Application of advanced microwave technology to enhance the heating efficiency of pork sausage heating

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Abstract. The most commonly used method for heating fermented pork sausage in Thailand is grilling over a charcoal stove. However, this method presents several drawbacks, including air pollution, which directly affects human health. Therefore, the combination of microwave and hot air heating presents a promising alternative. Microwaves can penetrate the food's interior, heating it from the inside out, while hot air ensures heating of the outer surface. This synergy facilitates rapid and more uniform cooking of fermented pork sausage. This study develops a three-dimensional model (3D) to simulate the heating of fermented pork sausage using microwave energy, hot air, and a combination of both. Maxwell's equation and the heat transfer equation are employed to investigate the effects of waveguide position on the distribution of temperature and cooking completeness. The results show that the Type C waveguide configuration in a microwave-hot air oven at 100 °C provides the most uniform distribution of temperature, achieving the highest cooking completeness at 97.7%. These findings can contribute to the design and development of microwave heating systems for sausages and other food products.

1 Introduction

Fermented pork sausage is a traditional food product of Thailand that has gained widespread popularity. It consists of pork meat, pork fat, cooked rice, salt, pepper, star anise, spices, and other seasonings, undergoing a microbial fermentation process to develop its unique flavor [1]. However, since fermented pork sausage is made from raw pork, it must be cooked before consumption to ensure food safety and hygiene. The United States Department of Agriculture (USDA) recommends that microwave cooking temperatures for pork and beef should exceed 72 °C to effectively eliminate pathogenic microorganisms [2]. The most common cooking method for fermented pork sausage is grilling, which has

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several drawbacks, such as long cooking times and uneven heating. Additionally, grilling requires frequent flipping to achieve uniform heat distribution.

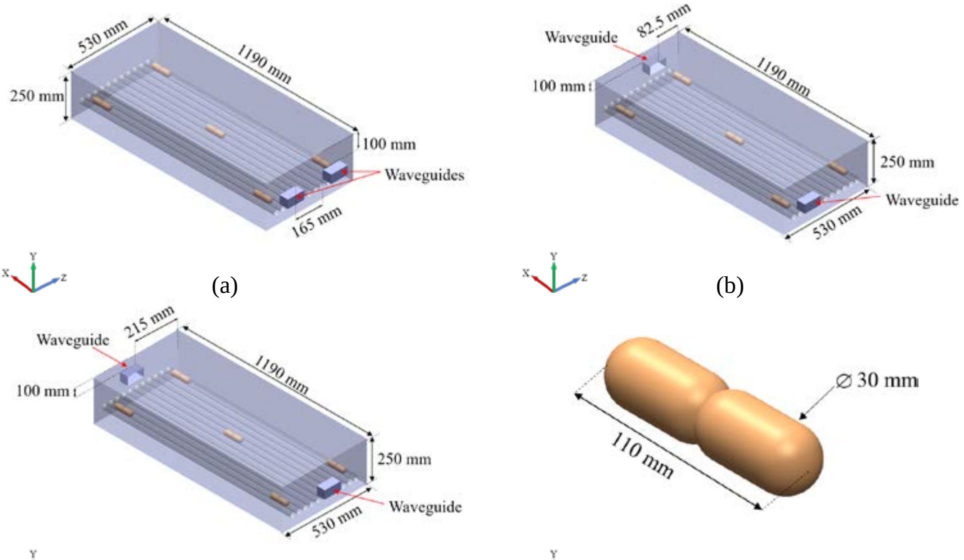
Microwave heating is an effective alternative for food heating because microwaves can penetrate and transfer energy inside the food more efficiently than grilling. It also significantly reduces cooking time [3], conserves energy, and does not produce pollution [4]. However, microwave heating still suffers from non-uniform temperature distribution inside the food, potentially creating hot spots and cold spots that cause uneven cooking. Therefore, it is necessary to study optimal waveguide placement to enhance uniform heat distribution. Hot air convection heating is a widely used industrial method that transfers heat through high-temperature air to the food surface before slowly heating the interior. Combining microwave and hot air heating has gained interest in food processing because it leverages the rapid heating of microwaves and the precise temperature control of hot air, improving texture and heat distribution.

