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Full Length Article

Multicomponent conjugate heat and mass transfer in biomass materials during microwave pyrolysis for biofuel production

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ABSTRACT

The aim of this paper is to investigate the heating behavior of biomass materials under microwave pyrolysis process. A detailed computational fluid dynamics (CFD) model is developed based on the finite volume method using ANSYS CFX (14.0) software to describe the heat and mass transfer during the microwave processing of biomass pellets. The article presents a modeling approach for incorporating the basic fundamentals of microwave pyrolysis process in the form of source terms for mass, momentum, heat and species into the general transport equations for nitrogen and volatiles in the gas phase and wood and bio-char in the solid phase. The model covers the complex coupling between several key elements of the process including microwave heating, pyrolysis kinetics, phase change, rapid variation in mixture properties and gas phase transport. The developed CFD model is validated through the experimental trials in a custom-built microwave pyrolysis unit. The model predicts the maximum temperature, temperature rates and temperature profiles during the process. Close agreement is obtained between the results obtained from the experiments and simulations. It was found that the biomass temperature is affected by the microwave absorbed power which is a function of biomass mixture properties and the released volatile during the process. The results also indicated that increase in microwave power level increases the maximum obtained temperature; however, the amount of absorbed power within the material decreases significantly in higher temperature levels. As temperature and power requirement are vital factors in making microwave processing viable, a useful CFD tool that provides this information could be invaluable for industry.

1. Introduction

Biomass is one of the most promising alternative energy resources which is abundantly available on earth and has the potential to alleviate the reliance on fossil fuel, reduce pollution and global warming, and it can contribute to sustainable development [1]. Biomass can be used directly to produce energy e.g. dead trees/wood, or can be converted into value-added bio-products such as bio-oil, biodiesel, biofuels, bio-char and a variety of different bio-chemicals [2]. There are several thermal conversion routes available to process the biomass and waste materials such as torrefaction, pyrolysis and gasification. Pyrolysis is one of the emerging thermo-chemical processes in which the biomass is converted into solid, liquid and gaseous products at elevated temperatures (300–600 °C) and it takes place in the total absence of oxygen. Of various pyrolysis approaches, microwave technology has been demonstrated as an energy efficient technique for thermal processing of materials [3]. Microwave pyrolysis brings several advantages compared to conventional pyrolysis including rapid, selective and volumetric heating [4]. Microwave systems have overall higher efficiencies and they can process high moisture content and large size materials. This can save considerable cost on unit operations such as drying and particle size reduction and ease the treatment and utilization of non-homogeneous wastes [5].

The microwave assisted pyrolysis of biomass material has been reviewed extensively by Motasemi et al. [5]. Based on this review, microwave has been used to process different types of agricultural and forestry based biomass materials such as switchgrass [6], wheat straws [7], rice straws [8], corn stover [9], algae [10], coffee hulls [11], oil palm biomass [12], and different types of wood [13–15]. This technology has been used to process a variety of different waste materials as well and produce value added products such as bio-oil and bio-char [3]. The liquid or oil fraction is product of biomass pyrolysis which can be a promising alternative energy source for fuel oil or diesel [16]. It also has application in production of resin [17], adhesives [18] and several other bio-chemicals. Bio-char is another product of pyrolysis with several industrial applications such as feedstock for activated carbon

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Nomenclature

A	cross section area
A_0	specific surface area
A_{fs}	interfacial area between the liquid and solid
C_p	specific heat
D	diameter
D	binary diffusion coefficient
D_h	hydraulic diameter
D_P	penetration depth
f	mass fraction
h	enthalpy
j	imaginary unit
k	thermal conductivity
k_0	shape factor
k_K	Kozeny constant
K	permeability
L	sample thickness
MP	microwave input power
P	pressure
P	power
P_0	microwave surface power absorption
S	source term
T	temperature
u	mixture velocity
u_D	filter velocity
u_P	pore velocity
V_P	volume of the pellets
wt	weight

