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Numerical simulation of heating behaviour in biomass bed and pellets under multimode microwave system

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ABSTRACT

Domestic multimode microwave (MW) systems have been extensively used to process biomass materials for proof of concept. However, one of the major drawbacks for these systems is the non-uniform heating. Therefore, the aim of this article was to predict the heating behavior of empty fruit bunch (EFB) biomass in both bed and pellet form using finite element based COMSOL Multiphysics software. The temperature data from a modified domestic multimode MW system at 2.45 GHz frequency was used. Quantitative validation of 10 s heating profile was performed by comparing the simulated temperature profile with the experimental temperature. The agreement of simulated temperature profiles depended on various factors such as biomass loading bed height, defining specific heat capacity value and form of biomass shape (bed or pellet). Interestingly, the location of local hot spots during MW heating of EFB bed and pellets were almost close enough in both simulation and experimental study. An optimal biomass loading height was found whereby maximum MW energy is absorbed by the sample. The effect of biomass loading height on the distribution of electromagnetic fields is discussed in the paper. This study provides a framework and required model parameters to predict temperature and optimum biomass loading for a specific geometry of MW cavity. Further, the model can be effectively used to identify hot and cold spots in the biomass material during MW heating and thereby help to design and optimize the MW applicators in terms of heating uniformity. The proposed model can also be useful to identify the electromagnetic field distribution inside the cavity.

1. Introduction

A series of articles published (about 450 derived from Scopus database) in last few decades (1980–2013), which clearly indicates the brisk progress of microwave (MW) technology in processing biomass materials because of its rapid, volumetric and selective heating features providing significant reduction in processing time. Most of the researchers [1–7] have modified the domestic MW systems in order to prove the concept of biomass heating under MW. Early works related to domestic MW assisted heating of biomass material have been reviewed in recently published papers [8–11]. Domestic MW ovens were mostly used at lab-scale to prove the concept due to their easy accessibility from the market, economical, can be easily modified, low maintenance, and the system can be set-up easily and quickly. In addition to this, microwave applicators are easy to construct, electromagnetic field inside the cavity can be homogenised by stirring the load [12] or by installation of mode stirrer, and multiple MW inlet ports can be installed [13].

However, the main issue with the domestic multimode MW system is the non-uniform heating behavior which results in a substantial temperature gradient. Besides this, use of domestic MW system can lead to inaccuracy in temperature profiles and non-homogeneous electric fields [14]. Estimating right temperature within the biomass material under MW is very critical to the advancement of MW technology in field of biomass processing. Thus, according to Antonio and Deam [15] “Without a mechanism to explain what is going on, most people developing microwave processing techniques fall back on conventional explanations for anomalous results, such as: hot spots within the samples, ‘inverted’ temperature gradients across the samples, and an inaccurate temperature measurements”. Further, to achieve quality and uniformity in product, one has to ensure fast and thorough decomposition of biomass material under microwave. If the material is not evenly decomposed under the MW, it may not only result in a poor

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quality product, but will also consume high amount of energy. Therefore, temperature uniformity is very critical for ensuring product quality and saving in energy.

Regarding the temperature gradient, Robinson et al. [16] compared the simulated and experimental results to present significant temperature gradients within the heated materials, and dissimilar results existed depending on the method used to measure the temperature. Causes for such large thermal gradients could be uneven distribution of electric field and power density inside the MW cavity, variation in dielectric, physical, and thermal properties of biomass materials with temperature during MW processing, shape/size of microwave cavity, position of sample in the cavity, type and characteristics of sample and its heating behavior. Among these, knowledge of the electric field configuration is very essential to control the microwave heating [17] and to avoid local hot spots [18]. The changing electric field and material properties with time and temperature might contribute to an uneven absorption of MW energy and subsequent non-uniformity in heating pattern. Bradshaw et al. [19] studied the heating uniformity in a multimode MW cavity and found that the electric field was concentrated on the top of the reactor. Thus, non-uniform temperature in domestic MW system is one of the major problems [14,20]. Interestingly, the electric fields in an empty cavity are more uniform, but once the dielectric material is placed in the cavity it gets distorted [18,21]. Typically, the material in the region of high electric energy density will absorb considerably high amount of MW energy than the sample in the region of low or damped electric energy density. This is how the formation of local hot spot initiates.