Previous studies have used computational models to analyze food heating in microwave ovens, especially three-dimensional (3D) models that accurately simulate electric field distribution and temperature inside food. For example, Chen F. et al. [5] used 3D simulation to study microwave heating of frozen pies, validating their model experimentally. Song C. et al. [6] simulated microwave heating of frozen food containing chicken pieces and toasted bread, studying turntable rotation speed effects and temperature-dependent material properties. Tepnatim W. et al. [7] developed a 3D model to simulate temperature and electric field distributions to identify hot and cold spots in four packaged sausages heated by microwaves, also studying optimal sausage orientation using FEM. Braeckman L. et al. [8] studied combined infrared grilling and hot air cooking effects on moisture, fat content, texture, and color of burger patties using lab-scale ovens. Shi S. et al. [9] studied stepwise hot air gradient drying effects on dried beef jerky quality Maskan M. [10] compared drying methods for kiwi fruit using hot air, microwave energy, and combined, finding microwave significantly reduced drying time but increased shrinkage and reduced rehydration. Although many studies have addressed microwave heating, hot air heating, and combined methods for various foods, no research has focused on heating processes for fermented pork sausage, particularly on developing a realistic 3D model of fermented pork sausage. Such a model would form the basis for further heating process studies on fermented pork sausage and other foods.

Therefore, this study aims to develop a 3D model of fermented pork sausage heating using microwave energy, hot air convection, and combined microwave–hot-air heating. The finite element method (FEM) is applied alongside Maxwell’s equations and heat transfer equations to analyze the temperature distribution inside the fermented pork sausage and efficiency heating. Additionally, the effects of three different waveguide positions are investigated using a microwave power input of 400 W at 2.45 GHz frequency for 300 s. Hot air heating is performed at 80 °C and 100 °C. The results can guide the design and development of microwave ovens capable of efficiently heating fermented pork sausage and similar food products.

2 Mathematical Models Used for Analysis

In this study, a 3D model of fermented pork sausages and a microwave heating oven are developed. Five sets of fermented pork sausages (each set containing two) are positioned at different locations within the oven for simulation. This study investigated the influence of installing the waveguide at three different positions within the heating chamber of the oven, referred to as MW-Type A, MW-Type B, and MW-Type C, as illustrated in Fig. 1. The dimensions of the simulated microwave heating oven are 1190 × 530 × 250 mm, while the waveguide had dimensions of 100 × 50 × 100 mm.



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

Fig. 1. The dimension of the mathematical models in this study (a) MW-Type A and (b) MW-Type B, (c) MW-Type C, and (d) Fermented pork sausage model.

3 Governing Equation and Boundary Conditions

3.1 Electromagnetic wave propagation analysis

The domains of the microwave heating chamber and the fermented pork sausage are modeled using Maxwell's equations [11], as shown in Equation (1), to analyze the electric field distribution inside the microwave oven.

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\mathbf{E} = 0 \tag{1}$$

when $\mathbf{E}$ represents the electric field (V/m), ε_r denotes the relative permittivity (-), σ refers to the electric conductivity (S/m), $\omega = 2\pi f$ indicates the angular frequency (rad/s), ε_0 represents the permittivity of free space (F/m); $\varepsilon_0 = 8.8542 \times 10^{-12}$ F/m, μ_r denotes the relative permeability (-), and k_0 indicates the free space wave number (m^{-1}).

The walls of the microwave oven represent the surface of a lossless metallic conductor; a perfect electric conductor (PEC) boundary condition is imposed.

3.2 Heat transfer analysis

The domain of the fermented pork sausage is analyzed using the heat transfer equation shown in Equation (2) to study the temperature distribution [12].

