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Analysis of Electromagnetic Interactions of Foods in a Microwave Oven

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This study presents an electromagnetic (EM) model of food placed inside microwave ovens, aiming to optimize cooking processes by thoroughly understanding the food-microwave energy interaction. Investigated the microwave heating characteristics of three common food items: Potato, Meat, and Pizza. The analysis focused on the relationship between Microwave Power (Watts), internal Electric (E) and Magnetic (H) Fields, and Volume Loss Density (VLD). Simulations were conducted across six varying microwave power levels (1000 to 2000W) and two distinct food placement positions (center and edge). A linear correlation was observed between increasing microwave power and all measured electromagnetic and thermal parameters. Significant differences in energy coupling were found across the food types. Potato and Meat demonstrated superior heating efficiency, exhibiting VLD values up to 8.0 x 107 W/m^3, compared to Pizza, which only reached 4.9 x 10^7 W/m^3. This difference is attributed to material-specific dielectric properties, particularly high moisture content. The optimal heating position was found to be highly dependent on the food type: VLD was maximized at the center for both Meat and Potato, but maximized at the edge for Pizza. Furthermore, the position that yielded the highest or field often did not correspond to the position with the highest VLD, demonstrating that heating is a result of complex coupling. Analysis of the S_{11} parameter confirmed that efficient heating requires minimal reflection and good impedance matching. The findings underscore the necessity of a material-specific approach to microwave processing. We conclude that achieving uniform and efficient heating requires precise control over both microwave power and food placement, tailored to the unique dielectric properties of the item. This study provides quantitative data for optimizing power settings and food placement to enhance cooking consistency, improve food quality, and promote energy efficiency. The model holds promising implications for integrating advanced cooking control into smart kitchen appliances.

Keywords: Microwave, Food, Cooking, Electromagnetic, Volume loss density, Dielectric properties

1 Introduction

Microwave ovens have become a vital part of modern kitchens, providing quick and convenient cooking solutions for a wide range of food items. However, the optimal cooking time and power settings for various dishes remain a common challenge, often resulting in undercooked or overcooked meals. The microwave oven has ability to rapidly heat and cook a wide variety of dishes. The challenges of achieving precise and consistent results in microwave cooking persists, driven by the complex interaction of microwave energy, food properties, and heat transfer. This paper presents an innovative approach to microwave cooking that highlights the electromagnetic interactions of food, with the goal of understanding microwave heating and improving cooking outcomes. This study is also useful to gain a deeper understanding of the microwave cooking process and use this knowledge to develop a predictive model that considers not only the food properties but also the time-dependent heat distribution within the microwave cavity. Computational fluid dynamics (CFD) simulations were employed to design an innovative heating oven, hinting at the potential of advanced modeling techniques for cooking appliances[1].Study of temperature changes in food cooked within flatbed microwave ovens, providing essential insights into the intricacies of heat distribution within the cavity[2]. Developed the modeling of heat and mass transfer during microwave heating, particularly in the context of frozen foods rotated on a turntable, revealing the need for comprehensive models to account for various factors[3]. Explored the issue of moisture loss in relation to heating uniformity in microwave processing, underscoring the importance and effects of food properties on microwave cooking outcomes[4]. Employed a two-dimensional finite difference model to predict temperature profiles during microwave heating, focusing on foods with finite cylinder geometry, a crucial factor often overlooked in traditional microwave cooking models[5]. Developed

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*Corresponding author: E-mail: umesh.chavan@vit.edu into the intricacies of simulating micro-wave processes, underscoring the significance of advanced modeling techniques in understanding and optimizing microwave cooking[6].

Moreover, researchers[7]have significantly contributed to the field by developing finite element models of heat and mass transfer in food materials during microwave heating. This work provided invaluable insights into the intricacies of microwave heating, highlighting the importance of comprehensively modeling these processes. Extended these insights by conducting finite element analysis of microwave heating for solid foods, contributing to a deeper understanding of heat distribution during the cooking process[8]. Focused on modeling and simulating microwave heating of foods under varying process schedules, emphasizing the need for adaptable and versatile models to cater to different cooking scenarios[9].Another field explored was cake baking, understanding of alternative carbohydrates for potential sucrose replacement was explored[10]. The work focused on developing a predictive model for baking cakes, demonstrating the potential for precise and adaptable cooking models[11]. Examined the transient model of a professional oven, shedding light on the intricacies of heat distribution within ovens. This approach allows to capture the dynamic changes in food temperature during microwave heating, providing insights into the evolution of temperature profiles within the food item[12]. In the context of microwave heating, conducted a computational analysis of temperature distribution in microwave-heated potatoes[13]. Analyzed heat and mass transfer during microwave drying of food products, unveiling fundamental principles of heat transfer in microwave environments[14]. Finite element analysis has also played a pivotal role in the study of microwave heating. Employed this technique to analyze the transient temperature profiles of microwave-heated potatoes, providing invaluable insights into the dynamics of microwave cooking[15].The study[16,17]shows the practical application of HFSS (High-Frequency Structure Simulator) for simulating microwave devices and predicting device performance and behavior. While existing literature has widely covered transient thermal analysis, heat and mass transfer models, and the application of Finite Element Analysis (FEA) to microwave heating, a comparative study analyzing the combined influence of six discrete power levels (1000 to 2000 W) and two different tray positions (center vs. edge) across three distinct food types (potato, pizza, and meat) using a validated EM solver like ANSYS HFSS is lacking. This study uniquely quantifies the specific electromagnetic field distribution and resulting volume loss density for each power/position/food combination, providing highly actionable insights for developing smart, predictive cooking algorithms.

2 Electromagnetic Fields

The differential form of Maxwell's equations is widely used to solve electromagnetic boundary-value problems[18,19]. Gauss's law for electric fields (electrostatics) is given by Eq. (1). This signifies that the electric flux out of any closed surface is proportional to the total electric charge enclosed by that surface, divided by the vacuum permittivity εo. The electric field E, the electric charge density ρ.

$$\nabla . E = \frac{\rho}{\varepsilon_o} \quad \ldots (1)$$

Gauss's law for magnetic fields (magneto statics) is given by Eq. (2) represents the divergence of the magnetic field intensity H, which is zero, implying that there are no magnetic monopoles (isolated magnetic charges).

$$\nabla . H = 0 \quad \ldots (2)$$

Faraday's law of electromagnetic induction is expressed by Eq. (3). States how a changing magnetic field B induces an electric field E. It shows how a time-varying magnetic field generates an electric field and induces electric currents.

