Retraction

Retraction: Microwave heating of food materials: Role of susceptor (IOP Conf. Ser.: Mater. Sci. Eng. 1145 012022)

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This article (and all articles in the proceedings volume relating to the same conference) has been retracted by IOP Publishing following an extensive investigation in line with the COPE guidelines. This investigation has uncovered evidence of systematic manipulation of the publication process and considerable citation manipulation.

IOP Publishing respectfully requests that readers consider all work within this volume potentially unreliable, as the volume has not been through a credible peer review process.

IOP Publishing regrets that our usual quality checks did not identify these issues before publication, and have since put additional measures in place to try to prevent these issues from reoccurring. IOP Publishing wishes to credit anonymous whistleblowers and the Problematic Paper Screener [1] for bringing some of the above issues to our attention, prompting us to investigate further.

[1] Cabanac G, Labbé C and Magazinov A 2021 arXiv:2107.06751v1

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Microwave heating of food materials: Role of susceptor

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Abstract. Microwave heating technique has been used to cook and process food materials due to faster heating. In this work, the effect of susceptors (secondary materials) while microwave heating of two different food materials is theoretically examined. The heating of food materials and susceptors due to the microwave power absorption has been simulated for two different food materials (beef and bread) enclosed in susceptors. Alumina and SiC are the two different susceptors considered for the study. The alumina susceptor is found to elevate the heating rate of materials with high dielectric properties (beef). While, SiC susceptor suppresses the heating rate both the materials with high and low dielectric properties (beef and bread). However, uniformity in heating of materials with low dielectric properties is increased by using SiC susceptor. The effect of susceptor thickness on average power absorption has been analyzed and maximum amount of average power is absorbed for specific sample dimensions (lies in resonating regime).

Keywords: Finite element method: Microwave heating; Susceptor

1. Introduction
Microwave heating has gained remarkable attentiveness due to multiple advantages such as faster heating, uniform heating and energy efficient heating. Microwaves have been utilized for variety of applications such as heating, cooking, drying, melting, medical treatment and so on [1–3]. The propagating microwaves polarize the polar molecules within the dielectric material and these polar molecules rotate due to the alternating electric field of microwaves. This rotation induces friction on polar molecules, consequently, heat is liberated throughout the material. The dielectric properties of the material determine the amount of heat liberation within the material. The material with high dielectric loss heats up at a faster rate compared to the material with low dielectric loss.

A wide range of commonly used food materials and the vegetables are nearly cylindrical in shape. In this work, a theoretical examination of microwave heating of cylindrical food samples enclosed in tubular susceptor (secondary material) is carried out. A few works have been carried out to study the microwave heating in the presence of secondary material such as container [4-8]. Researchers in [9] have studied microwave heating of gel (similar properties of meat) in a polytetrafluoroethylene container. Researchers in [10] conducted experiments and numerical simulations to analyze the temperature distribution during microwave heating of agar gel in an acrylic container. Researchers in [11] studied microwave heating of kamaboko which is placed in a cylindrical acrylic container. Further, Researchers in [12] analyzed microwave boiling of fish kept in a vessel containing salt water. Microwave heating of multi-component meal in a tray was analyzed by [13]. Researchers in [14] carried out experiments and simulations to analyze microwave heating of dried mashed potato in a flatbed microwave oven and
provided an antenna to achieve uniform heating. Researchers in [15] analyzed microwave heating of frozen pie kept in a container (metallized film with paperboard) and Researcher in [16] confirmed that ferrite-particle-mixed silicone container can be used for microwave cooking process. In all these research works, the effect of secondary material (container or susceptor) on microwave heating is not studied in detail. Therefore, the principal aim of this study is to examine the influence of susceptor on microwave heating of food samples. Two different samples and susceptors have been considered to examine microwave heating attributes. One of the susceptors is made up of alumina, which is transparent to microwaves and another susceptor used in this study is the high lossy SiC. Two different samples considered in this study are (i) high lossy beef and (ii) low lossy bread. The analysis has been conducted for two different types of microwave incidences such as lateral and radial incidences.

2. Mathematical modelling of microwave propagation

2.1 Electric field distribution

Cylindrical samples of radius R1 enclosed in tubular susceptors of thicknesses R2 − R1 are exposed to lateral and radial incidences (TMZ polarized microwaves) [Figures 1(a) and (b)]. Helmholtz equations [Equations (1) and (2)] are used to solve the electric field distribution throughout the cylindrical sample and susceptor, respectively.

