validated with single component. However, frozen ready-to-eat foods contain heterogeneous components, and they undergo phase changes during the process. Therefore, it will be necessary to improvise the model to take this factor into account.

2. There are many parameters that affect heating profiles needing to be studied systematically to help food product developers to design foods to minimize food safety concerns.
3. A thin metal film (as a susceptor or resonator) has been used with frozen ready foods to improve the heat transfer effects and evenness of heating food.
4. There should be a database of dielectric and thermal properties of various type of foods. Therefore, food processors could do a virtual microwaveable food product development before they market the product.

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NOMENCLATURE

$\left\|\vec{E}\right\|$	the time-harmonic electric field strength (V/m)
μ_r	relative permeability
ε_r	relative permittivity
ε_0	free space permittivity (8.854×10^{-12} F/m)
f	frequency (Hz)
ε'	dielectric constant
ε''	dielectric loss factor
ρ	density (kg/m^3)
C_p	specific heat capacity at constant pressure (kJ/kg°C)
k	thermal conductivity (W/m°C)
T	temperature (°C) at simulation time t
n	normal to the direction
t	tangent to the direction
h	surface convective heat transfer coefficient (W/m^2°C)
T_{air}	ambient temperature (°C)
Δt	simulation time step (s)
Q	dissipated power per unit volume (W/m^3)

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs.

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