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad \ldots (3)$$

The Ampere–Maxwell law, given by Eq. (4), relates the curl of the magnetic field intensity H to the current density J and the rate of change of the electric field E. This demonstrates that electric currents and changing electric fields contribute to the generation of magnetic fields.

$$\nabla \times H = J + \varepsilon_o \frac{\partial E}{\partial t} \quad \ldots (4)$$

The equation describing the energy balance for heat transfer within food due to microwave heating, considering the internal generation term from microwave absorption, can be expressed in a simplified form as follows[9].

$$\frac{\partial U}{\partial t} = \nabla . (k\Delta T) + \sigma . E_{abs} \quad \ldots (5)$$

Microwave heating of food is volumetric. The heating power depends not only on the power source but also on the food materials. In microwave heating, the power absorbed by food is generally expressed as follows[20-24].

$$P(x,t) = 0.5\omega\varepsilon_o\varepsilon''E^2 \qquad \dots (6)$$

where ω is the angular frequency, εo is the permittivity of vacuum, E is the electric field, and ε" represents the dielectric loss factor.

3 Method and Materials

Present research objectives are to examine how potato, pizza and meat samples interact with microwave energy at different power levels, distribution and intensity of the electric field within the food materials. To analyze variations in electric field intensity, magnetic field intensity and volume loss density across the potato, pizza and meat samples, at varying microwave power inputs and at different food placement positions inside the microwave. To offer practical implications for optimizing microwave power settings in food preparation, getting accurate food placing position, aiming to improve cooking consistency, quality and energy efficiency based on the observed electromagnetic interactions with the food samples. ANSYS HFSS is a powerful electromagnetic simulation tool that is primarily designed for high-frequency applications, including microwave frequencies[16]. This study contributes to a comprehensive understanding of how electromagnetic energy interacts with materials and influences their thermal behavior. HFSS allows users to assign material properties accurately, which is crucial for modeling microwave devices, where the dielectric properties of materials significantly impact performance. Engineers use HFSS to validate designs by simulating the electromagnetic behavior and comparing the results with experimental data. It also facilitates design optimization to achieve the desired performance characteristics. The following process was followed to analyze food inside the microwave using Ansys HFSS:

Table 1 — Material properties of potato assigned to model

Name	Value	Units
Relative Permittivity	60	-
Relative Permeability	1	-
Bulk Conductivity	0	siemens/m
Dielectric Loss Tangent	0.26666	-
Magnetic Loss Tangent	0	-
Electric Coercivity	0	-
Magnetic Coercivity	0	m
Thermal Conductivity	0.75	W/m-^{0}C
Magnetic Saturation	0	tesla
Lande G Factor	2	-
Measured Frequency	0 9.4×10^9	Hz
Mass Density	1050	kg/m^3
Composition	solid	-
Specific Heat	3390	J/kg-^{0}C
Thermal Exp. Coefficient	2.33×10−5	1/^{0}C
Core loss model	none	-
Model wave port frequency	2.45	GHz
Power	1-2	kW

3.1 Placement of Food at Center of Microwave Cavity

The positioning of food inside a microwave can significantly impact the cooking or heating process. To understand its effect on the cooking of food, various iterations were carried out by changing the position of the potato, pizza, and meat inside the microwave. Two distinct food placement positions (center and edge) are considered to investigate the effects on the electric field, magnetic field, and volume loss density

3.1.1 Food - Potato

Figure 1 shows the model creation, which involved creating a 3D model of the microwave cavity, microwave source, and food geometry.

Potato properties are shown in Table 1. Appropriate electromagnetic and thermal properties of the food model were assigned based on its composition. The dielectric properties (Relative Permittivity, Dielectric Loss Tangent) and thermal properties (Thermal Conductivity, Mass Density, Specific Heat) of the potato Table 1, were sourced from established food science literature[20-24]. It is an inherent assumption of this steady-state electromagnetic simulation that these properties (dielectric and thermal) are held constant throughout the short duration simulation, neglecting their temperature dependent behavior, which would be the focus of future coupled electrothermal analysis.

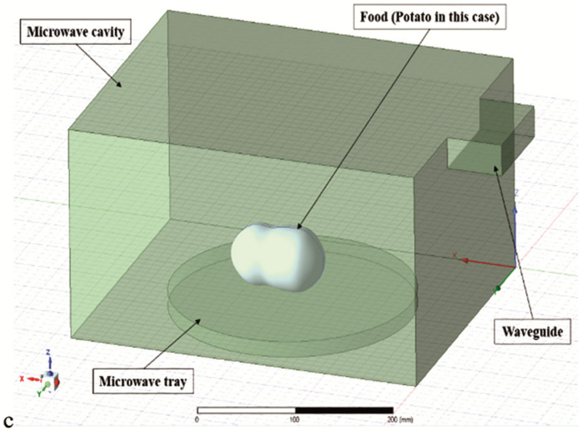

Fig. 1 — Model of microwave with food placed inside it potato placed at center of cavity

Material properties for the cavity walls (air) and microwave tray (aluminum) were also assigned.

The boundary conditions and excitations are shown in Fig. 2. Appropriate boundary conditions were applied to the microwave cavity to simulate the microwave environment. An excitation source representing microwave radiation was defined at the opening of the waveguide. Iterations at powers ranging from 1000 to 2000 W (operating powers of the available microwaves) were carried out. Furthermore, the effect of microwave radiation on food when the position of the food inside the microwave is changed is also analyzed using simulations. The wave port excitation assigned to the opening. The refinement step determines the frequency used to evaluate the mesh convergence. The refinement percentage and number of adaptive passes were both used in the adaptive solution process. The HFSS refines the mesh to attempt to converge. In HFSS, there are three types of frequency sweep settings, interpolating, discrete, and fast. The analysis and validation comprised configuring the simulation settings, such as the frequency range, convergence criteria, and solution method. The simulation of the electromagnetic fields inside the microwave cavity was executed. Post-processing includes the analysis of the electric field, magnetic field, and volume loss density for the food potato, as shown in Figs. 3–5. Executing the simulation for the electromagnetic fields inside the microwave cavity.

