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A Computational Analysis of How the Design of Multicompartment Containers and Placement Angle Affect Heat and Mass Transfer During the Microwave Heating Process

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Abstract

This study aims to use a 3-D coupled model to examine how multicompartment container designs and sample placement angles affect microwave heating uniformity and heating qualities of chilled ready-to-eat food (green curry and rice). To understand the moisture and temperature distribution of chilled ready-to-eat food in multicompartment containers following microwave heating, a simplified electromagnetic, heat, and momentum transfer coupling simulation was developed. The model simulated 50 s of microwave heating of a 280 g sample kept at the center of the cavity in a 1300 W microwave oven. Experiments validated the model. The spatial temperature patterns predicted by the simulation at the top layer were in excellent accord with the corresponding thermal image patterns. Comparing predicted point temperature profiles with experimental temperature profiles at six different points within the sample, RMSE values ranged from 3.6 to 11.2 °C. The results of this study indicate that samples filled in a PG04 container (in a semicircle shape) and placed at an angle of zero between the sample and the port have a high heating rate and uniformity. These findings are useful for designing a food container design strategy, especially for new food items and product packaging that require uniform microwave heating.

Keywords: A 3-D coupled model; Chilled ready-to-eat food; Microwave heating; Moisture distribution; Multicompartment container design.

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1. Introduction

Microwaves are a type of electromagnetic radiation characterized by frequencies ranging from 300 MHz to 300 GHz. When microwaves come into contact with the surface of a dielectric substance, their energy is divided into three distinct components, including the transmitted, reflected, and absorbed components. The conversion of absorbed microwave energy into heat is mostly attributed to the existence of permanent dipoles in electrical materials, resulting in an increase in the energy inside of the load.[1,2] The application of microwaves in food processing has revolutionized the industry by offering numerous advantages in terms of efficiency, speed, and improved food quality such as heating and cooking, pasteurization, sterilization, drying, extraction of compounds *etc*.[3] Microwaves are commonly used for heating and cooking food products, especially chilled ready-to-eat foods, because it is a convenient method for heating them quickly. Chilled ready-to-eat foods often abbreviated as "chilled RTE food," refers to food items that have been prepared, cooked, and packaged for quick consumption without the need for further cooking or heating. These foods are typically stored at refrigerated temperatures below 1oC to prevent potential pathogen growth, to maintain freshness and quality. Bacteria can multiply if they are not properly cooled and stored. Therefore, it is important to follow proper food safety practices when reheating or cooking ready-to-eat chilled foods in a microwave.[4–6] Before consuming chilled ready-to-eat foods, the United States Department of Agriculture (USDA) recommends heating them to a minimum internal temperature of 165°F (74 °C).[7,8] As known, the increase in temperature inside a food product during microwave heating is primarily caused by the absorption of microwave energy by water molecules and their rapid movement, leading to the conversion

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of energy into heat. Many researchers showed that the interactions of food, container, and microwave improved heating uniformity and predicted the hot spot temperature. Several factors can influence the temperature distribution and heating efficiency inside a food product during microwave heating.[9,10] These factors come from three main parts: food (composition,[11–15] dielectric properties,[16–18] geometry,[15,19-22] placement,[15,19,23,24] microwave system (power[24–28]), frequency[23,29] turntable or rotation[30–32]), and package or container design.[33–36] This work concerned in factor of container design, especially multicompartment containers. When placing different foods in multicompartment containers for microwave heating, it is primarily differences in the electric field and dielectric properties at different parts of the food. It is essential to be mindful of their properties and heating requirements to achieve the desired results in terms of both food safety and quality. In addition, the container design is important to consider for optimizing food design to achieve uniform heating.

Microwave food product development is very time-consuming and expensive. Utilizing a computer simulation tool helps shorten the product development cycle and lower production costs. Previous studies[17,25,34,36–39] have documented the utilization of computer-based simulations that integrate electromagnetic and thermal equations to determine the temperature distribution in microwave-heated food products. Because an experimental approach may not be the best way to understand the complex interactions of food components and the package with microwave energy, so simulation can be very helpful. For example, the work of Ref. [40] performed an analysis to develop a theoretical model to improve the energy utilization and quality of multiple specimens heated in a microwave oven. The uniformity of the distribution of state parameters and the concentrative degree were described by the coefficients of variation (COVE, COVT, COVM and COVP), the degree of focusing on the microwave, and the thermal runaway. The specific power absorption coefficient (SPAE) of cylindrical specimens was the best because of energy attenuation. Chen *et al.*[22] developed a simple 1-dimensional analytical model based on the planar wave assumption to predict the average heating rate of a food product and determine the thickness of multicompartment meals. A numeric "vpasolve" solver was used to adjust the thickness of two compartments to improve heating uniformity. A 3-D multi physics based numerical model and experimental microwave cooking were used to evaluate the average heating rate in the original and adjusted food designs. Most of the simulation models in the literature using COMSOL Multiphysics software to calculate the electromagnetic and heat transfer field distribution in sample. As the study by Ref. [33] offers an analysis of the effects of the container design on the heat transfer rate and food quality during microwave heating, which were explored and validated with numerical simulations and experiments. A simulation model was created to understand the moisture and temperature distribution of the pork patties after microwave heating.

In addition, Tepnatim *et al.*[36] developed a three-dimensional mathematical model to simulate the temperature distribution of four ready- to-eat sausages in a plastic package in a stationary and rotating microwave oven. It was validated experimentally and provided good agreement between predicted and actual values. The computational time using COMSOL in combination with MATLAB was reduced by 60%. Orientation was the key factor, and 135 degree was recommended to heat the packaged sausages in a stationary microwave oven.

However, more research is needed to fully understand the complex interactions between container design, food composition, and microwave heating conditions. There are still some knowledge gaps that need to be addressed. These potential topics are as the use multicompartment containers designed to minimize flavor transfer and optimize heat distribution, the arrange foods strategically within the container based on their heating requirements and properties, *etc*. In this work, we used a finite element method-based numerical solver, COMSOL Multiphysics, to simulate the heat and moisture transfer of the different foods in multicompartment containers for microwave heating. The heat transfer model was to be validated with experimental tests in terms of heating patterns and temperature. In addition, the microwave heat transfer model was to be integrated with the transport of diluted species model to monitor moisture transfer for individual compartments or foods. The effects of multicompartment container designs (number, size, shape, gap between compartments) and the laying style of samples in cavities (center, angle between the sample and the port) were studied. The findings of this study can be used to enhance the phenomena that must be considered for food packaging preparation, food safety, and other outcomes and to be a sample for further development in other related mathematical modeling work.

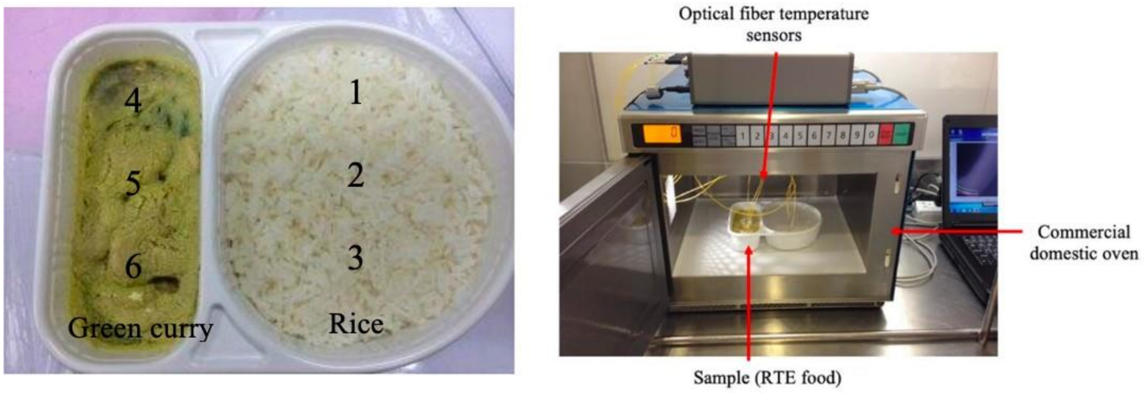
2. Materials and methods

In this work, the microwave heating of chilled ready-to-eat food in a multicompartment container was investigated using mathematical modelling. Results from simulations and experiments were compared. The accuracy of the model was verified in this manner.

