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# Analysis of pulsed microwave processing of polymer slabs supported with ceramic plates

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ABSTRACT

A detailed theoretical analysis has been carried out to study the role of ceramic supports (alumina and SiC) and pulsed microwave heating of polymer (Natural Rubber, NR, and Nylon 66) slabs due to various distributions of microwave incidences. Ceramic plates are typical representations as they withstand high temperature without any deformation. It is found that ceramic plates influence the heating processes significantly and local hot spots within samples are governed by specific type of ceramic plates for various sample thicknesses and distributions of microwave incidence (one side or both sides). Optimized pulsing of microwave incidence has been employed to minimize the thermal runaway or hot spots in order to achieve uniform temperature distribution and pulsing is introduced based on two parameters: setpoint ($\Delta T_S$) and on–off constraint ($T'$). Detailed spatial distributions of power and temperature are illustrated for a few representative length scales to demonstrate the role of local maxima in power and temperature on heating rate as well as thermal runaway with or without pulsing. Pulsing ratio (PR) has been defined as $PR = t_{off}/t_p$, where $t_{off}$ is power-off time and $t_p$ is the total processing time such that smaller PR denotes large processing rates. It is found that one side incidence gives smaller values of PR for both the ceramic plates whereas SiC plate may be suitable for both sides incidence with large sample thicknesses of NR samples. It is also found that larger values of setpoints also minimize PR. The setpoints along with the on–off constraint play critical role to select the heating strategy as a function of ceramic plates and types of incidence. Pulsing may not be important for smaller thicknesses of Nylon samples and SiC or alumina plates may be recommended for processing larger thicknesses of Nylon samples in presence of pulsing. Current study recommends the efficient microwave heating methodologies for polymer processing attached with ceramic plates by means of optimized pulsing for the first time.



## 1. Introduction

Microwaves are electromagnetic waves in the frequency range of 300 MHz to 300 GHz. During microwave heating, the material dielectric loss, which is a function of frequency of microwaves, is responsible to convert electric energy into heat and therefore volumetric heat generation would occur due to the interaction between material particles and electric field during wave propagation. In contrast, heat transport within the material volume occurs from the hot surface which is exposed to burner and no heat generation within the material would occur during the convectional heating process. Volumetric heat generation due to microwave propagation not only leads to larger processing rate, but the efficient processing with minimization of hot spots formation can be efficiently tuned with the operation of microwave source whereas unidirectional heating during conventional method often requires larger processing time and hot spots may occur near the hot surface-material interface. Unique applications of microwave heat processing are baking, cooking, curing, drying, enzyme inactivation, heating, precooking, thawing-tempering and many more. Based on various applications, microwave heating has gained significant attention due to brief start up time, internal heating, high efficiency and rapid processing over conventional heating methods (Wang and Chen, 2005; Polaert et al., 2005; Chen et al., 1993; Tao et al., 2006).

A few theoretical models on microwave heating have been reported by earlier workers (Yang and Gunasekaran, 2001, 2004; Gunasekaran and Yang, 2007a,b; Ayappa et al., 1991a,b, 1992; Barringer et al., 1995; Basak and Priya, 2005; Basak and Meenakshi, 2006; Jolly and Turner, 1990). Energy balance equation with a volumetric source term, which may be governed by Lambert's exponential law or Maxwell's equation, form the basis for the heating models of microwave (Basak and Priya, 2005). Earlier models mostly involve constant dielectric and thermal properties except a

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few studies by earlier researchers (Ayappa et al., 1991b, 1992). The dielectric property of a polymeric material is in general function of temperature (Mallorqui et al., 2001; Ayappa et al., 1991b, 1992). Thus energy balance equation is coupled with Maxwell equation and both equations need to be solved simultaneously for analysis of microwave heating characteristics within polymeric materials.

There are increasing demands for processing of polymeric materials in a cost-effective way. Microwave processing can also improve the properties of the material based on internal and selective heating (Chen et al., 1993; Tanrattanakul and Sae Tiaw, 2005; Porto et al., 2002; Chabinsky, 1983; Sombatsompop and Kumnuantip, 2006). In general, microwave curing of thermoset also enhances the rate of curing compared to conventional curing (Boey et al., 1999; Boey and Yap, 2001; Vimalasiri et al., 1987; Snow, 2001; Appleton et al., 2005). Snow (2001) reported that microwave heating is an effective method to preheat thermoset whereas other conventional methods pose problems. Microwave heating can also be implemented to process waste stream which involves scrap tyres and plastics (Appleton et al., 2005). A significant amount of earlier works reported that application of microwave in polymer processing is advantageous than that of conventional heating methods (Chen et al., 1993; Tanrattanakul and Sae Tiaw, 2005; Porto et al., 2002; Chabinsky, 1983; Sombatsompop and Kumnuantip, 2006; Boey et al., 1999; Boey and Yap, 2001; Vimalasiri et al., 1987; Snow, 2001; Appleton et al., 2005; Hoogenboom and Schubert, 2007; Jullien and Valot, 1983, 1985).