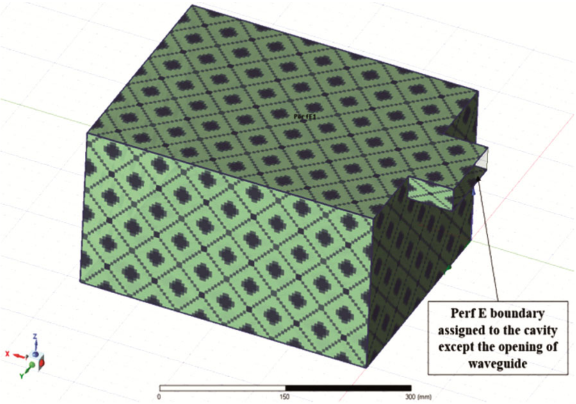

Fig. 2 — Boundary conditions of microwave for electromagnetic interactions with food placed inside it

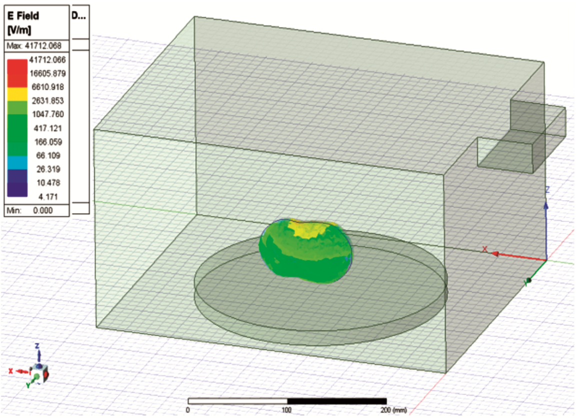

Fig. 3 — Electric field variation on potato when it was placed at center of cavity

3.1.2 Food - Pizza

Appropriate electromagnetic and thermal properties of the food model were assigned based on its composition. The dielectric properties (Relative Permittivity, Dielectric Loss Tangent) and thermal properties (Thermal Conductivity, Mass Density, Specific Heat) of the Pizza shown in Table 2. Placement of Pizza in microwave shown in Fig. 6. Post-processing includes plotting the electric field, magnetic field, and volume loss density for the pizza, as shown in Figs. 7–9.

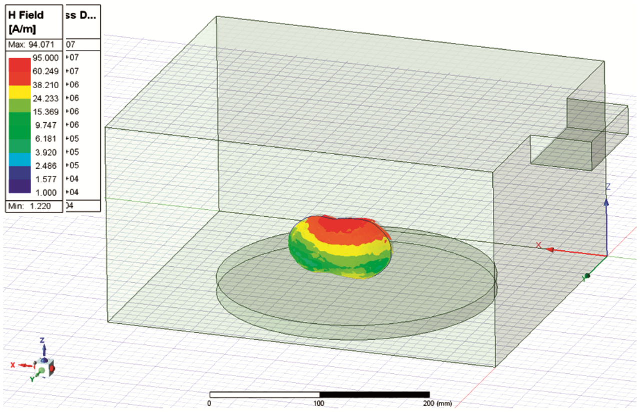

Fig. 4 — Magnetic field variation on potato when it was placed at center of cavity

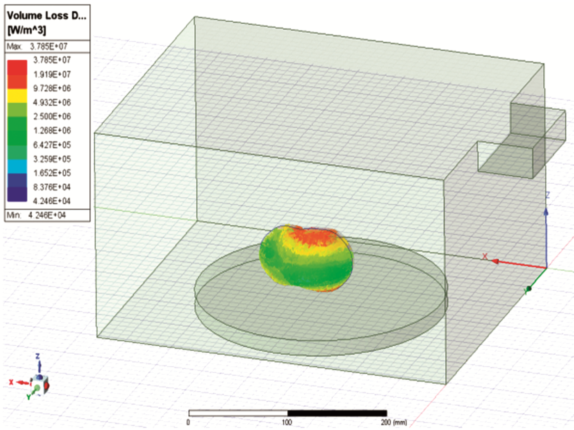

Fig. 5 — Volume loss density of potato when it was placed at center of cavity

Table 2 — Material properties of Pizza assigned to model

Name	Value	Units
Relative Permittivity	45	-
Relative Permeability	1	-
Bulk Conductivity	0	siemens/m
Dielectric Loss Tangent	0.44	-
Magnetic Loss Tangent	0	-
Electric Coercivity	0	-
Magnetic Coercivity	0	m
Thermal Conductivity	0.546	W/m-^{0}C
Magnetic Saturation	0	tesla
Lande G Factor	2	-
Measured Frequency	0 9.4×10^{9}	Hz
Mass Density	1000	kg/m^3
Composition	solid	-
Specific Heat	2930	J/kg-^{0}C
Thermal Exp. Coefficient	1×10^{-5}	1/^{0}C
Core loss model	none	-
odel wave port frequency	2.45	GHz
Power	1-2	kW

Table 3 — Material properties of Meat assigned to model

Name	Value	Units
Relative Permittivity	50	-
Relative Permeability	1	-
Bulk Conductivity	0	siemens/m
Dielectric Loss Tangent	0.36	-
Magnetic Loss Tangent	0	-
Electric Coercivity	0	-
Magnetic Coercivity	0	m
Thermal Conductivity	0.41	W/m-^{0}C
Magnetic Saturation	0	tesla
Lande G Factor	2	-
Measured Frequency	0 9.4×10^{9}	Hz
Mass Density	1040	kg/m^3
Composition	solid	-
Specific Heat	2750	J/kg-^{0}C
Thermal Exp. Coefficient	1.53×10^{-5}	1/^{0}C
Core loss model	none	-
Model wave port frequency	2.45	GHz
Power	1-2	kW

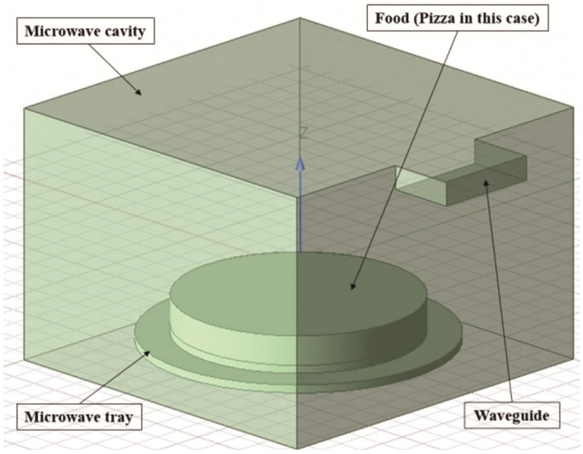

Fig. 6 — Pizza placed at center ofcavity

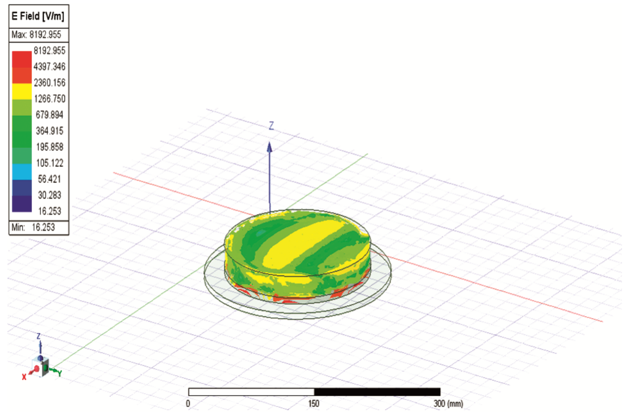

Fig. 7 — Electric field variation on pizza when it was placed at center of cavity