2.1 Experimental analysis

2.1.2 Sample preparation

The sample was chilled ready-to-eat food, namely green curry with rice. Green curry is a Thai variety of curry. Green curry sauce is made mainly of green curry paste and coconut milk. The sample included two parts, green curry, and rice that were filled in the polypropylene container (Fig. 1(a)). The sample was purchased from a convenience store in Thailand. Then it was chilled and preserved at 4 °C in a refrigerator until used for the experiments. The nutritional facts on the container were used to investigate the significance of the food composition in



(a) (b)

Fig. 1 Experimental setup (a) Ready to eat food in multicompartment container, and (b) microwave oven testing.

the microwave heating properties (Table 1).

Table 1. Nutrition composition of sample.

Composition	Mass fraction	
	Green curry	Rice
Water (g)	0.85	0.51
Carbohydrate (g)	0.05	0.43
Protein (g)	0.04	0.04
Fat (g)	0.06	0.02
Salt (g)	0.0036	0.000006

2.1.2 Experimental validation

The experimental apparatus for microwave heating was used commercial domestic oven (Panasonics model No. NE1356) with cavity dimensions of 33 × 31 × 17.5 cm and without a turntable (Fig. 1(b),[25]). The sample was placed in the centre of the cavity. During the magnetron experiment, the output was set at 1300 W for 50 s. Temperature was measured using optical fibre temperature sensors (6-channel reflex signal conditioner, accuracy ±0.8 °C, Neoptix Inc., Quebec, Canada) that recorded six different points inside the sample. Then, the thermal image was captured immediately after the heating was finished using an IR camera (SC640, accuracy ±2 °C, 640×480 pixels, FLIR systems, Boston, MA). The experiment was repeated three times to obtain the temperature results.

2.2 Numerical analysis

The model was developed to predict the transport of heat and moisture during the heating process of ready-to-eat chilled food in a commercial domestic microwave oven. Fig. 2 shows the movement and distribution of both heat energy and moisture (water vapor) within a system as it undergoes a heating process. During the heating process, heat energy is added to the sample to raise its temperature. This energy transfer occurs mainly through conduction mechanisms. Moisture refers to the presence of water (blue dot) or water vapor (red dot) within a sample. The movement of moisture is governed by temperature difference. A 3D computer simulation based on the finite element method was built in commercial software named COMSOL Multiphysics 5.3 (COMSOL Inc., Boston, MA, USA). A microwave oven cavity was modified from a commercial domestic microwave oven that was a metallic box connected to a port boundary. Then, it was followed by an unsteady heat transfer simulation to show how the heat was distributed in the sample during the heating process.

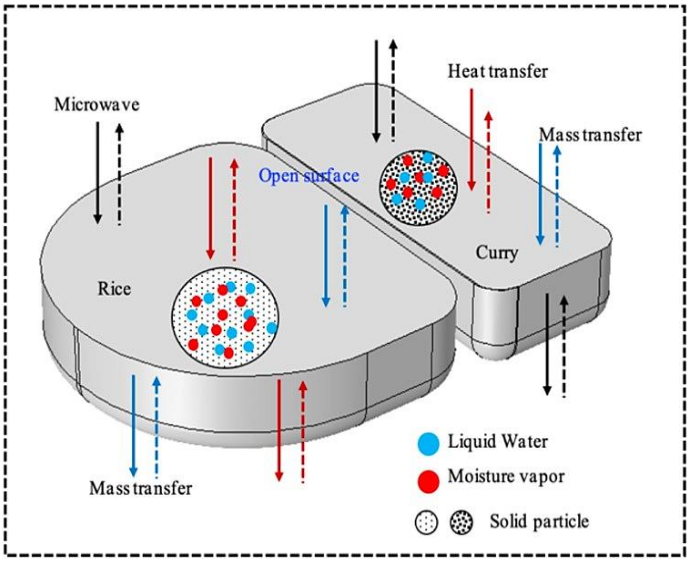


Fig. 2 Domain analysis.

2.2.1 Geometric model

The effects of multicompartment container designs are influenced by factors such as heat distribution, flavor separation, moisture exchange, food safety, user friendliness, stack ability, sustainability, customization options, and heat-resistant features. The specific design features and priorities of a container can result in varying outcomes and benefits for different applications and consumer preferences. The food placement inside the microwave oven is according to the shape of the containers. In this work, Fig. 3 shows the characteristics of the five multicompartment containers selected for study, which are as follows: (1) The container has two parts. (2) The rice was filled in the larger part of the container. (3) The shape of the food in each container is different, but the volume is the same. (4) The gap distance between each part of the container

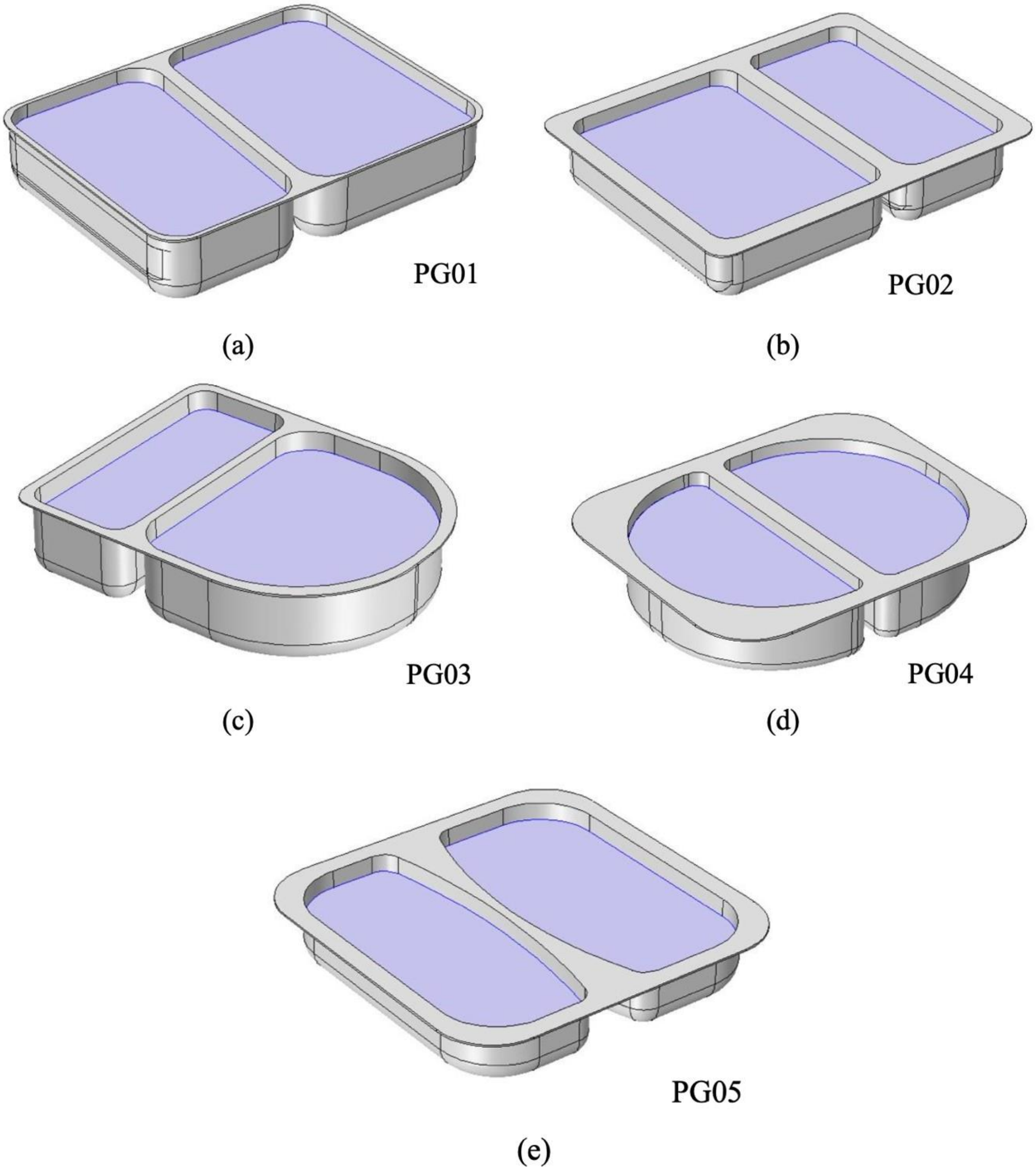


Fig. 3 Various designs of multicompartment containers.

is between 1.00 and 1.50 cm. The following are details for each type of container.