Greek symbols

α	volume fraction
ϵ	porosity
μ	dynamic viscosity (molecular)
ρ	density
Δt	time step
τ	tortuosity
Γ	molecular diffusion coefficient

Superscripts

h, h_1, h_2	energy
u	momentum
f	mass

Subscripts

s	solid phase
g	gas phase
r	relative
wp	wood pellet
v	volatile
c	char
mod	modified

production, feedstock for carbon nano-laments production and enhancing the soil quality as well [19–21]. The non-condensable gas produced during the pyrolysis process (light molecular weight gases) is an intermediate product which is mainly used for heating purposes.

Recently, NASA is investigating the application of microwave pyrolysis for processing of space craft solid waste [22]. It was concluded that the microwave pyrolysis is a feasible technique for waste recovery in space. This method brings a significant reduction in the total energy requirement (~70%) compared to conventional heating with a simpler and more compact apparatus [23]. Microwave pyrolysis has been also introduced as a method of recycling glass fiber from used blades of wind turbines in Europe [24]. Most of the previous studies have been completed using lab-scale microwave systems as a proof of concept. The following are the most relevant research works on microwave pyrolysis of biomass pellets into value-added products. Processing of Douglas fir sawdust pellet [25], wood pellets [26] and empty fruit bunch pellets [27] were reported using the microwave pyrolysis method. The results indicated that microwave input power, pyrolysis reaction temperature and material properties play critical roles in microwave processing of biomass materials which was in agreement with microwave pyrolysis of other sort of materials as well [5].

There is no doubt on the importance of experimental and theoretical studies in microwave heating; however, numerical simulations are crucial for further understanding of the microwave processing of materials, in particular the complex multiphysics problems which includes coupling between several elements of the process including microwave heating, pyrolysis kinetics, phase change, rapid variation in mixture properties and gas phase transport. This will allow us to have a more accurate temperature profile prediction during the process (thermal behavior of the material), and avoiding the design of unnecessary experimental prototypes. Numerical simulation of the microwave heating process is basically a multicomponent analysis which includes the microwave absorption equations (i.e. Lambert equation) and the mass, momentum, heat and species transport equations. The heating source in energy equation can be calculated by microwave dissipated power; however, the high temperature variation during the heating process can cause the change of material properties.

There have been a few numerical studies conducted on the microwave processing of materials. The following are two representative studies on microwave pyrolysis simulation of biomass materials. Recently, Hussain et al. [28] investigated the microwave heating of large samples of oil palm empty fruit bunches using ANSYS CFX and Salema at al. [29] studied the effect of biomass loading height on the temperature profiles of empty fruit bunch (EFB) pellets under microwave irradiation. In both studies, energy equation was the only equation solved to predict the temperature profiles, while mass, momentum, energy and species equations along with microwave absorbed power equation need to be solved simultaneously in order to define the thermo-fluid phenomena correctly. Material properties were mostly assumed constant; however, the literature proves that these properties change greatly during the process [30–35]. Moreover, microwave pyrolysis is a transient problem; however, Hussain et al. assumed a steady state solution and Salema et al. solved the transient problem for only 10 s of the process which does not even present the moisture removal (drying) phase. Lastly, microwave absorbed power needs to be defined carefully based on the microwave theory and system efficiencies in order to obtain reliable results.

It is apparent that previous studies have investigated the numerical simulation of biomass materials under microwave heating, but none have completed a comprehensive analysis considering the variation on material properties, multicomponent analysis and conjugate heat and mass transfer for biomass materials as a porous media. In most of the simulations, material properties were assumed constant while these properties are changing significantly in respect to temperature and processing phase of the process. It was also found that the majority of simulation studies were completed on food, ceramic, minerals, water and even human tissues [36] and there is a lack of sufficient research work on the microwave processing in forestry or agricultural based biomass materials.

The main objectives of this research work are therefore: