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# Theoretical analysis of efficient microwave processing of oil–water emulsions attached with various ceramic plates

Sujoy Kumar Samanta, Tanmay Basak *

*Department of Chemical Engineering, Indian Institute of Technology, Madras, Chennai 600 036, India*

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**Abstract**

A detailed theoretical analysis has been carried out to study efficient microwave processing of 1D emulsion samples placed on ceramic plates (alumina, SiC). The effective dielectric property of an emulsion is a strong function of the continuous medium of the emulsion (o/w or w/o). A preliminary study has been carried out via average power within an emulsion vs emulsion thickness diagram for various cases. The maxima in average power, also termed as 'resonances', are observed for specific emulsion thicknesses and the two consecutive resonances are termed as $R_1$ and $R_2$ modes. The heating scenarios have been analyzed at the dominant resonance mode. Based on spatial distributions of power and temperature for various cases, alumina support at the left side may be recommended as the optimal heating strategy due to greater heating rates with controlled thermal runaway for both o/w and w/o emulsion samples whereas SiC support may be favored for o/w emulsion samples due to lesser thermal runaway. A comparison of the heating characteristics has been illustrated for 50% o/w and 50% w/o emulsion samples to analyze the role of continuous medium of an emulsion on heating effects. The distribution of microwave incidences also plays an important role to minimize thermal runaway for specific o/w and w/o emulsions.


*Keywords:* Microwave; Emulsion; Oil-in-water; Water-in-oil; Ceramic plates

## 1. Introduction

Much attention has recently been devoted to microwave energy due to its potential applications in food and chemical process industries (Ayappa, Davis, Crapiste, Davis, & Gordon, 1991; Basak & Ayappa, 1997; Chan & Chen, 2002; Chatterjee, Basak, & Ayappa, 1998; Fakhouri & Ramaswamy, 1993; Fang & Lai, 1995; Fowler & Bejan, 1991; Khraisheh, Cooper, & Magee, 1997; Khraisheh, McMinn, & Magee, 2000, 2004; Kratchanova, Pavlova, & Panchev, 2004; Lin, Anantheswaran, & Puri, 1995; McMinn, 2004, 2006; McMinn, Khraisheh, & Magee, 2003; Oliveira & Franca, 2002; Shiinoki, Motouri, & Ito, 1998; Xia, Lu, & Cao, 2004). Various oil-in-water (o/w) and water-in-oil (w/o) emulsions occur in industrial operations, such as oil and gas production, food processing industries, which include dressings, sauces, butter, mayonnaise, and many more. Microwave heating offers a faster processing rate due to its 'volumetric heating' effects. During microwave heating, the material dielectric loss which is a function of frequency of microwaves, is responsible to convert electrical energy into heat.

The theoretical studies on combined microwave and thermal transport were first reported by Ayappa et al. (Ayappa et al., 1991; Ayappa, Davis, Davis, & Gordon, 1992) for heating of 1D slabs and 2D cylinders. The theoretical analysis is primarily based on solutions of wave propagation equation. The microwave power absorption may exhibit several local maxima within a sample based on constructive interference of waves. Consequently, the

* Corresponding author. Tel.: +91 44 2257 4173; fax: +91 44 2257 0509. *E-mail address:* tanmay@iitm.ac.in (T. Basak).

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**Nomenclature**

| | |
|---|---|
| $A_{x,l}$ | amplitude of stationary wave for $l$th layer ($\mathrm{V\,m^{-1}}$) |
| $c_p$ | specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$) |
| $c$ | velocity of light ($\mathrm{m\,s^{-1}}$) |
| $E_x$ | electric field intensity ($\mathrm{V\,m^{-1}}$) |
| $f$ | frequency (Hz) |
| $h$ | heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$) |
| $H_y$ | magnetic field intensity ($\mathrm{A\,m^{-1}}$) |
| $k$ | thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$) |
| $L$ | half-slab thickness (m) |
| $L_s$ | sample thickness (m) |
| $q$ | microwave source term ($\mathrm{W\,m^{-3}}$) |
| $t$ | time (s) |
| $T$ | temperature (K) |
| $z$ | distance (m) |