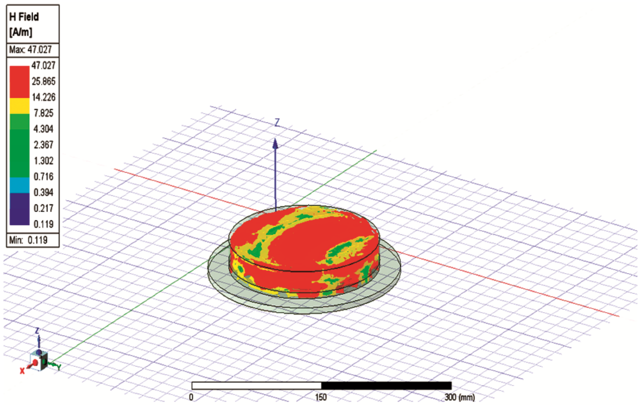

Fig. 8 — Magnetic field variation on pizza when it was placed at center of cavity

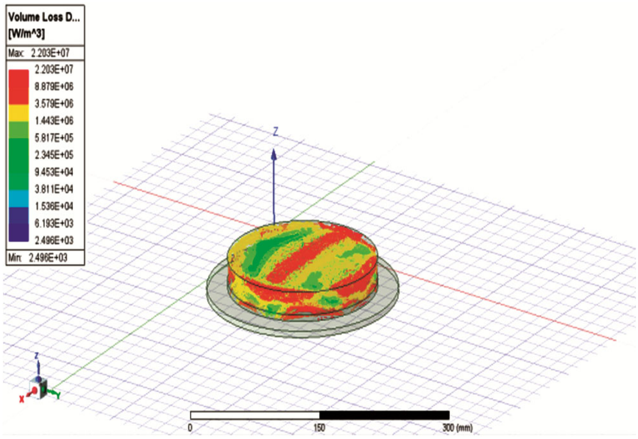

Fig. 9 — VLD variation on pizza when it was placed at center of cavity

3.1.3 Food - Meat

The dielectric properties (Relative Permittivity, Dielectric Loss Tangent) and thermal properties (Thermal Conductivity, Mass Density, Specific Heat) of the Meat shown in Table 3. Placement of Meat in microwave, shown in Fig. 10. Post-processing includes analyzing the electric field, magnetic field, and volume loss density for the meat, as shown in Figs. 11–13.

3.2 Placement of Food at Edge of Microwave Cavity

The positioning of food inside a microwave can significantly impact the cooking or heating process. because of the way microwaves interact with food. To understand its effect on the cooking of food, various iterations were carried out by changing the position of the potato, pizza, and meat inside the microwave. The food position effects on the electric field, magnetic field, and volume loss density for potato, pizza, and meat are shown in Figs. 14–22.

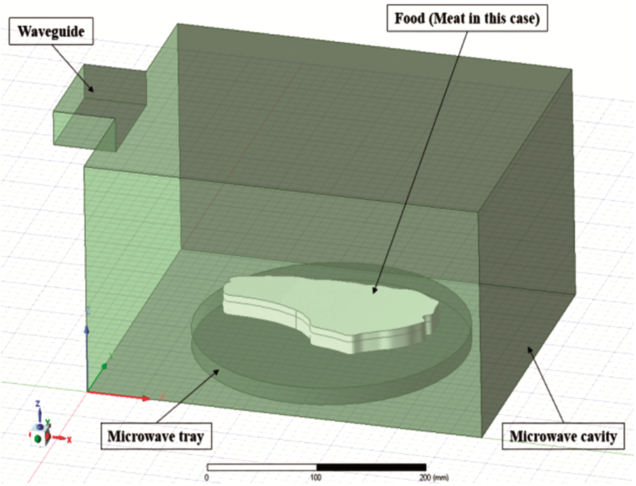

Fig. 10 — Meat placed inside microwave when it was placed at center of cavity

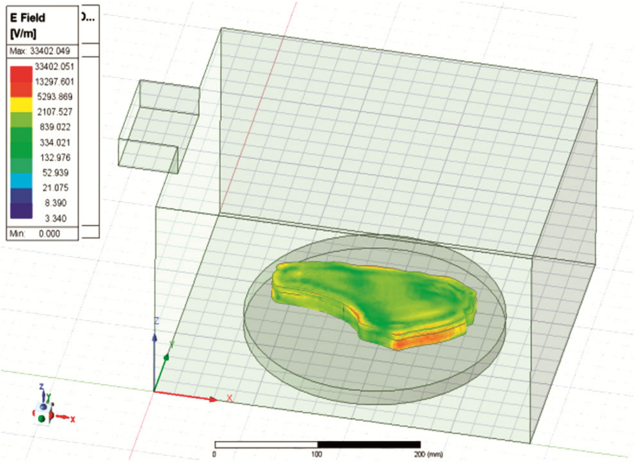

Fig. 11 — Electric field variation on meat when it was placed at center of cavity

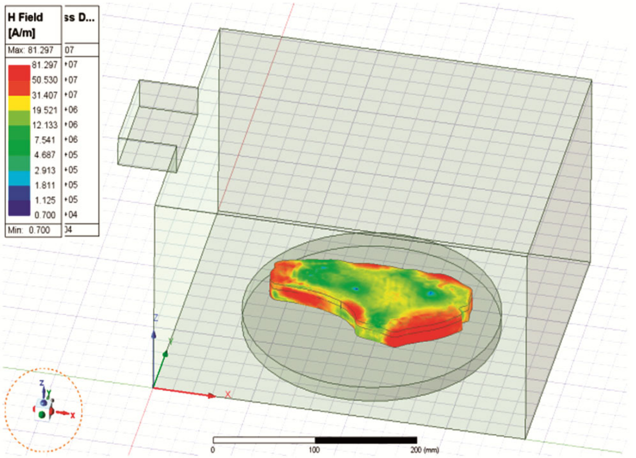

Fig. 12 — Magnetic field variation on meat when it was placed at center of cavity

