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A theoretical analysis on the effect of containers on the microwave heating of materials

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ABSTRACT

Microwave heating is generally performed by positioning the sample within a container. The container can reflect, absorb or transmit microwaves based on the dielectric properties and that can influence the microwave heating characteristics of the sample. This work is an attempt to theoretically analyze the alteration of the microwave heating characteristics of materials due to the use of either a low-lossy alumina container or a high lossy SiC container. The heating characteristics have been simulated for the high-lossy beef and low-lossy bread samples of a fixed dimension by solving the coupled energy balance equation and detailed Helmholtz wave propagation equations within the sample-container assembly. It has been shown that the microwave heating characteristics can be significantly altered in the presence of the container based on the relative dielectric properties of the materials. The alumina container has been found to be efficient to enhance the microwave heating efficiency of the high lossy material such as beef, while the rapid microwave heating of the SiC container has been found to be beneficial to enhance the heating of the low lossy material such as bread in some cases.

1. Introduction

Microwave heating has been used for a wide variety of applications due to its high efficiency, short processing time and uniform heating. Major processing applications of microwaves include heating, drying, food processing, material processing, medical therapy, chemical reactions etc. [1–9]. Microwave heating is caused by the interaction of the propagating waves with the dielectric materials and the energy dissipation due to this interaction leads to the volumetric heat generation within the material. The dielectric loss of the material quantifies the ability of the material to convert the microwave energy into heat. The high lossy materials heat up faster while the low lossy materials take comparatively longer time.

In addition to the dielectric properties, the efficiency of microwave heating also depends on several other factors (such as shape and size of the sample, type of the cavity, and position of the sample within the cavity). It has been shown that the dimension of the sample plays a critical role in determining the microwave heating pattern based on the dielectric properties of the material [10–15]. Microwave heating occurs internally with either a single heating front or multiple heating fronts if the sample dimension is lower than the microwave penetration depth (a function of the dielectric properties of the material). On the other hand, microwave heating occurs from the surface and approaches the conventional heating pattern, if the sample dimension exceeds the penetration depth. An earlier study shows that based on the dielectric properties, the heating pattern can undergo a significant change due to even a slight change in the sample dimension [16]. Microwave heating has also been shown to be significantly influenced by either the shape of the sample [17–22] or the position of the sample within the cavity [23,24] due to the alteration of the electromagnetic field. Another important factor that may influence the microwave heating pattern is the presence of a secondary material such as the container or support. Microwave processing is generally carried out by placing the sample either on a support or within a container (tubular in most of the cases). Correspondingly, there is a possibility of the modification of the electromagnetic field based on the thickness and dielectric properties of the container or support. Microwaves can be absorbed, transmitted or reflected back by the secondary material leading to an alteration of the microwave heating characteristics of the sample. It has been shown in the earlier works on the theoretical analysis of microwave heating of semi-infinite slabs that the presence of a high-lossy support (e.g. silicon carbide) may suppress the

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microwave heating of the slabs, but that may improve the uniformity of the microwave heating based on the slab dimension and material dielectric properties [25–28]. On the other hand, it was possible to enhance the heating of the slabs via the use of a low-lossy support (e.g. alumina) in some cases [25–28].

The present work considers the effect of the commonly used low and high lossy tubular containers on the microwave heating characteristics of 2D cylindrical samples. The cylindrical samples are encountered in majority of the applications including food processing, material processing and synthesis. It may be noted that a wide range of food items (including vegetables, sandwich rolls etc.) as well as the green compacts used for the material processing (such as sintering and synthesis) are near cylindrical in shape. As the processing is carried out in tubular containers in majority of the cases, there is a demand to analyze the effect of the container in order to provide a better understanding of the process and achieve the optimum heating scenario. This work numerically simulates the detailed microwave propagation within the sample-container assembly and investigates the influence of low lossy alumina and high lossy SiC containers on the microwave heating of two different samples (high-lossy beef and low-lossy bread) during the exposure to lateral and radial irradiations. The microwave propagation has been modelled via Helmholtz wave equations (time harmonic representation of the Maxwell's equations). The heating dynamics have been simulated by using Galerkin finite element method and Crank-Nicholson time integration scheme. The finite element based solution technique has been shown to be computationally efficient involving a coarser mesh and a much larger time step than the other solution techniques such as FDTD [2,4]. This work also provides the analytical solutions for some cases to justify the accuracy of the numerical simulations.