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial E_1}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 E_1}{\partial \theta^2} + \kappa_1^2 E_1 = 0 \quad (1)
\]

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial E_2}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 E_2}{\partial \theta^2} + \kappa_2^2 E_2 = 0, \quad (2)
\]

where \( E_1 \) and \( E_2 \) are distribution of electric fields of sample and susceptor, respectively. Note, that \( \kappa_1 \) and \( \kappa_2 \) are propagation constants for the sample and susceptor, respectively. The electric and magnetic fields at the interface between the sample and susceptor are assumed to be continuous and the interface continuities at \( r = R_1 \) are shown in Equation (3).

\[
r = R_1 \Rightarrow \begin{cases} E_1 = E_2, \\ \frac{\partial E_1}{\partial r} = \frac{\partial E_2}{\partial r} \end{cases} \quad (3)
\]

In addition, the following radiation boundary condition (at \( r = R_2 \)) is applied on the exterior surface of the susceptor for lateral irradiation as shown in Equation (4) and Equation (5).

\[
\left. \frac{\partial E_2}{\partial r} \right|_{R_2} = \sum_{n=0}^{\infty} \left[ \epsilon_n \kappa_0 (\kappa_0 R_2/H_n^{(1)}(\kappa_0 R_2)) \left( J_n(\kappa_0 R_2) - J_n(\kappa_0 R_2) \right) \right] \cos(n\theta)
\]

\[
+ \frac{\epsilon_n \kappa_0 (\kappa_0 R_2/H_n^{(1)}(\kappa_0 R_2))}{2\pi H_n^{(1)}(\kappa_0 R_2)} \int_{0}^{2\pi} E_2 \cos[n(\theta - \theta')] d\theta' \quad (4)
\]

Where

\[
\epsilon_n = \begin{cases} 1 & \text{if } n = 0 \\ 2 & \text{otherwise} \end{cases} \quad (5)
\]

The applied radiation boundary condition for radial incidence is given below in Equation (6).

\[
+ \frac{\epsilon_n \kappa_0 (\kappa_0 R_2/H_n^{(1)}(\kappa_0 R_2))}{2\pi H_n^{(1)}(\kappa_0 R_2)} \int_{0}^{2\pi} E_2 \cos[n(\theta - \theta')] d\theta' \quad (6)
\]
Here, $J_n$ and $H_n^{(1)}$ are Bessel and Hankel functions of first kind, respectively and prime denotes the first derivative of the function, $\kappa_0$ is the free space propagation constant and $E_0$ is electric field intensity of incident radiation for lateral incidence. Figure 1 shows the Pictorial illustration of microwave incidence.

**Figure 1.** Pictorial illustration of microwave incidence on sample and susceptor (container): (a) lateral incidence and (b) radial incidence.

### 2.2 Temperature distribution

The temperature distribution throughout the sample and susceptor can be determined by solving following energy balance equations. The variation of thermal and dielectric properties of materials with temperature are neglected as it is extremely small and is represented in Equations (7) and (8).

\[
(\rho C_p)_1 \frac{\partial T_1}{\partial t} = k_1 \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T_1}{\partial r} \right) - \frac{1}{r^2} \frac{\partial^2 T_1}{\partial \theta^2} \right] + q_1, \quad \{r, \theta\} \tag{7}
\]

\[
(\rho C_p)_2 \frac{\partial T_2}{\partial t} = k_2 \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T_2}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T_2}{\partial \theta^2} \right] + q_2, \quad \{r, \theta\} \tag{8}
\]

where $T, k$ and $(\rho C_p)$ are the temperature, thermal conductivity and specific heat capacity with subscripts 1 and 2 sample and susceptor, respectively. Here, $q_1$ and $q_2$ are the volumetric heat generations sample and susceptor, is represented in Equations (9) and (10).

\[
q_1 = \pi f \epsilon_0 \kappa_1'' |E_1|^2 \tag{9}
\]

\[
q_2 = \pi f \epsilon_0 \kappa_2'' |E_2|^2 \tag{10}
\]

The exterior surface of the susceptor is coated with a perfect thermal insulator and the initial temperatures of sample and susceptor are assumed to be constant. Therefore, the boundary, interface and initial conditions for solving energy balance equations are represented in Equations (11),(12) and (13).