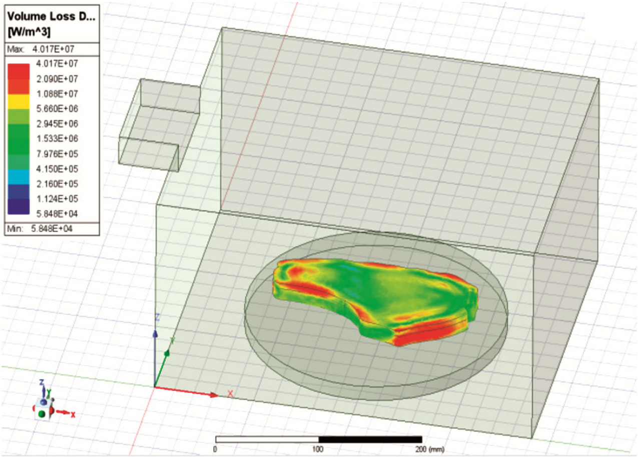

Fig. 13 — Volume loss density of meat when it was placed at center of cavity

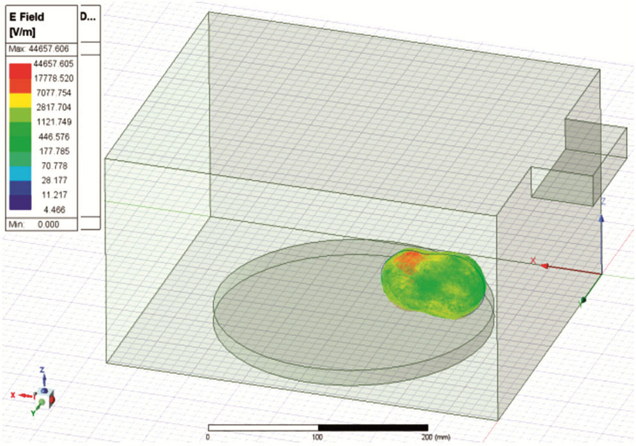

Fig. 14 — Electric field variation on potato when placed at the edge of the microwave tray

4 Results and Discussion

The power of a microwave oven refers to the rate at which it delivers electromagnetic energy to heat or cook food. A typical Microwave operates from 1000 to 2000 W. The power rating of a microwave is a crucial factor to consider when determining cooking times and ensuring efficient and uniform heating of food. Adjusting power levels according to specific

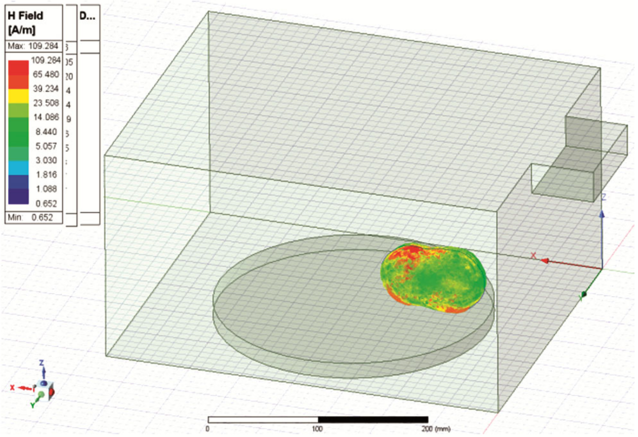

Fig. 15 — Magnetic field variation on potato when placed at the edge of the microwave tray

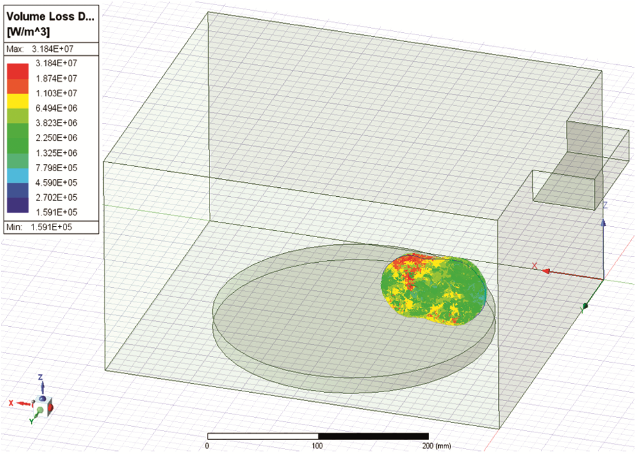

Fig. 16 — Volume loss density of potato when placed at the edge of the microwave tray