- PG01: Each part of the container has a trapezoidal shape with rounded corners.
- PG02: Each part of the container has a rectangular shape with rounded corners.
- PG03: The smaller part has a rectangular shape with rounded corners and the larger part has a semicircle shape.
- PG04: Each part of the container has a semicircle shape.
- PG05: Each part of the container has a composite shape (rectangular and triangle).

2.2.2 Model assumptions

The following assumptions were made to simplify the microwave heating of chilled ready- to-eat food model as:

1) Heat transfer was not considered in the air and PP tray as a result of the negligible dielectric loss factor.

2) The initial temperature of sample compartments was considered as homogeneous and isotropic.

3) The convective natural heat flux boundary at the food-air interface and air temperature was assumed to be constant at 25 °C.

4) The simulation was performed by considering a single 2.45 GHz magnetron frequency.

5) In this study, a coupling technique was employed to address the simultaneous solution of electromagnetic and heat transfer equations. Specifically, the electromagnetic equations were solved over a specified time interval to determine the power density, which was subsequently utilized as a source term in

the heat transfer analysis.

2.2.3 Analysis of the electromagnetic wave model

The Maxwell's equations were solved to obtain the electric field distribution inside the oven cavity and sample. It was coupled with a multi-physics model to obtain heat and mass transport inside the sample. In this work, the electromagnetic wave or heat source was computed in the stationery and frequency domains because it does not have a turntable. The Maxwell's equation can be written as[25]:

$$\nabla \times \left(\mu_r^{-1} \nabla \times \vec{E}\right) - \left(\frac{2\pi f}{c}\right)^2 (\varepsilon' - i\varepsilon")\vec{E} = 0 \qquad (1)$$

For this work, the dielectric properties were dependent on the chemical composition of the material. In general, the dielectric properties of materials, particularly the water content in food, have a significant impact on how efficiently and effectively a substance heats when exposed to microwaves (FZE, 2018[41]). Dielectric Constant,

$$\varepsilon' = -22.9 + 172.4\,(x_1) + 71.8\,(x_4) - 114(x_1)^2 - 263.4(x_1)\,(x_4) \qquad (2)$$

$$\text{Dielectric Loss factor, } \varepsilon" = 11.243 - 15.69\,(x_4) \qquad (3)$$

where x_1 = Water content, x_1 = Carbohydrate content, x_3=Protein content, x_4= Fat Content, x_5= Salt content.

Microwave loses its energy while travelling through a lossy dielectric medium such as food because the part of microwave energy was converted to thermal energy within the food. It is directly proportion to the dielectric loss factor, the square of the electric field strength, and the frequency of the microwave. The microwave power absorbed (Q) is a heat source term in transient heat transfer and it can be calculated as[25]:

$$Q = \pi . f . \varepsilon^0 . \varepsilon" . \left|\vec{E}\right|^2 \qquad (4)$$

Boundary conditions: The model used copper for the walls of the rectangular waveguide and the oven cavity. Thus, the walls were assumed to be the impedance boundary, where the electromagnetic field penetrated only a short distance outside the boundary.

$$\sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon_r - j\sigma/\omega}}\, \vec{n} \times \vec{H} + \vec{E} - (\vec{n}.\vec{E})\vec{n} = (\vec{n}.\vec{E_s})\vec{n} - \vec{E_s} \qquad (5)$$

In the symmetry case, a part of the sample was cut away for mechanical stability, simulating only half of the problem. The symmetry cut has mirror symmetry for the electric field as follows:

$$\vec{n} \times \vec{H} = 0 \qquad (6)$$

The magnetron generated microwave energy that was transmitted along the rectangular waveguide in TE10 mode at 2.45 GHz into the cavity, which did not change the direction between the broad faces. Thus, the microwave source in TE10 mode was simulated using the following equations.[42]

$$E_z = E_{zin} sin\left(\frac{\pi y}{b}\right) \sin(2\pi f t) \qquad (7)$$

$$H_y = \frac{E_{zin}}{Z_H} sin\left(\frac{\pi y}{a}\right) \sin(2\pi f t) \qquad (8)$$

E_{zin} = the intensity of the input value of the electric field. From the Poynting theorem, the input value of electric field intensity was obtained by the microwave power input as follow:[42]

$$E_{zin} = \sqrt{\frac{4 Z_H P_{in}}{A}} \qquad (9)$$

$$\rho C_p u . \nabla T = \nabla . (k . \nabla T) + Q \qquad (10)$$

2.2.4 Heat transfer and moisture flow model

A 3D multi-physics model was formulated to obtain the heat and moisture transfer inside the sample. The two samples (green curry and rice) were in the same multicompartment container. Heat transfer physics was solved by including a source term obtained from the electromagnetic wave model.[25,33]

Inside the sample, diffusive processes describe both heat transfer and moisture transport. The specific heat capacity was a function of temperature. The moisture diffusion was coupled to the heat equation in two ways: (1) the increasing of thermal conductivity with moisture concentration, and (2) the vaporization of water at the outer surface boundaries generated a heat flux out of the sample.[33]

$$C_p = 3017.2 - 2.05\Delta T + 0.24(\Delta T)^2 + 0.002(\Delta T)^3 \qquad (11)$$

$$k = 0.194 + 0.436\,\left(\frac{C_w}{\rho}\right) \qquad (12)$$

when the temperature reached the boiling point, all the dissipated energy was used to evaporate the water. The continuity equation for the water in the material was written.[33]

$$\frac{\partial C_w}{\partial x} + \nabla . (-D_w \nabla C_w + C_w u) = R_w \qquad (13)$$

And $R_w = \frac{Q}{L}$

This is the simplified evaporation model that has been widely used for the simulation of microwave heating.[33]

Boundary conditions: The top surfaces of the two samples were in the same multicompartment container, which exchanges heat with the surrounding air by convection.

$$\vec{n} . (-k\nabla T) = 0 \qquad (14)$$

$$\vec{n} . (-k\nabla T) = h_c(T_{air} - T) + L\vec{n} . (\mathrm{D}\nabla C_w) \qquad (15)$$

$$\vec{n} . (-D\nabla C_w) = 0 \qquad (16)$$

$$\vec{n} . (D\nabla C_w) = k_c\,(C_b - C_w) \qquad (17)$$

The heat exchange occurring between the air and the sample within a multicompartment container was estimated by making the assumption that the heat transfer coefficient had a value of 10 W/m^2/°C. This value is commonly employed to represent natural convective heat transfer in air. The initial temperature of the sample was 7 °C The dielectric properties as a function of chemical composition, thermal properties (specific heat capacity, thermal conductivity, density, and coefficient of thermal expansion) for air, food, containers, and data computation are shown in Table 2.

