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Role of various distributions of discrete samples on efficient microwave associated material processing

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HIGHLIGHTS

- Efficient microwave processing is analyzed with discrete samples.
- Discrete samples replace continuous samples where microwave absorption is less.
- Intermediate air layer plays a critical role on the interference patterns within discrete samples.
- Microwave power is found to be enhanced 2–3 times for specific length scales.
- Multiple discrete samples are found to be effective based on minimal degree of thermal runaway.

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ABSTRACT

Microwaves are shown to provide higher heating rates, however, the destructive interference of propagating waves leads to poor heating performance for specific lengths of samples. Enhanced processing rates for all length scales due to microwave incidence would be important for material processing and current work on discrete material processing involving intermediate air layers with microwave incidence attempts to fill the gap. Simulation studies involve electric field, microwave power and temperature which are obtained based on microwave propagation and energy balance equations. A preliminary investigation on average power absorption within beef (highly lossy) and bread (low dielectric loss) samples vs sample thickness exhibits a few local minima of average power which forms the basis of investigation on the role of discrete samples. The thickness of air layer plays a significant role to dramatically alter the interference of waves and power absorption within each sample layer. It is observed that three discrete sample layers (case 3) exhibit larger heating rate than that within the continuous sample (case 1) for specific sample thicknesses. In general, case 2 samples (with one intermediate air layer) show lesser power or heating enhancement in the presence of either one side or both sides microwave incidence. Based on two factors, 'large heating rate' and 'optimal thermal runaway', the efficient heating strategy may be derived for both high and low lossy food substances.

1. Introduction

Due to the volumetric heating effects, microwaves are largely used in various processing applications involving heating, drying, chemical reactions, heat and mass transfer, oil extractions, food processing, nanomaterials processing and many more (Basak, 2007a, 2007b, 2007c; Bhattacharya et al., 2011; Ciacci et al., 2010; Constant et al., 1996; Finegan et al., 2006; Kajbafvala et al., 2012; Kowalski et al., 2010; Lam et al., 2010; Navarrete et al., 2012; Nezihe et al., 2011; Salagnac et al., 2008; Tyagi et al., 2011; Wang and Chen, 2007; Weerts et al., 2003; Wu et al., 2004). Microwaves propagate within the materials and due to interaction between propagating waves and materials, electric energy is dissipated and converted into heat throughout the material volume. Electromagnetic radiations in the frequency range 300 MHz to 300 GHz are known as microwaves. Microwave heating is characterized by the interaction of waves with the materials in the entire volume and the dissipation of electric energy during the transport process results into heat. Therefore, microwave assisted material processing is accompanied by volumetric heat generation within the material. The material dielectric loss which quantifies the ability to convert microwave into heat energy is also responsible for heating rates within samples. Consequently, highly lossy samples heat up faster and substance with low loss takes up longer time to heat. Enhanced processing rates are typical characteristics for microwave heating and a number of earlier research is focussed on enhanced material processing assisted by microwave heating.

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Nightingale et al. (1997) studied microstructural development during microwave sintering of yttria–zirconia ceramics. Microwave sintered sample is compared to conventionally heated samples. It was observed that microwave heating enhanced the densification processes occurring during constant rate heating for both materials. Bradshaw (1999) also explored possibilities of enhanced mineral processing using microwave heating. Basak (2004) carried out theoretical studies on enhanced processing rates during microwave heating of oil–water emulsions. The enhanced rate is observed during resonance which corresponds to constructive interference of propagating waves within emulsions. Later, Basak and Priya (2005) and Basak (2007a) analyzed enhanced heating rates for microwave heating of samples in the presence of metallic or ceramic or metallic-ceramic composite plates. Basak (2007b) studied the role of lateral and radial irradiations of microwaves on enhanced processing rates of cylindrical shaped samples. The enhanced processing rates and characteristics have been studied for various samples with a range of dielectric loss. Wilson et al. (2006) observed rapid heating rates and extremely rapid rates of crystallization for finite Ostwald ripening by a microwave hydrothermal process. Kowalski and Mielniczuk (2008) carried out analysis on effectiveness and stress development during convective and microwave drying. They found that the volumetric heat generation due to microwave heating enhances convective drying and combined convective-microwave drying process develops less stress in dried material. Tanaka et al. (2009) established that the mechanism of rapid and selective heating of magnetic metal oxides occur under the magnetic field of microwaves. Kharissova et al. (2010) presented a review on microwave assisted glass processing and various case studies illustrate that microwave heating is a much-faster process (requiring minutes rather than hours), yielding good product quality, in comparison with the prolonged conventional thermal treatment of glass precursors. Demirskyi et al. (2010) found that the densification kinetics rate for sintering of copper powder is faster in a single-mode microwave applicator than in the multi-mode applicator. A recent experimental investigation shows that microwave melting is twice faster than the conventional melting processes (Chandrasekaran et al., 2011).