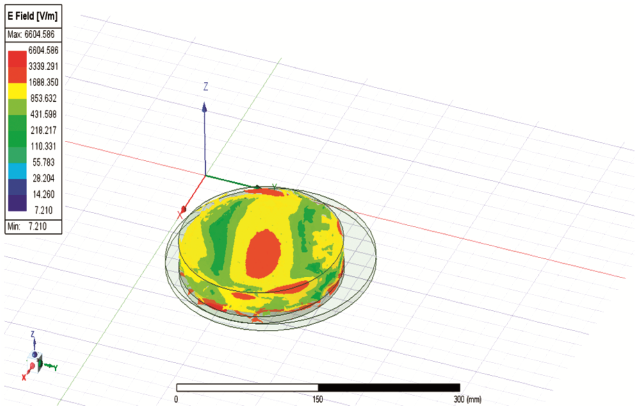

Fig. 17 — Electric field on pizza when placed at the edge of microwave tray

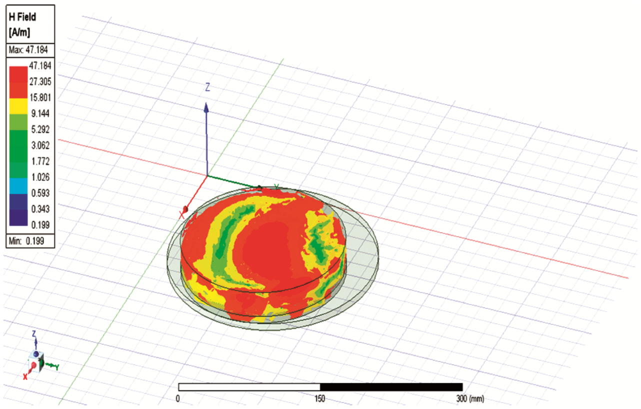

Fig. 18 — Magnetic field on pizza when placed at the edge of microwave tray

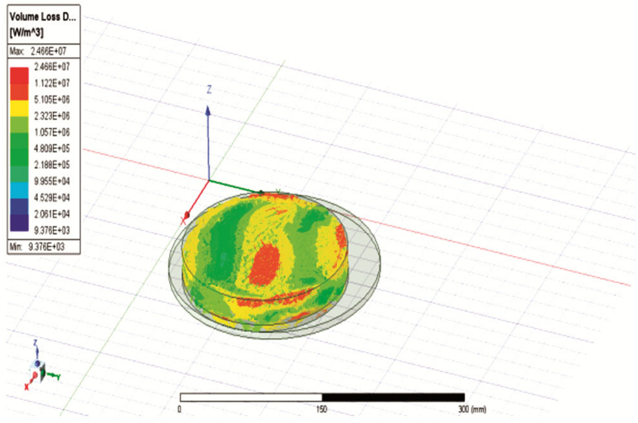

Fig. 19 — Volume loss density of pizza when placed at the edge of microwave tray

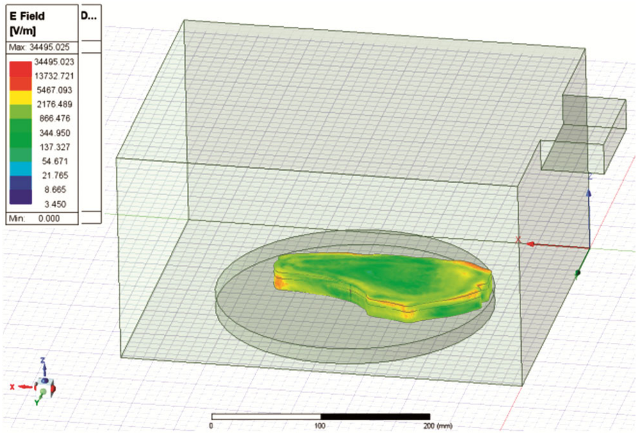

Fig. 20 — Electric field of meat when placed at the edge of the microwave tray

cooking requirements can enhance cooking outcomes and prevent food from being undercooked or over cooked. Analysis is carried for power levels 1000 W, 1200 W, 1400 W, 1600 W, 1800 W and 2000 W. The food used is potato, pizza and meat. The following graphs depicts the change in electric field, magnetic field and volume loss density for potato, pizza and meat at varying powers.

Figures 23 − 25 shows E field, H field, and Volume Loss Density. There is a strong, positive, and nearly linear relationship with the increasing input power (Watts). As power increases, all output parameters increase. Figure 23 shows Electric field, Potato consistently exhibits the highest E Field ranging from 42000 to 59000 V/m and Pizza consistently exhibits the lowest E field ranging from 8000 to 12000 V/m. Figure 24 illustrates Magnetic field, the pattern for the H field is inverse to the E field. Potato now has the highest H field ranging 95 to 133 A/m and Pizza has the lowest H field 47 to 67 A/m. This suggests that the food properties (e.g., moisture, dielectric constant) cause the microwave energy to partition differently into the Electric and Magnetic components, although Potato dominates both fields. Figure 25 shows Volume Loss Density which represents the rate of internal energy deposition (heating), closely tracks the E field and H field

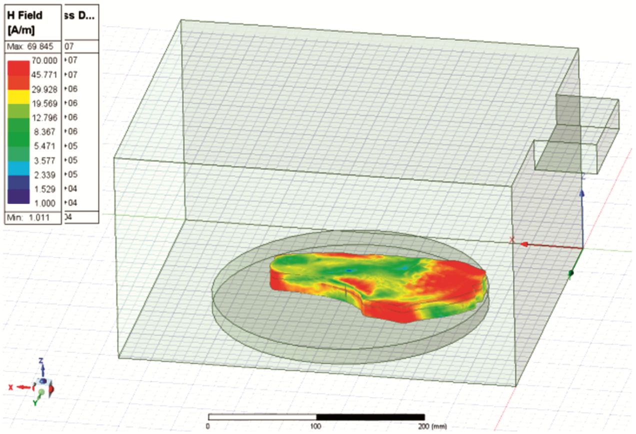

Fig. 21 — Magnetic field of meat placed at the edge of the microwave tray

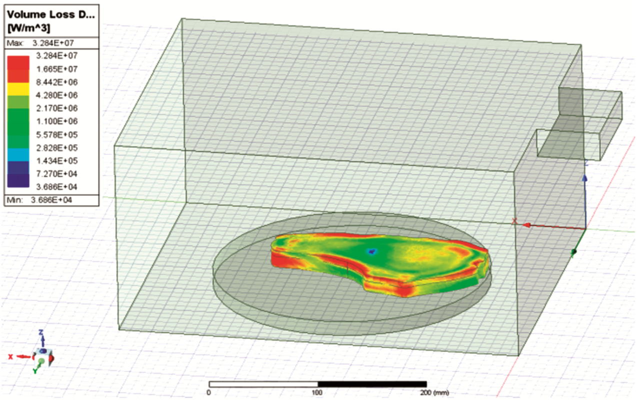

Fig. 22 —Volume loss density of meat placed at the edge of the tray

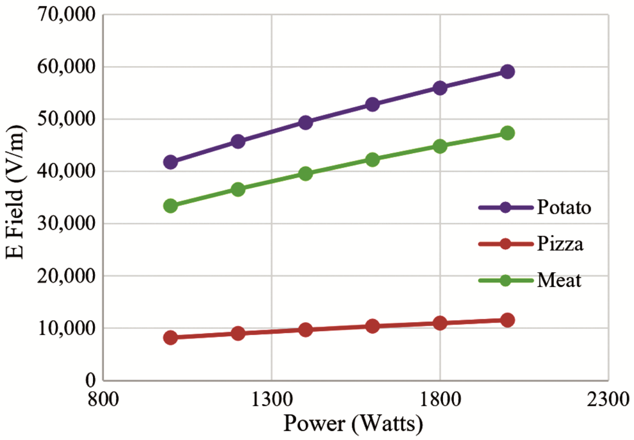

Fig. 23 — Effect of Electric field and Power level on cooking of Poato, Pizza and Meat when placed at centre of cavity

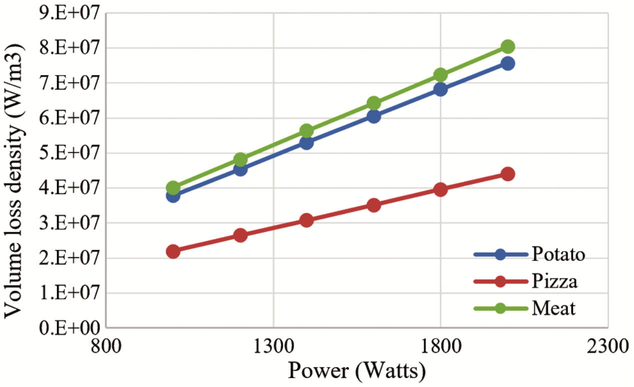

Fig. 24 — Effect of VLD and Power level on cooking of Poato, Pizza and Meat when placed at centre of cavity

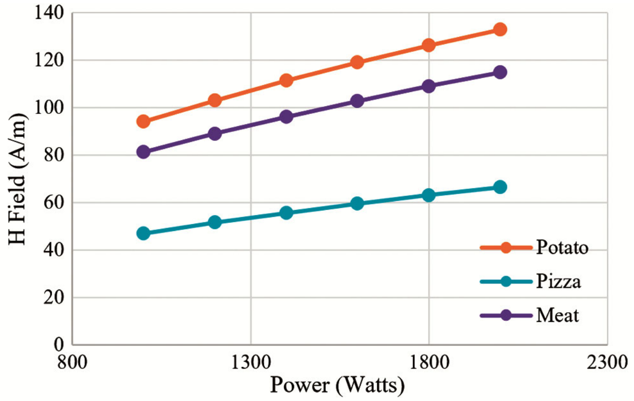

Fig. 25 — Effect of Magnetic field and Power level on cooking of Poato, Pizza and Meat when placed at centre of cavity

behaviors. Meat and Potato exhibit the highest loss densities around $8*10^7$ W/m^3, indicating they heat up most efficiently for a given power input. Pizza shows the lowest loss density around $4.5*10^7$ W/m^3, consistent with its lower E and H field absorption. In summary, increasing the microwave power leads to a predictable increase in both the E Field and H Field strengths, which directly results in a higher Volume Loss Density (heating rate) within the food, with Potato and Meat showing the greatest energy absorption / heating efficiency.