2.2.5 Numerical procedures

The microwave heating process of chilled ready-to-eat food in a multicompartment container was a two-way coupling process of multiple physical fields. The equation was solved by COMSOL software, and the calculations predicted the distribution of the electric field inside the oven, the temperature, and the moisture content of the sample. The Maxwell equations for electric fields were solved in the Radio Frequency (RF) module using a generalized minimum residual

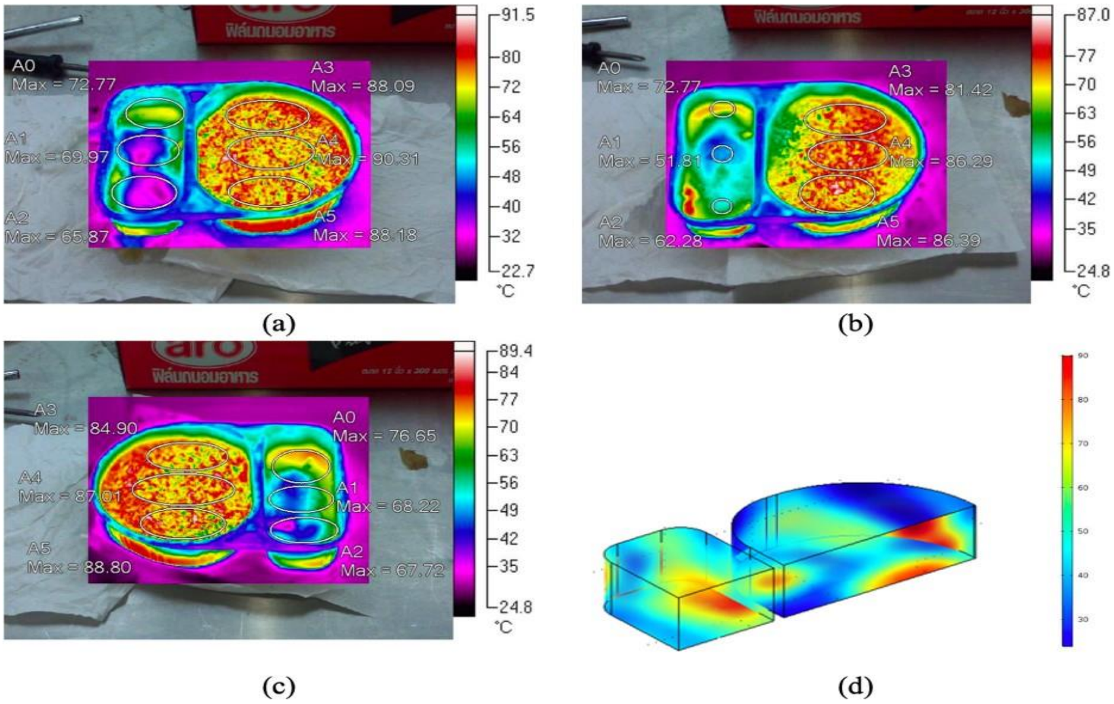
Table 2. Summary of the initial settings of the model and the materials applied.

Parameter	Sample		PP container	Air
	Green curry	Rice		
Initial temperature [°C]	7	7	7	25
Dielectric constant [-]	from ref. [44]	from ref. [44]	from ref. [36]	1
Dielectric loss factor [-]	from ref. [44]	from ref. [44]	from ref. [36]	-
Specific heat capacity [$kJkg^{-1}{}^{o}C^{-1}$]	from ref. [33] & [44]	from ref. [33] & [44]	from ref. [36]	-
Density [kgm^{-3}]	from ref. [33] & [44]	from ref. [33] & [44]	from ref. [36]	-
Thermal conductivity [$Wm^{-1}{}^{o}C^{-1}$]	from ref. [33] & [44]	from ref. [33] & [44]	from ref. [36]	-

solver (GMRES) to calculate the heat generation, which was then coupled with the solved energy balance equations (Heat Transfer module). Finally, it was used to solve momentum and continuity equations (Transport of Dilute Species module). The energy and mass balance equations were solved with a parallel direct linear solver (PARDISO). This work used the mesh size according to the general rule for all objects (cavity, waveguide, food, container). To guarantee accurate approximation and prevent unnecessary computer memory usage, a convergence study as a function of mesh size was also carried out. The COMSOL simulation models consisted of 1 068 344 elements. The COMSOL computer simulations are run on a personal computer (Intel i6- 4200U, 16 GB RAM, Windows 10 (64-bit system) for 50 s microwave heating. The average total computation times were 65 min, 16 s (full model), and 20 min (half model).

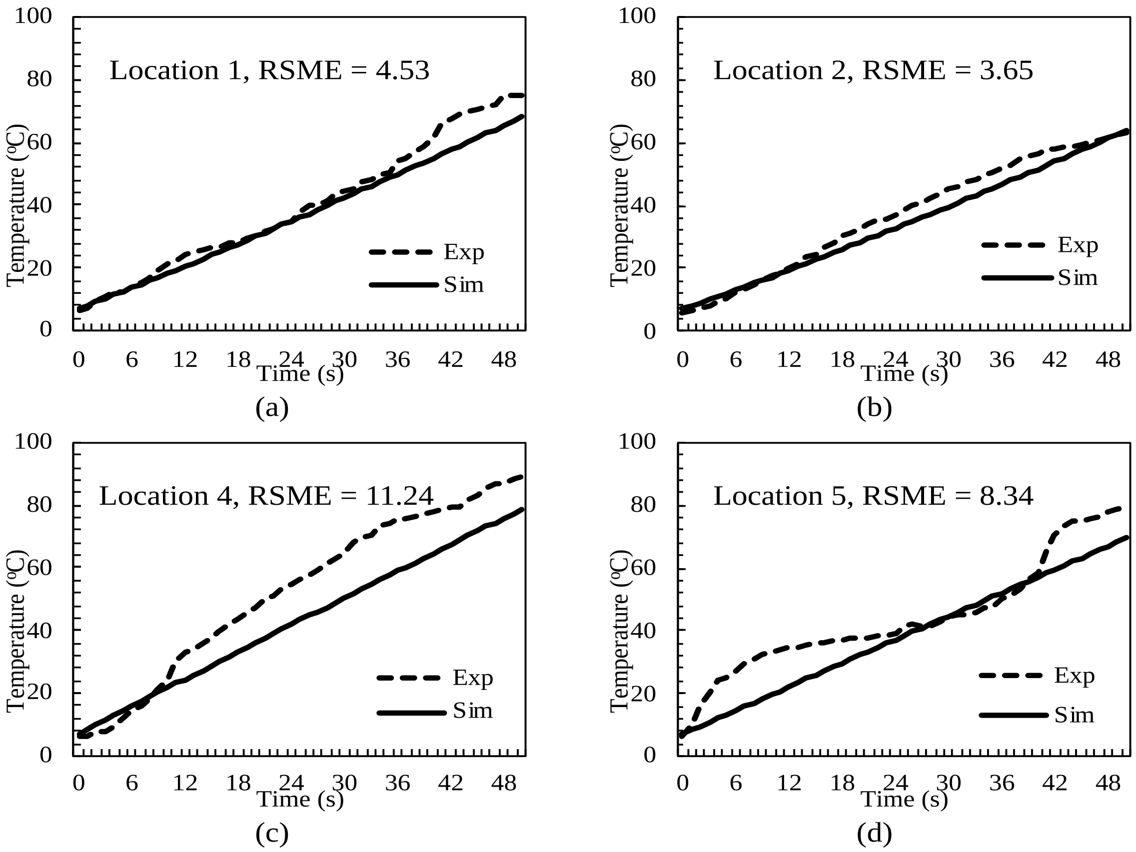
3. Validation of the model

The accuracy of the model was measured by comparing the difference between the temperatures that were simulated and those that were actually measured at different places over time. The thermal image was compared with the simulated temperature profile for 2.45 GHz and root mean square error (RMSE) was calculated.[30,43] Two samples, including rice (low dielectric constant but high porosity material) and green curry (high dielectric constant but low porosity material), were filled in multicompartment containers (PG03) for validation case. The sample was placed at the center of the microwave cavity and at 0-degree angles with the power port. Fig. 4 shows three duplicates of experimental and simulated transient temperature profiles at six locations. The simulation temperature of the chilled ready-to-eat food was compared with the thermal image of the sample for 50 s of the microwave heating process. It was found that the maximum temperature occurred at the edge of the sample, close to the container. While the minimum temperature appeared in the middle of the sample. Additionally, the simulated temperature was lower than the measured temperature. For this study, the main reasons contribute to the temperature difference observed between simulation and measurement. First, the properties of materials used constant in simulation, such as thermal conductivity and heat capacity. The actual properties of the sample were related to the temperature of the sample during the heat transfer process. Second, the model assumptions as the material's thermodynamic behavior was anisotropic rather than isotropic. However, the simulation model was thought to



(a) (b) (c) (d)

Fig. 4 Comparison of the surface temperature profiles of sample heated for 50 s in a 1300 W microwave oven in both simulation and experiment.