*Greek symbols*

| | |
|---|---|
| $\epsilon_0$ | free space permittivity ($\mathrm{Farad\,m^{-1}}$) |
| $\kappa$ | propagation constant |
| $\kappa'$ | relative dielectric constant |
| $\kappa''$ | relative dielectric loss |
| $\kappa^*$ | relative complex dielectric properties |
| $\lambda_m$ | wavelength in the medium (m) |
| $\rho$ | density ($\mathrm{kg\,m^{-3}}$) |
| $\phi$ | fraction of the dispersed phase (–) |
| $\delta_{x,l}$ | phase difference in stationary wave for $l$th layer |
| $\omega$ | angular frequency ($\mathrm{rad\,s^{-1}}$) |

*Subscripts*

| | |
|---|---|
| c | continuous phase |
| d | dispersed phase |
| eff | effective property |
| l | layer number |

*Superscripts*

| | |
|---|---|
| t | transmitted wave |
| r | reflected wave |

localized or non-uniform heating in samples occurs due to volumetric heating effects, and considerable further studies were devoted on analysis of maxima in power or 'resonances' due to microwave propagation. Ayappa et al. (Ayappa, Davis, Barringer, & Davis, 1997) found maxima in average power occurring only for fixed sample dimensions of 1D slabs and 2D cylinders. They also established suitable relationships between occurrence of resonance and sample size. Microwave heating and transport models were further applied for thawing and heating of multiphase systems in recent investigations (Barringer, Ayappa, Davis, Davis, & Gordon, 1995; Basak, 2003, 2004; Basak & Ayappa, 1997, 2001, 2002) and greater rates in material processing are observed due to resonances. Recently, Basak and Priya (Basak & Priya, 2005) have investigated the heating of water (high dielectric loss) and oil (low dielectric loss) samples with various ceramic supports. A large amount of earlier research is primarily devoted on microwave heating of pure substance or layered materials and a few studies revolve around microwave heating and processing of multiphase systems, especially emulsions.

Emulsion consists of a continuous phase and a dispersed phase and based on the nature of continuous medium, two typical emulsions are considered as oil-in-water (o/w) and water-in-oil (w/o). A few earlier studies on oil–water emulsions were carried out for several applications such as measurement of dielectric properties of oil–water emulsions (Pal, 1994; Erle, Regier, Persch, & Schubert, 2000), heating of oil–water emulsions (Barringer et al., 1995; Basak, 2004), stability analysis of oil–water emulsions (Gu, Decker, & McClements, 2007; Hodge & Rousseau, 2003; Mitidieri & Wagner, 2002; Xia et al., 2004), and demulsification of water-in-oil emulsions (Fang & Lai, 1995; Chan & Chen, 2002). Pal (1994) reported a comprehensive review of the available techniques on measurement of the oil and water content of emulsions and effective dielectric properties of oil–water emulsions. Later, Erle et al. (Erle et al., 2000) also studied dielectric properties of o/w and w/o emulsions measured at a frequency of 2.45 GHz by an open-ended coaxial-line probe. They proposed correlations for the effective dielectric properties of oil–water emulsions and their correlations are found to be strong functions of the continuous medium.

An earlier theoretical and experimental investigation on microwave heating of oil–water emulsion systems was carried out by Barringer et al. (Barringer et al., 1995). They carried out experimental studies for various oil–water fractions with fixed beaker radii in a microwave oven. Based on their observations they found maxima in average power occurring only for fixed sample dimensions. Fang and Lai (Fang & Lai, 1995) and Chan and Chen (Chan & Chen, 2002) carried out experimental studies on the conditions of demulsification, especially on water-in-oil emulsions. Basak (2004) carried out preliminary theoretical analysis on enhanced heating of oil–water emulsions (o/w and w/o) for specific emulsion contents in absence of any support or plate.

Emulsions may be processed in containers and ceramic materials are generally used in microwave processing as ceramics withstand high temperature during microwave heating. A detailed analysis on microwave heating of emulsions in presence of various ceramic plates may be important for studying efficient heating process which may be useful for industrial processing. Microwave heating of emulsion in presence of various ceramic plates may be non-trivial due to complex interaction between emulsions (o/w and w/o) and ceramic supports. In addition, the distributed