Analysis shown in Fig. 26, Electric field (E Field in V/m) versus Power (Watts) for three food items (Potato, Meat, and Pizza) under two placement conditions (Centre and Edge). All E field values show a positive, nearly linear correlation with increasing power. Potato (edge) consistently exhibits the highest E Field 63000 V/m at 2000 W. Pizza (edge) shows the lowest E field values, starting at 6600 V/m at 1000W and 9300 V/m at 2000W. Meat E field values fall in the mid-range spanning from 30000 V/m to 48000 V/m. Placement effect shows Potato at edge placement gives a significantly higher E field than the center 4000 V/m at 2000 W. The center placement of Pizza gives a significantly higher E field than the edge 2200 V/m difference at 2000 W. The difference between center and edge is minimal in case of Meat i.e. Approximately 1000 V/m at 1000 and 2000 W.

The Fig.27 illustrates the Magnetic Field (H Field in A/m) versus Power (Watts) for Potato, Meat, and Pizza under Centre and edge placement conditions. A strong, positive, and nearly linear correlation exists between Power and H Field for all cases. Potato exhibits the highest H fields, ranging from 95 A/m (center, 1000 W) to 155 A/m (edge, 2000W). Pizza shows the lowest H fields, ranging from 47 A/m to 66.5 A/m. The Edge placement results in a significantly higher H Field than the center. Difference is approximately 21 A/m at 2000 Watts. The center placement results in a higher H field than the edge. The difference is approximately 15 A/m at 2000 Watts. The H field is virtually independent of placement, with the center and edge lines being nearly identical across all power levels. The difference in H field between the highest point (Potato Edge, 155 A/m) and the lowest point (Pizza, 47 A/m) is over three times at 1000 Watts, demonstrating a major difference in magnetic field interaction across the food types.

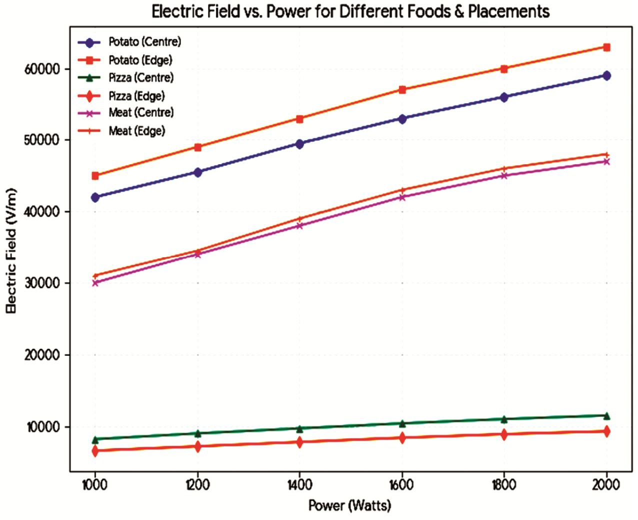

Fig. 26 — Effect of Electric field, Power and placement on cooking of Poato, Pizza and Meat

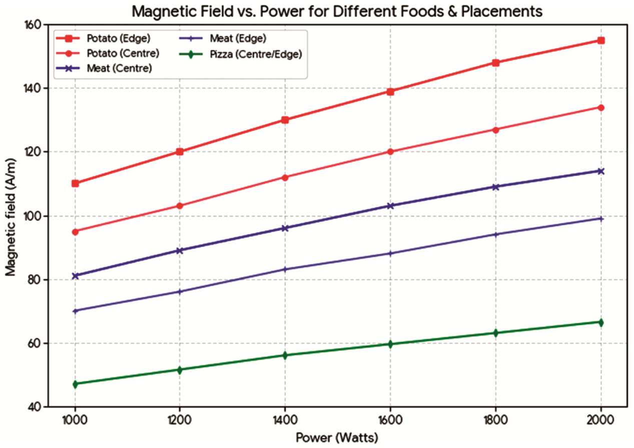

Fig. 27 — Effect of Magnetic field, Power and placement oncooking of Poato, Pizza and Meat

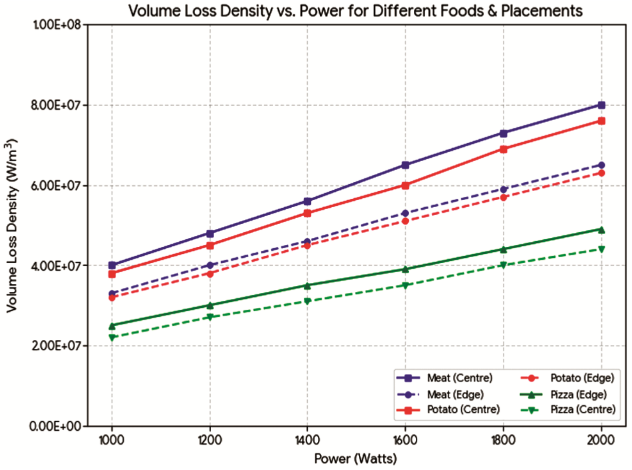

Fig. 28 — Effect of Volume Loss Density (VLD), Power and placement oncooking of Poato, Pizza and Meat

Figure 28 effectively visualizes the internal heating rate for all food types and placements. Highest VLD

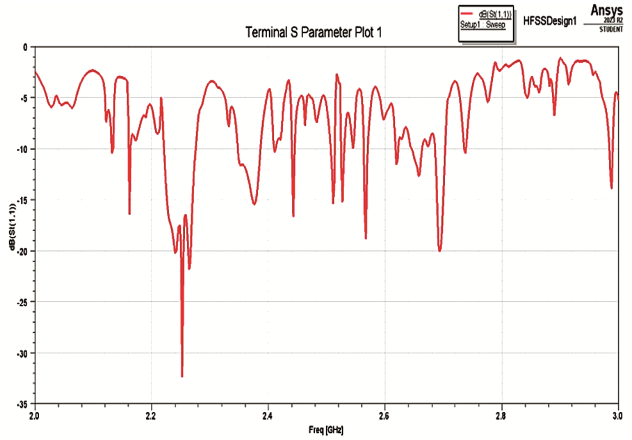

Fig. 29 — Analysis of S11 parameter and frequency- Incident electromagnetic energy at the interface between the food item and the surrounding microwave cavity

means the highest heating rate, Meat (center) shows the highest heating rate,8.0 x 107 W/m^3. Pizza (center) shows the lowest heating rate 2.2 x 107 W/m^3. Meat and Potato VLD is highest when the food is placed at the center. Pizza VLD is highest when the food is placed at the edge.