(a) (b) (c) (d)

Fig. 5 Simulation and averaged experimental time-temperature profile at different locations of samples subjected to 50 s of heating in a 1300 W microwave oven.

suit the experiment well. The simulated results were agreement with measured data. Fig. 5 shows comparing of simulated transient temperature and average transient temperature profiles at location 1 (edge of rice), location 2 (center of rice), location 4 (edge of green curry), and location 5 (center of green curry). The RMSE values in green curry were higher than in rice. The RMSE was calculated using average experimental time temperature profile in comparison with simulated time temperature profile for each location.[30] Thus, it is difficult to consistently retain probe placements and the ensuing consistency in spatially specific measurements during heating can be blamed for some of the mistakes in model predictions. This is really the largest obstacle to employing fiber-optic probes for real-time temperature measurement while microwave heating since even a tiny movement or change in the placement of the probes in the sample might have a significant impact on the temperature that is detected. However, the developed model was able to predict the thermal behavior of food with different properties in the multicompartment container subjected to the microwave heating process with an error range of 5–15%.

4. Results and discussion

4.1 Electromagnetic distribution and electromagnetic power loss density

Figure 6 shows the section plot of the distribution of the electromagnetic field and the power density through the middle of the microwave oven and in the sample, respectively. It is necessary to compute the power density beginning with the electromagnetic field configuration to calculate the temperature change inside the sample during microwave heating. A high-power density was appearing on the edge of

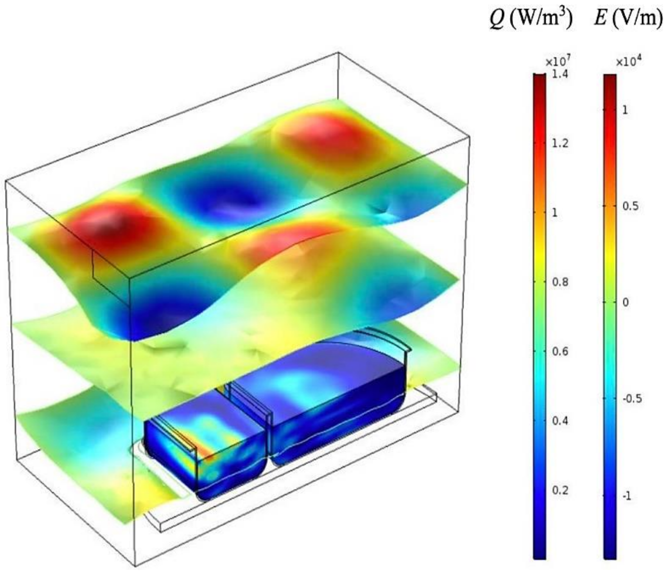


Fig. 6 Distribution of the electric field (E) and electromagnetic power density (Q) inside the microwave oven at 2.45 GHz and 1300 W.

the sample. This is because 1) the sample was placed where the microwave energy was more concentrated, and 2) when microwaves encounter the outer edges of the food sample, they may undergo refraction. Furthermore, the outer edges of the food have a larger surface area exposed to microwave energy. As a result, this phenomenon can lead to the formation of localized hot spots along the food's periphery. In addition, from Fig. 6, the electromagnetic power loss density inside the food corresponds to the electric field distribution inside the microwave oven.

4.2 Effect of various design multi-compartment containers

The design of multicompartment containers have several effects, particularly in the context of microwave heating and food preparation. Containers that are well designed provide more consistent heating and moisture retention, lowering the risk of overcooking or drying out specific food sections. For this study, a total of 5 styles of multicompartment containers were studied, with all 5 styles giving the food different shapes. The green curry was filled in a compartment that was smaller than the rice compartment for every different design of multi-compartment containers. Rice was in a rectangular shape in PG01, PG02, and PG05, while in a semicircle shape in PG03 and PG04. Green curry was in a rectangular shape in PG01, PG02, PG03, and PG05, while in a semicircle shape in PG04. Figs. 7 to 9 show the significant effects of various multicompartment container designs on the microwave absorption and conversion of microwave energy within the sample. The sample was placed at the center of the microwave cavity and at 0-degree angles with the power port.

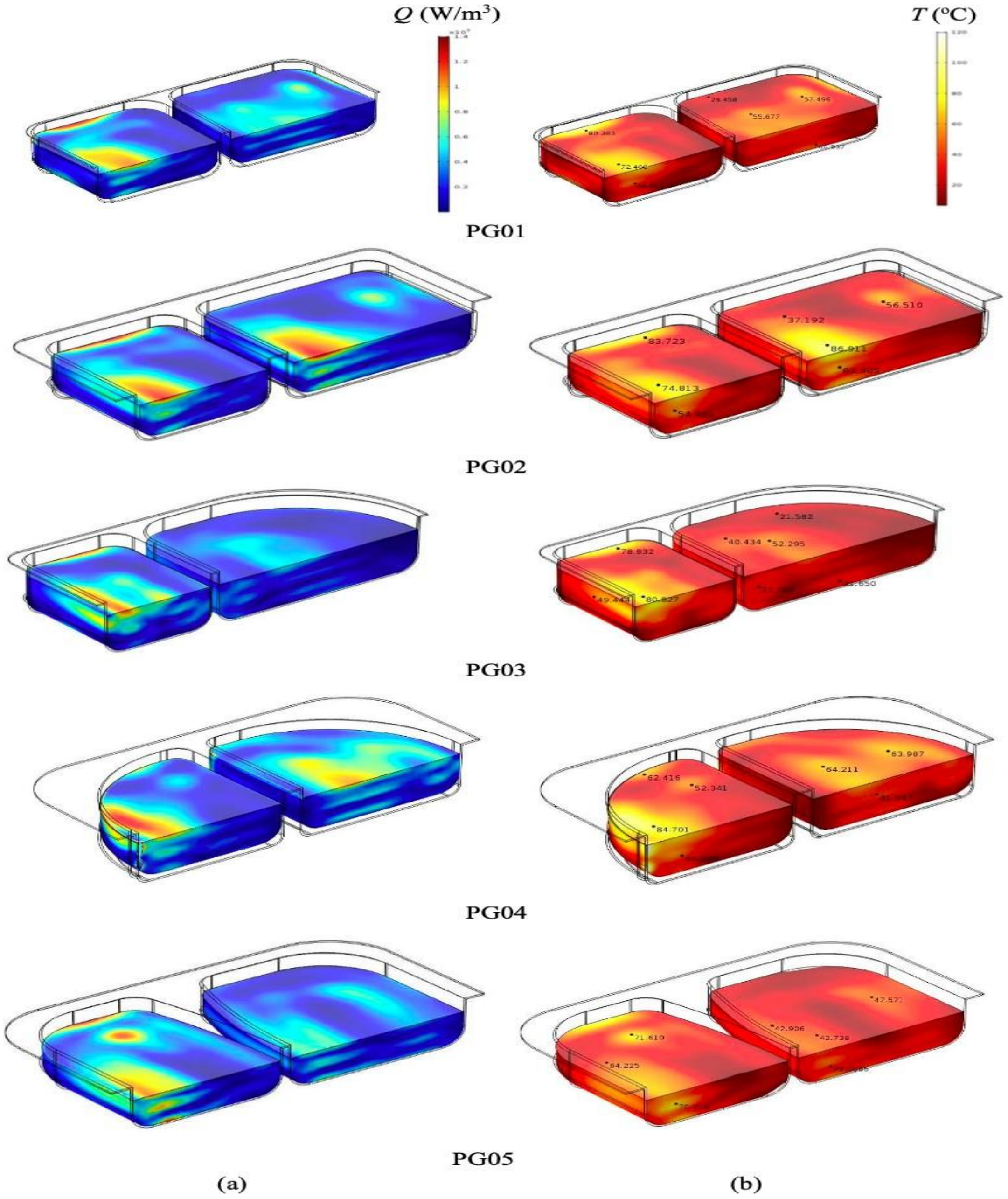


Fig. 7 Simulated phenomena inside the sample within different designs of multicompartment containers subjected to microwave 50 s, 2.45 GHz, 1300 W: (a) Electromagnetic power density(Q) and (b) Temperature distribution (T).