Moreover, the electric field distribution in the MW cavity is highly sensitive to changes in the dielectric, thermal properties of materials [22] and the load geometry [21,23,24]. For instance, dielectric properties of materials such as empty fruit bunch (EFB) biomass [25], switchgrass [26], coal [27], and other materials [13] were reported to depend on temperature, MW frequency and moisture content. It was also reported that thermal property such as specific heat capacity (C_p) of EFB biomass is a function of temperature [25]. Other factors that determine the heating characteristics of object when subjected to MW radiation include the geometry and size of the object [28] and electromagnetic and thermal parameters [28,29]. To our knowledge, very little or no information is available in the literature that presents how the loading height and biomass material property such as C_p can affect the temperature profiles and electromagnetic fields with the means of simulation data.

As per the earlier discussion, the major problem that arises due to non-uniform distribution of heat and electric field is the formation of local "hot and cold spots" within the sample. These "hot spots" can also be generated as a consequence of mineral impurities [30]. The development of hot spot is caused due to non-uniform heating and is usually referred to as thermal runaway which is difficult to control [31]. Whatever reason could be behind the formation of hot spot, in conclusion they are not favorable for material processing. Numerical simulation can greatly help to identify and understand quantitatively about the generation of hot spot and the interaction of MW field with materials. Extensive simulation runs on computer can help to predict the occurrence of such hot spots [32] and prevent it by controlling process design and its parameters. It was reported that analytical solution of the Maxwell equations describing the electromagnetic field in the case of partially loaded domestic MW applicators are not available [13]. However, with the advancement in computational code, now it is possible to compute complex electromagnetic Maxwell's equations coupled either with heat transfer, mass transfer, or fluid mechanics.

Computer based modeling and simulation is one of the best approaches to predict the sample heating behavior and electromagnetic field distribution in the MW cavity using a real base case design. This can facilitate to optimize, design and develop efficient MW applicators for bioenergy, bioproduct and MW industries. Zhao et al. [33] has thoroughly reviewed the numerical simulation of MW heating. The COMSOL Multiphysics (COMSOL Inc., Burlington, MA, USA) code has already been successfully implemented to model MW heating and compare it with experimental measurements [34]. This software has the ability to solve both electromagnetic and heat transfer equations simultaneously in order to predict and calculate the thermal and electromagnetic profile. Very few researchers [21,34] have focused on modeling and simulation of biomass heating under MW. The former authors [21] used MATLAB code (based on finite difference time domain) while the later authors [34] conducted simulation work using COMSOL software (based on finite element method). Very recently, Hussain [35] carried out computational fluid dynamic on microwave heating of EFB biomass (large size) using ANSYS CFX 13.0 software. They investigated the effect of parameters such as heating source orientation, nitrogen gas flow rate, microwave power intensity and microwave absorber efficiency on the pyrolysis condition of EFB biomass. However, these studies did not considered the effects of biomass loading height and values of C_p on the temperature profile and electromagnetic field. Furthermore, after surveying the above literature, it was concluded that previous studies carried out numerical simulation of biomass subjected to MW irradiation using finite element method (COMSOL) and other available code such as MATLAB, but not for densified or pelletized biomass. Most of the MW modeling and simulation research was focused on the wood, water, food, ceramic, chemical reactions, minerals and even human tissues [33], but few or none has given attention on agricultural biomass. Thus, due to the limited simulation work on MW heating of biomass, the effects of sample loading size and specific heat capacity in particular are not fully understood. Hence, the objectives of this research work were to:

i. solve a coupled electromagnetic and heat transfer model for EFB biomass bed and pellet using COMSOL Multiphysics code
ii. validate the numerical model with the experimental findings
iii. perform simulation based on constant and varying specific heat values
iv. investigate the effect of biomass bed loading height on temperature and electric field distribution

The major outcome of this study will be to prove that the commercially available COMSOL software can be applied confidently in bioenergy, biofuels, MW manufacturer and other related industries in order to design and develop efficient MW heating system for biomass materials.

2. Material

Empty fruit bunch (EFB) biomass pellets was used as sample material. The moisture content of EFB biomass was taken to be about 15 wt.%. The diameter of pellet was 7 mm. The biomass sample was irradiated under MW in its original form i.e. without doping or mixing with any absorber. Table 1 provides the necessary materials properties used in the simulation work. Thermal and dielectric properties of 15 wt% moisture content EFB biomass [25] were used for calculations (Table 1).

3. Governing equations and boundary conditions

Numerical solutions of coupled electromagnetic and heat transfer equations for MW heating of EFB biomass bed and pellet was computed in the framework of the COMSOL Multiphysics