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-K\nabla T) = Q_{dis} \tag{2}$$

where ρ represents the density (kg/m³), c_p denotes the specific heat capacity (J/kg·K), T refers to the temperature (°C), K indicates the thermal conductivity (W/m·K), and Q_{dis} represents the external power dissipation from microwave energy (W/m³), which denotes equal to $Q_{dis} = \pi f \varepsilon_0 \varepsilon'' \cdot |\mathbf{E}|^2$. f refers to the frequency (Hz), considered at a frequency of 2.45 GHz, and ε'' indicates the relative dielectric loss factor (-).

The outer surface of the fermented pork sausage exchanges heat with the surrounding air through convection. In considering the hot air heating of the fermented pork sausage, heat transfer is assumed to occur at the surface of the fermented pork sausage by specifying the surface temperature.

The doneness of the fermented pork sausage is analyzed based on the calculation of the volume ratio of the region with a temperature exceeding 72 °C to the total volume of the fermented pork sausage, as expressed in Equation (3).

$$\frac{V_{T>72^\circ C}}{V_{Total}} \times 100 \tag{3}$$

Where $V_{T>72^\circ C}$ represents the volume of the fermented pork sausage with a temperature exceeding 72 °C (m³), and V_{tatal} denotes the total volume of the fermented pork sausage (m³).

In this study, the moving mesh technique is applied to analyze the influence of the motion of fermented pork sausages within the microwave heating chamber.

In the case study analyzing the effects of waveguide placement at different positions-MW-Type A, MW-Type B, and MW-Type C-the total number of elements used are 1,100,395; 1,090,455, and 1,135,625, respectively. The dielectric and thermal properties used in the simulations are summarized in Table 1.

Microwave heating is modeled using an input power of 400 W at a fréquence of 2.45 GHz and a heating duration of 300 s. For hot air heating, temperatures of 80 °C and 100 °C are applied, with the same heating duration of 300 s.

Table 1. The dielectric and thermal properties of fermented pork sausage used for the simulation calculations.

Pork	**Dielectric Properties**		**Thermal Properties**		
	Dielectric constant (-)	Dielectric loss factor (-)	Thermal Conductivity (W/m·K)	Density (kg/m³)	Specific heat capacity (J/kg·K)
	54.7 [13]	16.78 [13]	0.456 [14]	1,030 [14]	3,490 [14]

4 Results and Discussion

4.1 Verification of the model

To validate the accuracy of the numerical model, the simulated temperature results obtained in this study are compared with those from the work of Numuang C. [15], using the same modeling approach and analysis conditions as shown in Fig. 2., the temperature distribution trends observed in this study closely align with those reported by Numuang C. [15]. The average percentage errors at 120 °C, 140 °C, and 160 °C are found to be 0.769%, 0.577%, and 0.577%, respectively. These results confirm that the numerical approach employed in this study is accurate and reliable for further analysis.

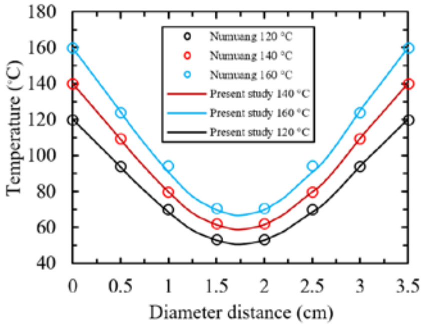
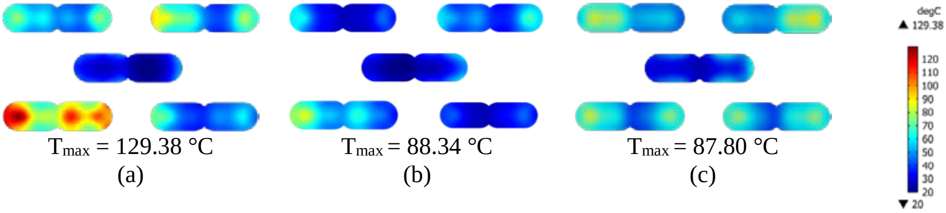


Fig. 2. Comparative analysis of radial temperature distribution in sausages at 120 °C, 140 °C, and 160 °C between this study and the work of Numuang C. [15].