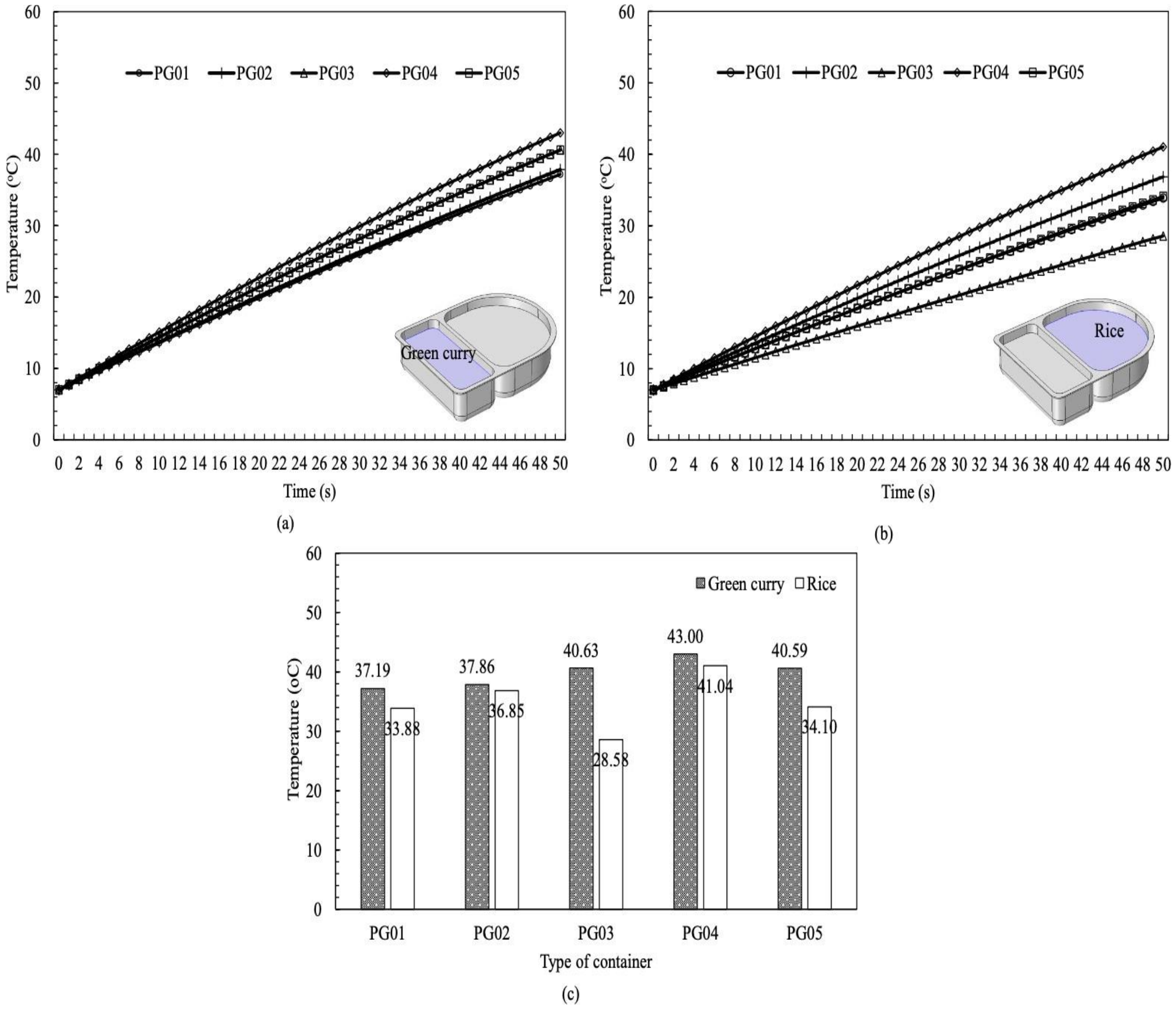


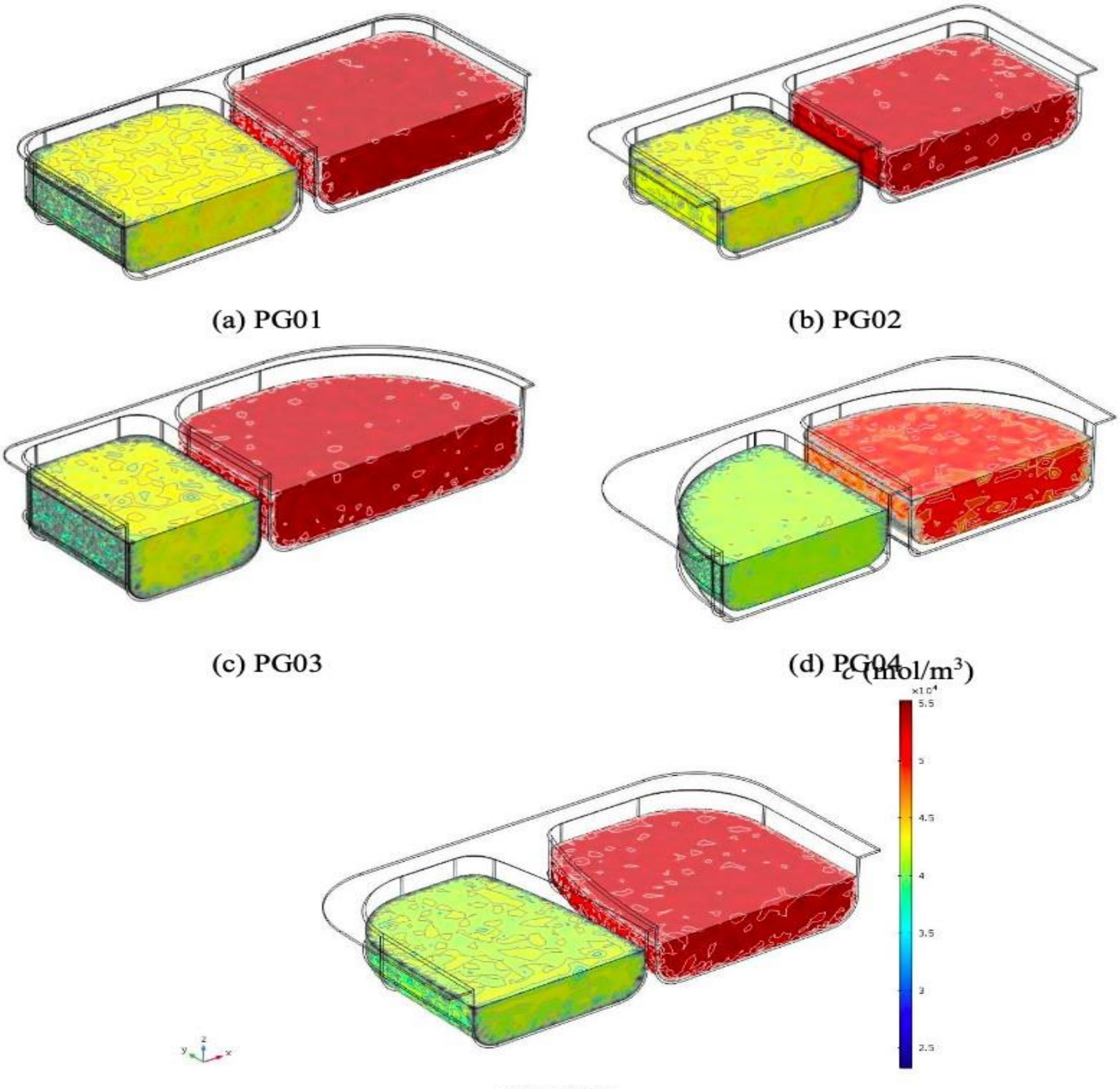
Fig. 8 Simulated transient temperature profile of sample within different designs of multicompartment containers subjected to microwave 50 s, 2.45 GHz, 1300 W: (a) green curry (b) rice and (c) final temperature comparison.