2. Governing equations and solution procedure

2.1. Electromagnetic wave propagation: induced electric field

Consider the lateral and radial incidences of uniform plane microwaves on the composite domain of a cylindrical sample of radius R_1 within a tubular container of outer radius R_2, as shown Fig. 1 (subplots (a) and (b), respectively). Here, the lateral incidence is assumed to be TM^Z polarized, such that the electric field is aligned along the longitudinal axis of the cylinder [refer to Fig. 1 (a)]. The propagation of microwaves through the composite cylinder can be represented via the following Helmholtz equations:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_l}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 E_l}{\partial \theta^2}+\kappa_l^2 E_l=0, \{r,\theta\}\in\Omega_l; l=1 \text{ and } 2, \quad (1)$$

where E_l is the induced electric field and k_l is the wave propagation constant within domain Ω_l ($l=1,2$) with the subscripts 1 and 2 referring to the sample and container respectively (see Fig. 1). The Helmholtz equations for the sample and container are coupled via the interfacial continuity of electric and magnetic fields (E_l and $\partial E_l/\partial r$, respectively) as follows:

$$@\ r=R_1:\left\{E_1=E_2, \frac{\partial E_1}{\partial r}=\frac{\partial E_2}{\partial r}.\right. \quad (2)$$

In addition, the Helmholtz equations are subjected to the following radiation boundary conditions at $r=R_2$ to account for the scattering of microwaves from the outer surface of the container [15]:

$$\left.\frac{\partial E_2}{\partial r}\right|_{R_2}=\sum_{n=0}^{\infty}\left[E_0^L\epsilon_n i^n\kappa_0\left(J_n'(\kappa_0R_2)-J_n(\kappa_0R_2)\frac{H_n^{(1)\prime}(\kappa_0R_2)}{H_n^{(1)}(\kappa_0R_2)}\right)\cos(n\theta)+\frac{\epsilon_n\kappa_0H_n^{(1)\prime}(\kappa_0R_2)}{2\pi H_n^{(1)}(\kappa_0R_2)}\int_0^{2\pi}\left.E_2\right|_{R_2}\cos[n(\theta-\theta')]d\theta'\right], \quad (3)$$

for the lateral irradiation (with $\epsilon_n=1$ for $n=0$ and $\epsilon_n=2$ for $n>0$) and

$$\left.\frac{\partial E_2}{\partial r}\right|_{R_2}=-\kappa_0\frac{H_1^{(1)}(\kappa_0R_2)}{H_0^{(1)}(\kappa_0R_2)}E_2|_{R_2}-\frac{4iE_0^R}{\pi R_2H_0^{(1)}(\kappa_0R_2)}, \quad (4)$$

for the radial irradiation. In the above equations, J_n and $H_n^{(1)}$ are the n-th order Bessel and Hankel function of first kind, respectively with the prime denoting the first derivative, κ_0 is the free space propagation constant and E_0^L and E_0^R are the intensities of the incident electric fields for the lateral and radial irradiations, respectively. The intensities of the incident electric fields are related to the corresponding fluxes of incident radiation (I_0^L and I_0^R for the lateral and radial incidences, respectively) as

$$E_0^L=\sqrt{\frac{2I_0^L}{c\varepsilon_0}} \text{ and } E_0^R=\sqrt{\frac{2I_0^R}{c\varepsilon_0}}, \quad (5)$$

where c and ε_0 are the speed of light and free space permittivity respectively. As shown in the previous work by Bhattacharya et al. [15], the flux of incident radiation for the radial incidence (I_0^R) has to be 25% of the flux of incident radiation for the lateral incidence (I_0^L) to maintain the equivalence between the two incidences, i.e. $I_0^L=4I_0^R\equiv I_0$ as shown in Fig. 1. It may be noted that the radial incidence can be simulated by considering the lateral incidence on a rotating sample, where the speed of the rotation is sufficiently high.

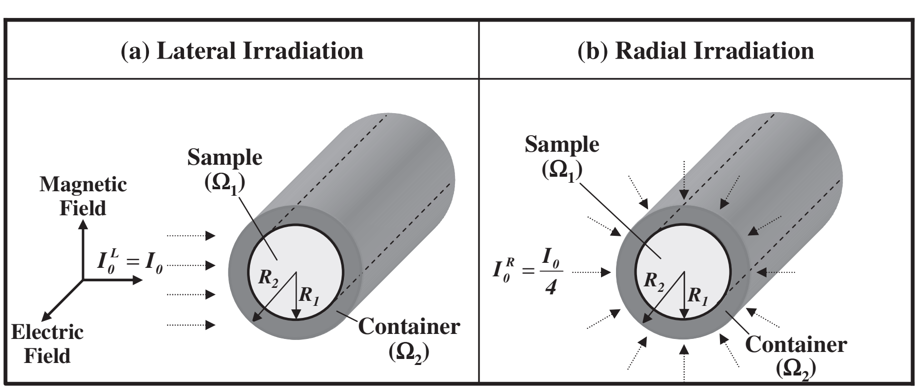

Fig. 1. Schematic representation of (a) lateral and (b) radial incidences on the sample-container assembly.