4.2 Investigation of the influence of waveguide position changes

Fig. 3. Shows the temperature distribution of the fermented pork sausages when subjected to microwave heating under different waveguide configurations.



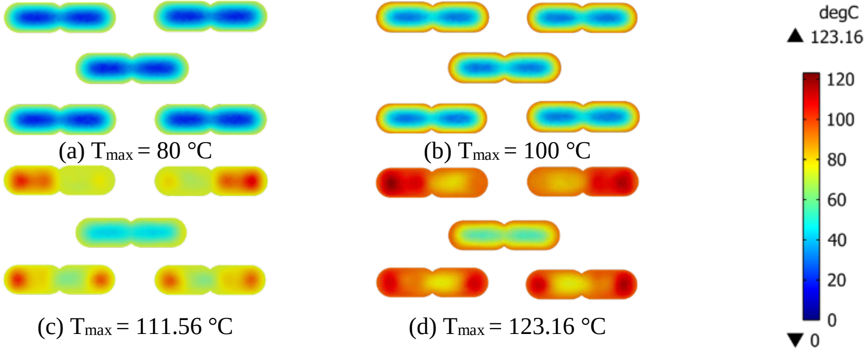
T_{max} = 129.38 °C
(a)

T_{max} = 88.34 °C
(b)

T_{max} = 87.80 °C
(c)

Fig. 3. The temperature distribution in fermented pork sausage using an input microwave power of 400 W at a frequency of 2.45 GHz with a heating duration of 300 s of (a) MW-Type A, (b) MW-Type B, and (c) MW-Type C.

Fig. 4. illustrates the temperature distribution of the fermented pork sausage subjected to hot air heating and combined microwave heating. It is found that combining microwave with hot air heating improved the uniformity of temperature distribution, particularly when using the MW-Type C waveguide along with hot air at 100 °C, which resulted in the highest and most uniform temperature distribution.



(a) T_{max} = 80 °C

(b) T_{max} = 100 °C

(c) T_{max} = 111.56 °C

(d) T_{max} = 123.16 °C

Fig. 4. Temperature distribution of fermented pork sausage after 300 s of heating using (a) hot air at 80 °C, (b) hot air at 100 °C, (c) combined microwave heating (Type C, 400 W, 2.45 GHz) with hot air at 80 °C, and (d) combined microwave heating (Type C, 400 W, 2.45 GHz) with hot air at 100 °C.

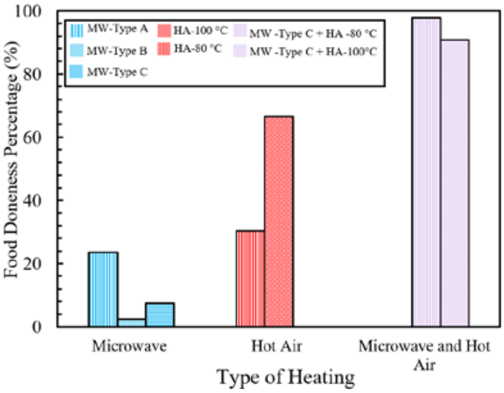


Fig.5. Percentage of doneness of fermented pork sausages over different heating durations using various heating methods.

Fig. 5. summarizes the final doneness percentages (at 300 s) under different heating methods. It clearly demonstrates that combining microwave heating particularly with the MW-Type C waveguide, which offers optimal temperature distribution with hot air at 100 °C leads to an almost completely cooked fermented pork sausage.

5 Conclusion

In this study, a 3D model of fermented pork sausage and a microwave heating chamber is developed to analyze the heating process using microwave energy, hot air, and a combination of microwave and hot air energy. The influence of waveguide placement is studied by comparing three different configurations: MW-Type A, MW-Type B, and MW-Type C. Among the three configurations, the MW-Type C waveguide provided the most uniform heating performance, minimizing the formation of hot spots. It also produced the widest and most consistent distribution of temperature, resulting in a uniform doneness across all five fermented pork sausages in the simulation. These simulation results can be applied to the development and design of alternative energy-based heating systems that integrate microwave and hot air technologies.

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