\[
\frac{\partial r}{r} = R_1 : \quad T_1 = T_2, \quad k_1 \frac{\partial T_1}{\partial r} = k_2 \frac{\partial T_2}{\partial r} \tag{11}
\]

\[
\frac{\partial r}{r} = R_2 : \quad \frac{\partial T}{\partial r} = 0 \tag{12}
\]

\[
t = 0: \quad T_1 = T_2 = T_0 \tag{13}
\]

The electric field equations and energy balance equations are simultaneously solved by using Galerkin finite element method and Crank-Nicholson method. The numerical solutions are perfectly agreeing with
the closed form solutions for microwave power absorption and temperature distribution for radial incidence.

3. Results and discussion

3.1. Microwave heating of cylindrical samples enclosed susceptor

In the present study, 1 cm radius of beef and bread samples are enclosed in 0.2 cm thickness of tubular susceptors (alumina and SiC). The dispersal of absorbed microwave power and temperature throughout samples and susceptors are analyzed in detail.

Figure 2 illustrates the power distributions and temperature distributions (at t = 40 and 90 s) within beef samples and susceptor for lateral irradiations. The spatial power distribution is found to be larger for sample within alumina susceptor compared to the sample within SiC susceptor. This is due to the alumina is transparent to microwaves and most of the incident microwaves are transferred into the sample, whereas the SiC susceptor absorbs the microwaves and mostly the heat is devolved from the SiC susceptor into sample by conventional mode. The maximum is accumulated near the central regime of the samples for samples within alumina and SiC susceptors. The spatial power near the center of sample within alumina susceptor is around 1.8 Wcm⁻³ whereas in the sample within SiC susceptor is around 1 Wcm⁻³. The constructive interference of various microwaves occurs at the central part of the sample and it leads to maximum power absorption at center. Hence, the temperature near the central regime is higher than the rest of the sample.

| Power (W cm⁻³) | Temperature (K) |
|----------------|----------------|
|                | t = 45 s       | t = 90 s       |
| Alumina Container | 305            | 310            |
| SiC Container   | 304            | 307            |

Figure 2. Dispersal of power and temperature within beef samples enclosed in susceptors during lateral incidence.

Figure 3 illustrates the dispersal of power and temperature within the susceptors and beef samples exposed to radial irradiations. Similar to samples exposed to lateral irradiations, spatial power distribution is larger in sample within alumina susceptor compared to sample within SiC susceptor. For the case of sample within the alumina susceptor, the maximum power is accumulated at the central regime as the alumina transfers the most of the microwaves into the sample. Consequently, the central regime heated up faster rate compared to the rest of sample. Although SiC absorbs most of the
microwave power and interior of the beef sample absorbs lesser power the maximum power is accumulated near the central regime of the samples due to the constructive interference of waves. Consequently, the central regime heated up faster rate compared to other regions.

| Power (W cm\(^{-3}\)) | \( t = 45\) s | \( t = 90\) s |
|------------------------|---------------|---------------|
| **Alumina Container**  |               |               |
| 0.2                    | 0.6           | 0.6           |
| 0.3                    | 0.8           | 0.8           |
| 0.4                    | 0.8           | 0.8           |
| 0.5                    | 0.8           | 0.8           |
| 0.6                    | 0.8           | 0.8           |
| **SiC Container**      |               |               |
| 0.1                    | 0.3           | 0.3           |
| 0.2                    | 0.5           | 0.5           |
| 0.3                    | 0.7           | 0.7           |
| 0.4                    | 0.9           | 0.9           |
| 0.5                    | 0.9           | 0.9           |
| 0.6                    | 0.9           | 0.9           |

**Figure 3.** Dispersal of Power and temperature within beef samples enclosed in susceptors during radial incidence.

Figure 4 illustrates the dispersal of power and temperature within the susceptors and bread samples exposed to lateral irradiations. It may be noted that for the same period of time the temperature of bread samples is much lower than the beef samples as the bread is a low lossy material. It is observed that bread samples within alumina susceptor heat up faster rate compared to the bread sample within SiC susceptor. It is due to the SiC absorbs most of the microwave power whereas the alumina transmits the power into the samples. Since the SiC absorbs most of the power the heat is transferred from the SiC into the sample mainly in conventional mode. Consequently, it is observed maxima in temperature at the interface between sample and susceptor and the temperature decreases when moves from the interface to the center of the sample.
Figure 4. Dispersal of power and temperature within bread samples enclosed in susceptors during lateral incidence.