The spatial electromagnetic power density distributions and temperature profile obtained from simulations as a section plot through the center of the sample (green curry and rice) after 50 s, 2.45 GHz, and 1300 W of microwave heating are shown in Figs. 7(a) and 7(b), respectively. As can be seen in Fig. 7, the electromagnetic power loss density corresponds to the temperature distribution within the sample. When microwave energy penetrates the sample, the green curry absorbs more microwave energy than rice. This is because green curry has higher dielectric constants and shallower penetration depths for microwaves, meaning that the microwaves are absorbed and converted into heat more effectively within a shorter distance from the surface of the sample. Further investigation showed that non-uniformity of heating within rice and green curry during microwave heating occurred in all various multicompartment containers, but the sample in PG04 container (rice and green curry were in a semicircle shape) had the least uneven temperature. These results show a significant relationship between the design of multicompartment container and hot spot formation. Transient temperature profiles were simulated inside green curry and rice, as seen in Figs. 8(a) and 8(b), respectively. From Figs. 8(a) and 8(b), it can be noted that the temperature of the sample increases with time during the heating process at 50 s, 2.45 GHz, and 1300 W. The increase in temperature during the heating process is a consequence of energy transfer from the heat source (electromagnetic energy) to the sample, leading to an increase in the kinetic energy of the particles within the sample. The simulated transient temperature profiles were found to be higher to lower in the cases of PG04, PG03, PG05, PG02, and PG01, respectively, for the green curry and PG04, PG02, PG05, PG01, and PG03, respectively, for the rice. Fig. 8(c) displays the difference in temperature of green curry and rice in various designs of multicompartment containers at 50 s. In this figure, it was found that there was not much of a temperature difference between green curry and rice for PG04. In this study, the transport of species (liquid water, water vapor, and air) inside the food during the microwave heating process has a considerable effect on the accuracy of the model. The temperature distribution and moisture content distribution were constantly calculated using the electronic module, heat transfer module, and momentum transfer module. Fig. 9 shows the distribution of the simulated moisture content of the sample within different multicompartment containers during the microwave heating process at 50 s, 2.45 GHz, and 1300 W. In Fig. 9, the pattern found here corresponds to that of the distributions of the electromagnetic power density and the temperature profile. The initial moisture concentration of rice was higher green curry, but the diffusion coefficient of green curry was higher rice. In addition, the green curry was placed where the microwave intensity was high. Therefore, this made the flow of moisture in green curry obvious.

Overall, these results indicate that the PG04 container (rice and green curry were in a semicircle shape) was advantageous in maintaining the uniform quality of the chilled ready-to-eat food after heating. These findings add substantially to our understanding of how the design of the container impacts how heat and moisture are distributed during microwave heating. Microwave containers are designed to hold food and allow it to be heated in a microwave oven. Thus, to achieve uniform heating, microwave containers do not absorb microwaves and do not release any harmful substances during heating. Special designs and features may be included to further enhance the heating process and prevent moisture buildup. However, there are several variables, especially the angle of the sample and power source, that affect the relationship between microwave power absorption and temperature.

4.3 Effect of the angle between the sample and the port

In the case where the microwave oven does not have a rotation system, the position of the food and power supply is important to consider because the position of the hot or cold spots of the standing wave may be missed. This work studied the effect of position angle (between the sample and the power source) on temperature prediction at five different angles: 0, 45, 90, 135, and 270 degrees. This effect was studied only in the case of a



(a) PG01 (b) PG02

(c) PG03 (d) PG04

(e) PG05

Fig. 9 Moisture transfer inside the sample within different designs of multicompartment containers subjected to microwave 50 s, 2.45 GHz, 1300 W.

sample within a multicompartment container with the best temperature distribution. According to the study findings in Figs. 7 to 9, the sample within PG04 and placed at the center contained the appropriate quantity of microwave power and uniformity in heating. The microwave heating conditions were 2.45 GHz, 1300 W, and 50 s. The results of the study are shown in Figs. 10 and 11.

Figure 10 shows the moisture profile, electromagnetic power density, and spatial temperature profile inside the sample at different angles subjected to microwaves at 50 s, 2.45 GHz, and 1300 W. The characteristics of moisture transfer correspond to microwave power absorption and temperature distribution. The region absorbs a significant amount of energy because it is an area with high electromagnetic field intensity, resulting in high temperatures as well. From Fig. 10, it can be noted that large hot spots formed at angles of 0, 45, or 135 degrees. Furthermore, it was found that the simulated energy absorption and temperature distribution were similar for the cases of 90 and 270 degrees, but the moisture transfer had different characteristics. Fig. 11 displays the time-averaged temperature profile of the sample within the PG04 container at different angles subjected to microwaves at 50 s, 2.45 GHz, and 1300 W. Fig. 11 shows an increase in temperature with time during the microwave heating process. The simulated transient temperature profiles were found to be higher to lower in the cases of 45, 0, 90, 270, and 135 degrees, respectively, for the green curry and 135, 90, 270, 0, and 45 degrees, respectively, for the rice, as seen in Figs. 11(a) and 11(b). Fig. 11(c) displays the difference in temperature of green curry and rice in various angle of multicompartment containers at 50 s. In this figure, it was found that there was not much of a temperature difference between green curry and rice for 0 degree. The results in Figs. 10 and 11 indicate that the sample was filled in a PG04 container with a 0o angle of placement inside a microwave oven, which was advantageous for maintaining the uniform quality of the chilled ready-to-eat food after heating.

Therefore, it can be concluded that the angle at which a sample is placed inside a microwave oven can significantly affect the uniformity of heating. The microwave radiation in a microwave oven is distributed in a specific pattern, which can result in uneven heating of the sample if it is not placed in the optimal position. The angle of placement of a sample inside a microwave oven is one of several factors that can affect the