Current work stems from a few applications of microwave heating for processing with thermoplastics and thermosets. Yarlagadda and Chai (1998) reported a novel process for joining thermoplastic polymers using microwave heating. They carried out the thermoplastics joining process in two separate stages: the first stage consisting of directly inducing microwave energy to the specimen joint interface, whilst the second stage compose of applying primers in the form of epoxy-based resin to promote the joining of the materials by means of microwave energy. Ku et al. (2000) studied variable frequency microwave (VFM) processing for five different thermoplastic matrix composites over a range of frequencies to achieve uniform heating. The optimum frequency band for microwave processing of these five materials was found in the range 8–12 GHz. Further studies of Ku et al. (2001, 2003) find that VFM heating offers rapid, uniform and selective heating over a large volume at a high energy coupling efficiency. Ku et al. (2005) also carried out experimental investigations and they found that microwave energy can rapidly cure several types of two-part epoxy-based adhesives, e.g., Araldite. Thostenson and Chou (2001) studied both microwave curing and thermal curing of 24.5 mm (1 in) thick-section glass/epoxy laminates based on numerical simulation and experiments for processing thick laminates within a conventional autoclave and a microwave furnace. Both numerical and experimental results showed that volumetric heating due to microwaves promotes an inside-out cure and can dramatically reduce the overall processing time. Although a number of attempts has been made on experimental and theoretical studies on microwave processing of thermoplastics and thermosets, but a detailed theoretical model to characterize microwave power, temperature and analysis on efficient microwave heating processes in waveguides for thermoplastics and thermosets attached with various supporting plates is yet to appear in literature.

An important issue on microwave processing of polymer samples is thermal runaway which is primarily due to large microwave power absorption or heat generation at high temperature for temperature dependent dielectric properties. Moriwaki et al. (2006) carried out experimental studies on microwave heating of poly(vinyl chloride) (PVC) and they elucidated the temperature dependency of microwave power absorption on PVC by observing the temperature profile during irradiation. Their work is based on following conclusions: (i) at the beginning of microwave irradiation onto PVC, the temperature rises in direct proportion to the strength of the incident microwave power and irradiation time, (ii) after exceeding a critical condition, the temperature on PVC starts to rise quickly leading to thermal runaway and (iii) at higher incident microwave power, the thermal runaway starting temperature is observed. Finally, they found that dehydrochlorination of PVC is maximum at a critical temperature which is achieved during thermal runaway condition. A few applications on microwave heating of materials require uniform temperature within the entire volume and that can be achievable with control of microwave incidence (Gunasekaran and Yang, 2007a). However, thermal runaway may be a critical issue either to achieve uniform temperature or to reach a critical maxima of temperature and temperature control within samples may be essential.

Pulsed microwave heating may be useful to reduce the unevenness of temperature distribution within samples as proposed by earlier researchers (Yang and Gunasekaran, 2001, 2004; Gunasekaran and Yang, 2007a,b). Pulsing was employed for fixed sets of power-on time ($t_{on}$) and power-off time ($t_{off}$) for various levels of microwave power inputs (Yang and Gunasekaran, 2001, 2004; Gunasekaran and Yang, 2007a). Yang and Gunasekaran (2001, 2004) reported that the unevenness of temperature distribution obtained during continuous microwave heating was dramatically reduced when pulsed microwave heating was used. However, they found that pulsed microwave processing requires more processing time than that with continuous microwave incidence. Later, Gunasekaran and Yang (2007a) reported that pulsed microwave heating resulted in more uniform temperature distribution in samples than continuous microwave heating at the same average microwave output power based on the oven settings. Optimized pulsed microwave processing for precooked smashed potato has also been analyzed recently by Gunasekaran and Yang (2007b). They have proposed a different pulsing strategy based on temperature difference in two locations within samples, maxima in temperature within samples and fixed processing time. They found that maximum microwave power-on and power-off temperature constraints are very critical for optimal application of pulsed microwave heating. Power-on temperature constraint produced suitable temperature gradient whereas power-off temperature constraint allowed the temperature equalization to occur. Their analysis was aimed to optimize total power consumption by suitably constraining the process parameters for a given sample size. They finally recommended the most efficient process among all the cases considered is the heating of 2.4-cm sample under $\Delta T = 20\,^{\circ}$C during power-on period whereas $\Delta T = 3\,^{\circ}$C during power-off period.

Pulsing applications of microwave heating have also been investigated for strength analysis of ore samples (Jones et al., 2007) and for curing of epoxy resins (Fu and Hawley, 2000). Fu and Hawley (2000) found that continuous microwave assisted curing produced noticeably higher reaction rates than pulsed microwave curing. However, they have not reported thermal runaway during curing operations. Jones et al. (2007) reported power densities in both continuous wave and pulsed microwave applications and they concluded that pulsed treatment is more effective for weakening rocks.

Although Gunasekaran and Yang (2007b) carried out the analysis on optimization of pulsed microwave heating with constraints for microwave power off and on conditions, but their study does not compare the importance of reduction in thermal runaway with pulsed incidence that with continuous microwave heating. Current study focuses on microwave heating policy with one side and both sides incidence to the polymer sample and thermal runaway situation has been studied for specific sample thickness which has spatial resonances or maxima in power absorption both for continuous and pulsed microwave incidence. In addition, the supporting plate is also a key factor which also governs the thermal runaway and these issues have been addressed first time in this work. The difference in