Figure 5 illustrates the dispersal of power and temperature within the susceptors and bread samples exposed to radial incidence. It may be noted that the power and temperature distributions within the samples and susceptors due to radial incidence are lower compared to that of the lateral incidence (Figure 4). It is observed that the difference in temperature is small when comparing the temperature distribution in the bread sample within the alumina susceptor and bread sample within the SiC susceptor due to radial incidence.

3.2. Average power absorption: Effect of susceptor

The variations of average power absorption with sample dimension for beef and bread samples enclosed in alumina and SiC susceptors of varying thickness are shown in Figs. 6(a)−(d). The resonating sample dimension can be characterized in terms of wave number \( N_{w,1} = \frac{2R_1}{\lambda_1} \), which is the ratio of the sample dimension (2\( R_1 \)) to the wavelength of microwave within the sample (\( \lambda_1 \)) [6]. Thin sample regime corresponds to \( N_w \leq 0.1 \).
where, almost the entire sample undergoes a similar power absorption [6]. In contrast, power absorption occurs only near the incident surface for thick samples corresponding to \( (\frac{N_w,1}{\lambda_1} > 3D_p,1,1) \).

In thin sample regime, the average power is found to be monotonically increase for smaller susceptor thicknesses \( (t_s = 1 \text{ and } 2 \text{ mm}) \) [Figures 6(a)–(c)] except for bread samples with SiC susceptor. For bread samples with SiC susceptor, the average power is found to monotonically decrease even with the addition of smaller thickness of SiC susceptors for thin sample regime [Figure 6(d)]. However, for larger susceptor thicknesses \( (t_s = 5 \text{ mm and } 1 \text{ cm}) \), the average power is found to monotonically decrease for all cases within thin sample regime While, the average power is decreased to 3.79 W cm\(^{-3}\) for the addition of larger susceptor thickness \( (t_s = 1 \text{ cm}) \) [Figure 6(a)]. Similar non-linear behavior of average power absorption is found for thin sample regime with particular sample radius for the rest of the cases [Figures 6(c)–(d)].

The non-linear trend of average power is found to more predominant in resonating regime for samples with alumina susceptor [Figures 6(a) and (c)]. The average power reaches a primary maximum in the resonating regime and thereafter decreases to a minimum for
Figure 6. Average power within samples enclosed in susceptors (containers): (a) beef enclosed in SiC (b) bread enclosed in alumina (c) beef enclosed in SiC and (d) bread enclosed in SiC. Various susceptor thicknesses ($t_s$) such as 1 mm, 2 mm, 5 mm and 1 cm are considered samples with alumina susceptor. Further, the average power reaches to a secondary maximum. This oscillating behavior of average power is found to occur within resonating regime due to resonance. However, the SiC susceptor is found to suppress the oscillating behavior of average power absorption for both beef and bread samples within resonating regimes [Figures 6(b) and (d)]. The average power is found to decrease with SiC susceptor thickness and reach almost uniform average power for larger susceptor thickness ($t_s = 1$ cm). In thick sample regime, the average power absorption is found to monotonically decrease with sample radius [Figures 6(a)–(d)]. The addition of both the susceptors decreases the average power absorption for samples within thick sample regimes [Figures 6(a) – (d)]. Therefore, the average power is found to be almost constant for larger susceptor thickness.

4. Conclusion
A preliminary analysis has been conducted to examine the influence of susceptor while microwave heating of 2D cylindrical food samples. Two different sample food materials (beef and bread) and two different susceptors (alumina and SiC) have been considered for the study. The alumina susceptor is recommended for heating high lossy materials as it enhances the heating rate. Even though SiC susceptor quell the power absorption of both high lossy and low lossy samples, it is recommended for low lossy materials as it increases the uniformity of heating. It is found the susceptor thickness and sample dimension strongly influence the average power absorption within the samples. The maximum average power absorption is occurred at specific sample dimension for particular susceptor thickness and these sample dimension lies within resonating regime. Therefore, it is recommended to use this specific sample dimension to achieve high heating rate.

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