A few earlier works on enhanced microwave power absorption involve theoretical studies on maxima on microwave power. The maxima in microwave power are often termed as ‘resonances’ which occur due to constructive interference of propagating waves within samples (Ayappa et al., 1997; Ayappa, 1999; Basak, 2003, 2004, 2005; Lee and Marchant, 2004; Bhattacharya and Basak, 2006a, 2006b; Basak, 2007a, 2007b). Resonances on average power absorption within samples were first reported by Ayappa et al. (1997) and Ayappa (1999). Later, mathematical foundation based on a closed form analysis was established to illustrate the relationship between the occurrence of resonance and sample dimensions (Bhattacharya and Basak, 2006a, 2006b). Resonances in microwave power are also observed for heating of multiphase systems and melting processes (Basak, 2003, 2004, 2005; Lee and Marchant, 2004). Analysis of resonances was also studied for lateral and radial incidences of microwaves and resonances were also found to be influenced by various elliptic to circular samples (Basak, 2007b, 2007c). While enhanced processing in the presence of microwave is advantageous, spatial hot spots may be formed and minimization of thermal runaway is one of the important issues for efficient thermal processing (Basak, 2008; Samanta and Basak, 2009).

Introduction of the concept on discrete samples was first proposed by Basak et al. (2008) and the efficient heating strategy based on higher processing rates with optimal thermal runaway was investigated for the two discrete samples separated by various thicknesses of air layers. Encouraged by optimal heating scenarios, the role of multiple discrete layers on efficient heating situation has been investigated for the first time in this work. Two typical food materials have been identified as beef (high dielectric loss) and bread (low dielectric loss). The reference sample thicknesses are chosen based on local maxima or minima on average power absorption of the continuous sample. Enhancement of overall power absorption and degree of thermal runaway are compared for two and three discrete samples.

2. Modeling and simulation

2.1. Electric fields: amplitudes and phase states

Analysis of electric field, microwave power absorption and temperature distributions was carried out in the presence of uniform plane waves where electric and magnetic fields are perpendicular to the direction of propagation. A sample incident with microwave radiation is schematically illustrated in Fig. 1. Current study involves one continuous slab (case 1; Fig. 1a), two

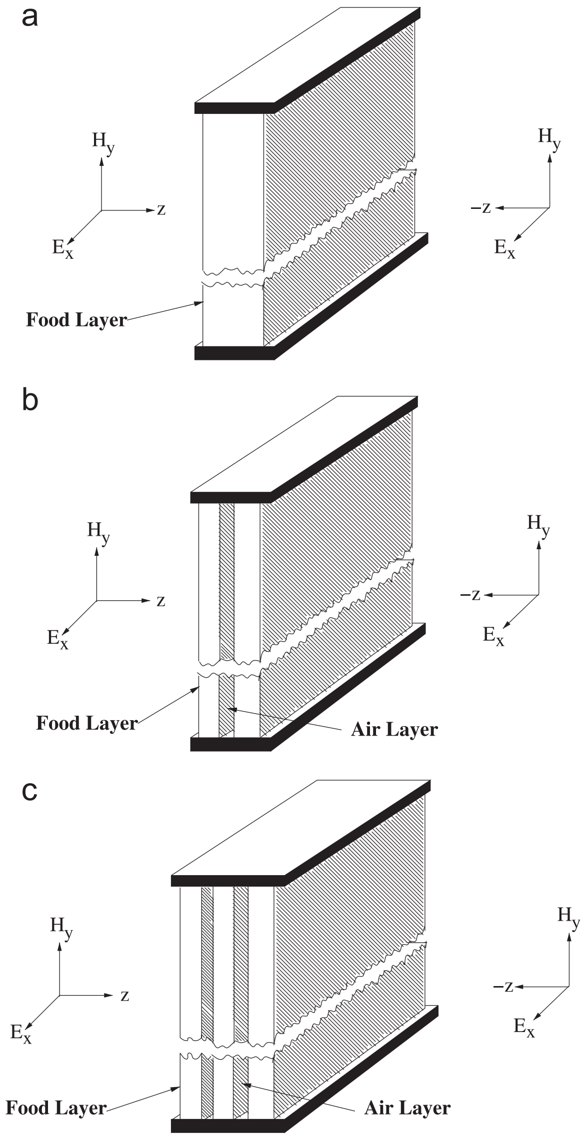

Fig. 1. Schematic illustration of (a) continuous food sample (case 1), (b) two discrete food samples with intermediate air layer (case 2) and (c) three discrete food samples with two intermediate air layers (case 3) incident with microwave radiations.