Analysis shown in Figs. 26-28 suggests electromagnetic energy physics of mixed field influence, inverse field heating and center dominated. Mixed Field Influence: VLD, the heating rate, is highest at the center, despite both E and H fields being highest at the Edge. This suggests a complex field structure where the center has optimal conditions for maximum power dissipation. Centre Dominated: The center position consistently maximizes both the H field and the resultant VLD (heating rate). Inverse Field / Heating: E field is higher at the center, yet the VLD (heating) is higher at the edge. This unusual behavior is likely due to its geometry or lower moisture content, where edge interactions (potentially related to reflection / refraction effects near walls) may become dominant for energy coupling. Figure 29 presents an analysis of the parameter as a function of frequency. The parameter represents the ratio of reflected to incident electromagnetic energy at the interface between the food item and the surrounding microwave cavity. This value is critical for understanding the energy coupling between the microwave field and the food material, which directly contributes to the assessment of cooking efficiency. A low value indicates minimal reflection and high energy absorption by the food, signifying excellent impedance matching and efficient microwave heating. Conversely, a higher value suggests that more energy is reflected back into the cavity, and less is absorbed by the food. When an electromagnetic signal is used to heat food, the resulting temperature increase arises from power absorption due to dielectric and/or magnetic material losses. The power absorbed from the signal leads to molecular interactions and subsequent heating. For these material losses, the theoretical temperature rise is generally proportional to the square of the signal amplitude and is linearly dependent on the operational signal frequency. To examine these effects of both power and frequency, the High-Frequency Structure Simulator (HFSS) was employed to computationally

5 Conclusion

The core heating mechanism is governed by the food material's dielectric properties, which drive how effectively the food absorbs and converts electromagnetic (EM) energy into heat. Potato consistently exhibits the highest E Field (ranging from 42, 000 to 59, 000 V/m), driven by its higher dielectric constant, indicating active engagement with the microwave electric field. Pizza shows the lowest E field (ranging from 8,000 to 12, 000 V/m). Magnetic field (H field) pattern is similar, with Potato having the highest H field up to 155 A/m and lowest to 47 A/m. This suggests that the food's properties partition the EM energy and Potato dominates both field components. The high moisture content in food like Meat and Potato is crucial, as water's high polarity strongly interacts with microwaves. This elevated moisture enhances the material's conductivity, which may contribute to the relatively higher magnetic fields and greater energy absorption compared to Pizza. The analysis of E field (Fig. 23), H field (Fig. 24), and Volume Loss Density (VLD, Fig. 25) show a consistent and critical trend. There is a strong, positive, and nearly linear relationship between the increasing Input Power (Watts) and all three measured output parameters (E field, H field, and VLD). As power increases, all three parameters increase predictably. The Volume Loss Density (the rate of internal heating) closely tracks the field strengths. Meat and Potato exhibit the highest VLD, around 8.0 x 107 W/m^3 and 7.6 x 107 W/m^3 respectively, confirming their greatest efficiency in converting microwave energy into heat. Pizza shows the lowest VLD, showing around 4.9 x 107 W/m^3, consistent with its lower E and H field absorption. Effect of food placement (Centre vs. Edge Figs. 26–28) The position of the food in the microwave tray significantly alters field distribution and heating rate. In summary, achieving optimal and uniform microwave heating requires an optimum approach that considers both the microwave power level and the specific food properties, as well as the tray placement which dictates the local field concentration and subsequent power dissipation.

References

1 Rek Z, Rudolf M & Zun I, *J Mech Eng*, 58 (2012).

2 Liu S, Ogiwara Y, Fukuoka M & Sakai N, *J Food Eng*, 131 (2014).

3 Chen J, Pitchai K, Birla S, Jones D, Negahban M & Subbiah J, *Food Bioprod Process*, 19 (2016).

4 Ni H & Datta A, *J Food Process Eng*, 22 (1999).

5 Pankyamma V, Madhusudana B, Rao R, Debbarma J & Ravishankar C N, *Trends Food Sci Technol*, 123 (2022).

6 Birla S & Pitchai K, *Woodhead Publishing Series in Food Science, Technol Nutrition*, 18 (2017) 407.

7 Zhou L, Puri V, Anantheswarant R & Yehh G, *J Food Eng*, 25 (1995).

8 Lin Y, Anantheswaranat R & Purib V, *J Food Eng*, 25 (1995).

9 Campanone L & Paola C, *Food Bioprocess Technol*, 5 (2012).

10 Wang X, Feng T, Wang X, Xia S, Yu J & Zhang X, *Meat Sci*, 192 (2022).

11 Porter M T, Binner J, Cinibulk M K, Stern K E & Yakovlev V V, *J Eur Ceram Soc*, 43 (5) (2023).

12 Burlon F, Tiberi E, Micheli D, Furlanetto R & Simonato M, *Energy Procedia*, 126 (2017).

13 Singh D, Singh D & Husain S, *Food Sci Technol Int*, 26 (6) (2020).

14 Pandit P & Prasad S, *J Food Eng*, 60 (2003).

15 Verboven P, Datta A, Anh N, Scheerlinck N & Nicola B, *J Food Eng*, 59 (2003).

16 Sabbagh M, *Electr Eng Comp Sci Tech Rep*, 46 (2011) 1.

17 Yang Y & Xi Z, 8th Int Conference on Electronic Measurement and Instruments (2007).

18 Celuch M & Kopyt P, *Packaging and products for use in microwave ovens*, 14 (2014) 305.

19 Saltiel C & Datta A, *Adv heat transf*, 33 (1999).

20 Derbyshire P & Owen I, *Int J Heat Fluid Flow*, 9 (2) (1988).

21 Pitchai K, Birla S, Subbiah J, Jones D & Thippareddi H, *J Food Eng*, 112 (2012).

22 Campanone L & Zaritzky N, *J Food Eng*, 69 (2005).

23 Meda V, Orsat V & Raghavan V, *Microwave Process Food*, (2017).

24 Zhang H & Datta A, *Food Bioprod Process*, 81 (3) (2003).