Applied Thermal Engineering 36 (2012) 360–369

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Temperature profile prediction within selected materials heated by microwaves at 2.45GHz

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ARTICLE INFO

Article history:
Received 12 July 2011
Accepted 21 October 2011
Available online 30 October 2011

Keywords:
Microwave heating
Temperature profiles
Absorbing power
Temperature prediction
Heat equation
Energy efficiency

ABSTRACT

This work presents a three-dimensional mathematical model to simulate temperature profiles inside a material heated by electromagnetic waves (EMW) at 2.45GHz. COMSOL-Multiphysics was used to simulate transient temperature profiles of pinewood, carbon, Pyrex, and combinations of such under different conditions. The model predicts that, upon exposing an 86mm wooden cube to 2.45GHz EMW for 300 s, the core temperature reached 595 K at a setting of 60 K/min, while the outer surface 365 K at 15 K/min. By mixing 50% carbon with the wooden block, the model anticipated the cube core to reach 990 K at 140 K/min, compared to 1350 K at 212 K/min with 75% carbon at the same power and after the same time. By inserting a 125cm^3 carbon cube inside the wood cube, the core reaches 3200 K, while the outer surface was 375 K and 636 K for free convection (FC) and perfect insulator (PI), respectively. Placing the same volume of carbon on the surface of the wood cube yielded a maximum temperature of 660 K under FC, compared to 1280 K with PI. Changing the material of the core cube from Carbon to Pyrex yields a temperature of 324 K in the core, with 365 K and 605 K on the outer surface in the case of FC or PI, respectively. The average percentage relative error between the measured and the predicted temperatures was ±4% and ±15% inside the pinewood and carbon respectively.

1. Introduction

A number of industrial sectors have benefited from the contrast between of microwave heating (MWH) mechanisms and conventional heating (CH). Most importantly, MWH mechanisms reply on energy conversion directly with the target material, leading heat generation volumetrically rather than through the surface of the material, as is the case with CH. Furthermore, it is well established that electromagnetic waves (EMW) have a high interaction with powder samples [1–3]. This can be used to distribute hot spots inside the media being heated to increase the microwave-induced energy transfer. Under controlled conditions, it has been demonstrated that MWH can reduce energy consumption and allow for higher product selectivity in certain reactions compared to CH [1,3–20].

Theoretically, MWH should lead to equivalent heat generation within the material. However, in practice, it is likely to produce a non-uniform temperature distribution [21–27]. This aspect makes modelling of the heat transfer mechanisms rather complex. As an example, Fig. 1 shows wooden blocks heated in a microwave oven for 360 s at different power settings. Although Fig. 1-A and B were heated at same power setting (2.3 kW), use of thermal insulation on the outer surface influenced their core temperature. While 1-C was heated at 2.7 kW for the same time (360 s), 1-B still produced a higher temperature compared to others. These variances result from different parameters, the most important being the heat transfer on the outer surface [16,23].

Temperature profiles for materials exposed to MWH have been studied in the literature [21–29]; Most of these studies reported that MWH leads to non-uniform distribution of temperature and hot and/or cold spots inside the heated material [21–30], but a little effort has been done in order to study how can be controlling in those observations.

The primary objective of this work is to present the development and validation of a mathematical model to predict temperature profiles within a wood cube subjected to MWH. The model was solved using COMSOL-Multiphysics applications, taking into account the effect of (1) heat induction in a wooden cube of known dielectric and physical properties upon irradiation by 2.45GHz microwaves at 2.3 KW nominal power and (2) heat transfer due to free convection or perfect insulator (FC or PI) at the surface of the cube. The software COMSOL-Multiphysics will then be used to

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doi:10.1016/j.applthermaleng.2011.10.049

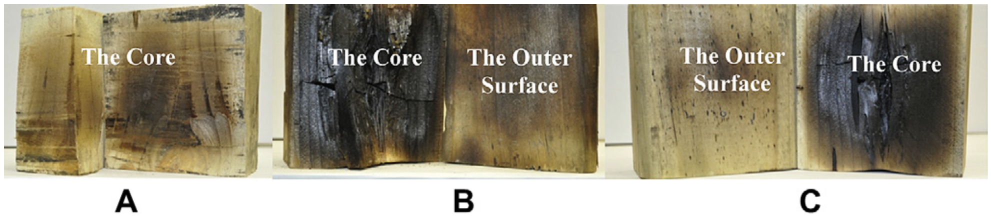

Fig. 1. Wood blocks heated by 2.45GHz microwaves for 360 s at: (A) 2.3kW with FC, (B) 2.3kW with PI, and (C) Power 2.7kW with FC.

predict temperature profiles within the wood cube (1) subjected to surface heat loss, (2) subjected to perfect insulation at the surface, (3) upon replacing a volume of wood with an excellent converter of microwave-to-heat (carbon), and (4) upon replacing the same volume of wood with a microwave-transparent material (Pyrex). Cases (3) and (4) are compared to (1) and (2) to highlight the variation of temperature profiles within composite exposed to microwave heating in the presence of materials of contrasting dielectric, and physical properties. Such discussions aim at (1) improving the understanding of temperature profiles within composite materials heated by microwaves and (2) developing approaches to influence/control temperature profiles through material selection.