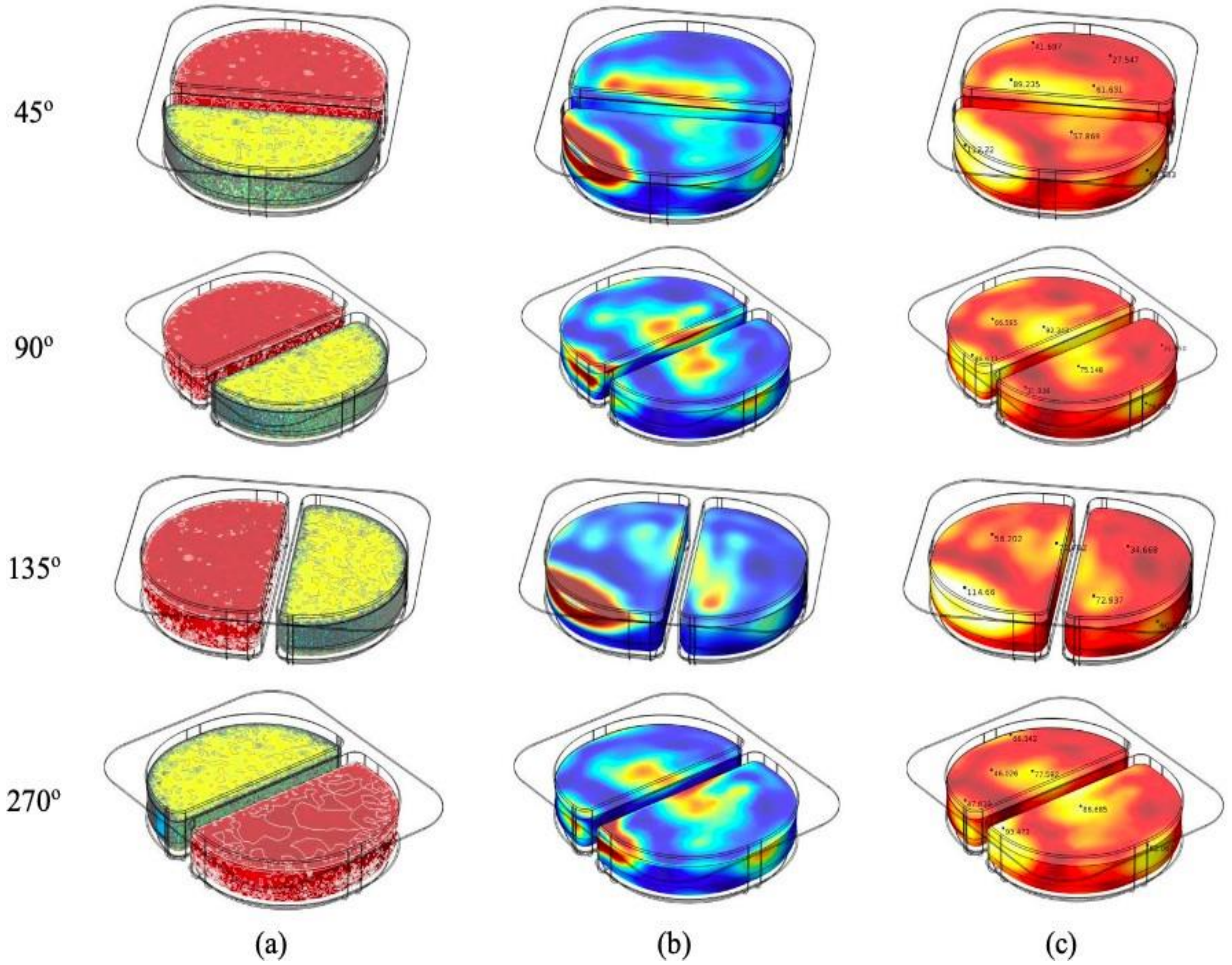


Fig. 10 Simulated phenomena inside the sample at different angle between the sample and the port subjected to microwave 50 s, 2.45 GHz, 1300 W: (a) Moisture transfer (b) Electromagnetic power density and (c) Temperature distribution.

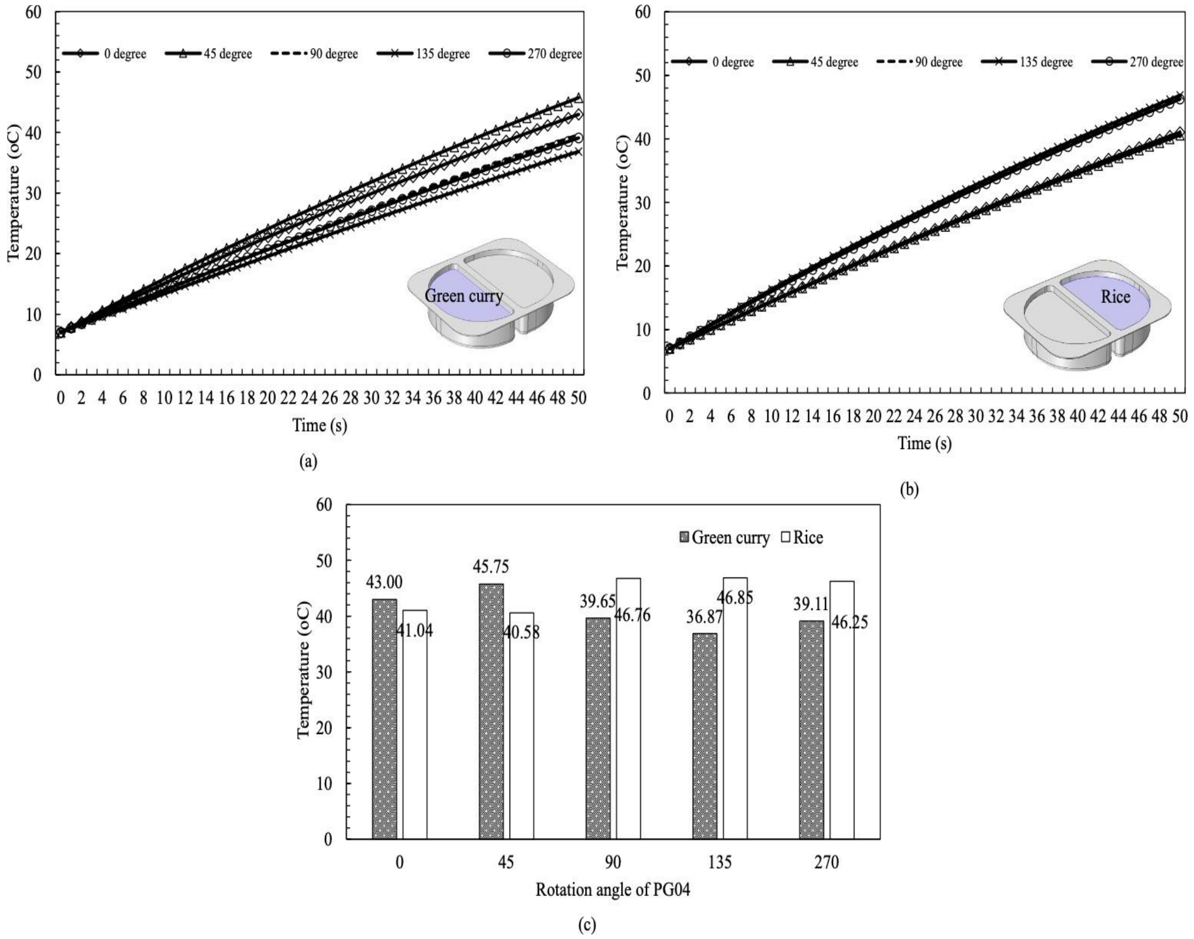


Fig. 11 Simulated transient temperature profile of sample at different angle between the sample and the port subjected to microwave 50 s, 2.45 GHz, 1300 W: (a) green curry (b) rice and (c) final temperature comparison.

uniformity of heating. It is important to consider all these factors and experiment with different cooking methods to achieve the best results.

4. Conclusions

Electromagnetic field distribution within a microwave oven, heat, and mass transport of chilled ready-to-eat food during the heating process were studied by developing a 3-D coupled model. The effects of different designs of multicompartment containers and different laying styles of samples (angle between sample and port power) on microwave heating uniformity and heating properties were investigated. According to the results covered by this study, it was determined that the chilled ready-to-eat food (green curry and rice) was filled in a PG04 container with a 0-degree angle of placement inside a microwave oven to achieve heating uniformity. In general, the findings determined within the scope of the study were the following.

- The temperature of green curry (high dielectric constant) was higher than rice in every multicompartment container design.
- The sample in semicircle shape (within PG04 container) has a uniform temperature distribution.
- The sample placed at an angle of zero between the sample and the port has a high heating rate and uniformity.

Consequently, it is a useful tool for planning and monitoring the microwave heating process. The primary benefit of this strategy is that the product composition does not need to be altered to achieve the necessary uniformity of the temperature and moisture distribution. These findings might be utilized to build a container design strategy for the food sector, particularly for the development of new items and product packaging.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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