2. Fundamentals of MWH

2.1. Microwave/material interaction

Electromagnetic waves consist of an electric and magnetic field orthogonal to each other. The dominant mechanism of microwave-induced heating at 2.45GHz involves the agitation of molecular dipoles due to presence of an oscillating electric field (for non-magnetic materials). In the presence of an oscillating field, molecular dipoles reorient themselves in order to be in phase with the alternating field. These orientations are restricted by molecular interaction forces, increasing molecular kinetic energy. As kinetic energy increases, system temperature increases within a short time. This period of time depends on the electrical and physical properties of the heated material [1,17,18,23,31–33].

Materials can be classified into three categories depending on their response to the EMW:

- Materials that reflect waves (highly conductive materials) e.g., metals.
- Materials that are considered EMW-transparent e.g., ceramics, quartz, glass.
- Materials that absorb waves, e.g., carbon, water, methanol. This category has the highest response to microwaves and most of them are relevant to microwave chemistry as they have high thermal response [30,33].

In order to apply microwave energy to a chemical process, at least one or more components of the system must be a good microwave absorber. Fortunately, many organic compounds, metal oxides and popular solvents are good or, at least, moderate absorbers for the EMW as they have high thermal response.

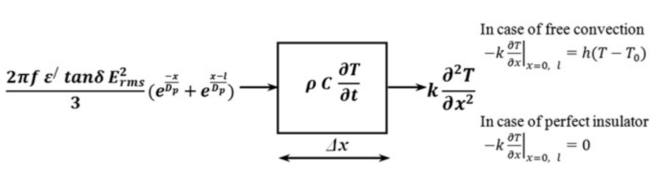

Fig. 2. Schematic representation of the thermal balance on a dielectric element in the system.

2.2. The main parameters describing MWH

For non-magnetic material, the main parameter which describes the level of heat generation inside a microwave absorbent material is the complex permittivity(ε^*) as represented in equation (1).

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

The real part of the complex permittivity is called dielectric constant (ε') which represents the amount of electric energy that can be stored within the heated material. The imaginary part is called “loss factor” (ε'') and represents the ability of the heated material to dissipate microwave energy. The ratio between these parts is called “loss tangent”; it is used to convert microwave energy to thermal energy within a material [1,3,20,31,34,35], as represented in equation (2).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2}$$

2.3. Dissipated/absorbed power

The dissipated power inside a microwave cavity could be represented as energy generated inside a heated material. For non-magnetic materials, it can be represented in the form of equation (3).

$$P = \omega\varepsilon_0\, \varepsilon''_{\text{eff}}\, E^2_{\text{rms}} \tag{3}$$

or

$$P = 2\pi f\, \varepsilon' \tan\delta\, E^2_{\text{rms}} \tag{4}$$

Where P is the absorbed power per unit volume $[W/m^3]$, $\varepsilon''_{\text{eff}}$ is the effective dielectric loss factor ($\varepsilon_0\varepsilon''_{\text{eff}} = \varepsilon'\tan\delta$) [-], ω is the angular frequency ($\omega = 2\pi f$) $[s^{-1}]$, and E_{rms} is the root mean square of the electric field $[V/m]$.

In the case of magnetic materials, equation (4) should be replaced by equation (5) [26,32,36,37].

$$P = \omega\varepsilon_0\, \varepsilon''_{\text{eff}}\, E^2_{\text{rms}} + \omega\mu_0\, \mu''_{\text{eff}}\, H^2_{\text{rms}} \tag{5}$$

Table 1
Input parameters for MWH model [39,40,42].

Sample type	C (kJ/kg K)	ρ (kg/m^3)	k (W/mK)	ε'	ε''	D_p (mm)
Pinewood	2.5	470	0.17	2.7	0.53	59
Carbon	0.93	380	0.11	7	2	26
Pyrex	0.75	2230	1.005	4	0.005	7800
25% carbon and 75% wood	2.1	447.5	0.155	3.77	0.9	42
50% carbon and 50% wood	1.7	425	0.14	4.85	1.27	34
75% carbon and 25% wood	1.3	402	0.125	5.92	1.634	29