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Fast microwave assisted pyrolysis of biomass using microwave absorbent

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HIGHLIGHTS

- A new concept of fast microwave assisted pyrolysis using absorbents was developed.
- Wood sawdust and corn stover were pyrolyzed using SiC as absorbent.
- Wood sawdust fMAP obtained the maximum bio-oil yield of 65 wt.%.
- Corn stover fMAP obtained the maximum bio-oil yield of 64 wt.%.
- The results show that the use of absorbents for fMAP of biomass is feasible.

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ABSTRACT

A novel concept of fast microwave assisted pyrolysis (fMAP) in the presence of microwave absorbents was presented and examined. Wood sawdust and corn stover were pyrolyzed by means of microwave heating and silicon carbide (SiC) as microwave absorbent. The bio-oil was characterized, and the effects of temperature, feedstock loading, particle sizes, and vacuum degree were analyzed. For wood sawdust, a temperature of 480 °C, 50 grit SiC, with 2 g/min of biomass feeding, were the optimal conditions, with a maximum bio-oil yield of 65 wt.%. For corn stover, temperatures ranging from 490 °C to 560 °C, biomass particle sizes from 0.9 mm to 1.9 mm, and vacuum degree lower than 100 mmHg obtained a maximum bio-oil yield of 64 wt.%. This study shows that the use of microwave absorbents for fMAP is feasible and a promising technology to improve the practical values and commercial application outlook of microwave based pyrolysis.

1. Introduction

In order to improve the global energy efficiency, alternative energy resources and technologies for sustainable development of world's economy are required. In addition to being abundant and widely available, biomass is a potentially carbon–neutral energy source (McKendry, 2002). Solid wastes such as crop residues and processing byproducts can be converted into solid, liquid, and gaseous products through various thermochemical processes including pyrolysis (Bridgwater and Bridge, 1991; Huber et al., 2006).

Pyrolysis is a well-recognized thermochemical platform for production of bio-oil, combustible gases and char from organics in biomass (Bridgwater and Peacocke, 2000; Yaman, 2004). The commercial uses of fast pyrolysis are thought to be as a source of high valued, speciality chemicals in the short term, and as petroleum fuel substitutes in the long term (Bridgwater, 2008). How to obtain higher yields and better quality of bio-oil from pyrolysis have been investigated by many groups. Extensive reviews on the physical (Fagernäs, 1995) and chemical properties (Fagernäs, 1995; Radlein, 1999) of pyrolysis bio-oils have been published.

Currently, fluidized bed and fixed bed (downdraft or updraft) are the dominant reactor types for biomass pyrolysis, in which the heating is provided by heated surfaces, sands, etc. (Czernik and Bridgwater, 2004; Meier and Faix, 1999; Mohan et al., 2006). Microwave irradiation is an alternative heating method.

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Integrating microwave heating into pyrolysis is a novel concept which has been attracting increasing attention in recent years.

This method offers many advantages over traditional processes, including uniform internal heating of large biomass particles, instantaneous response for rapid start-up and shut down, no need for agitation of fluidization and hence fewer particles (ashes) in the bio-oil, no syngas dilution by the carrying gas, and easy-to-implement technology. Furthermore, studies suggest that this is a highly scalable technology suitable for distributed conversion of bulky biomasses (Budarin et al., 2009; Domínguez et al., 2007; Huang et al., 2010; Miura et al., 2004; Wan et al., 2009; Wang et al., 2009; Yu et al., 2007).

In recent work, Yin (2012a) discussed microwave-assisted pyrolysis (MAP) of biomass and reviewed the researches and developments efforts and their major findings. Most of the MAP methods developed previously used batch-type process. Also, since the biomass takes several minutes to be heated to the reaction temperature, these processes fall into the intermediate rate pyrolysis category. In fact, increasing the heating rate and consequentially reduce the reaction time, is one of the most challenging issues in order to obtain higher yields and quality of bio-oil.

Carbon materials (e.g., carbon, charcoal, activated carbon) are easily heated by microwaves as they are, in general, very good absorbents of microwaves (Menéndez et al., 2010). Recently, a novel concept of pyrolysis utilizing microwave absorbents is being developed, in which the use of these absorbents could significantly improve the heating rate. With minimal energy input through microwave irradiation, the temperature of the reactor is steady when the solid residue is dropped directly onto the heated absorbent. In this concept, the biomass is heated due to two heating mechanisms simultaneously used: the microwave irradiation and conduction due to the high temperature of the absorbents. Since the biomass is almost instantaneously heated (less than 1 s) to the reaction temperature, it can be feed continuously or semi-continuously to the reactor. These findings suggest that MAP, which was in the intermediate rate pyrolysis category, can reach fast microwave assisted pyrolysis (fMAP) conditions with this new heating mechanism, thus achieving higher product yield and quality at the same time.

A small bench scale of fMAP was developed in the authors' lab to process biomasses with semi-continuous biomass feeding, in the presence of microwave absorbents. In this study, wood sawdust and corn stover were pyrolyzed using SiC as microwave absorbent. The preliminary data showed that the temperature of SiC samples could reach up to 960 °C in a small 750 W microwave oven system. The objective of the study was to examine the effects of microwave absorbent on yields and properties of the bio-oil, char and gas. The effects of key process variables, such as temperature, feedstock loading, particle sizes of absorbent and biomass, and vacuum degree, on the bio-oil yield were also analyzed. Detailed physical and chemical characterization of the bio-oil, char and gas produced were carried out.

2. Methods

2.1. Materials

Wood sawdust and corn stover were used in the fMAP experiments. The wood sawdust was a residue from pine wood pelleting process, obtained from Spearfish Pellet Company LLC, and located in Spearfish, South Dakota. The corn stover was obtained from corn crop residue from St. Paul Campus, at the University of Minnesota, Twin Cities. Both biomasses samples were milled and dried at 80 °C for 24 h. The main characteristics of the wood sawdust and corn stover are listed in Table 1.

Table 1
Characteristics of wood sawdust and corn stover.

	Wood sawdust	Corn stover
Proximate analysis (wet basis, wt.%)		
Moisture content	5.15	5.27
Ash content	0.11	2.06
Volatiles	95	93
Elemental analysis (dry basis, wt.%)		
C	42.62	40.38
H	5.47	5.16
N	0.38	0.38
O[a]	51.43	52.01

[a] Calculated by difference, O (%) = 100–C–H–N–Ash.

2.2. Microwave assisted fast pyrolysis

The fMAP experiments were carried out in a small bench scale using a microwave oven (MAX, from CEM Corporation), with a power of 750 W at a frequency of 2450 MHz The experimental apparatus consists of: (1) feeder that allows semi-continuous biomass feeding; (2) quartz inlet connectors; (3) microwave oven; (4) specially made quartz reactor with two necks; (5) absorbent bed; (6) thermocouple (*K*-type) to measure the cavity temperature; (7) thermocouple (*K*-type) to measure the temperature of the absorbent bed and to control the heating; (8) quartz outlet connectors; (9) liquid fraction collectors; (10) condensers; (11) connection for gas sampling and to a vacuum device to draw the volatiles out of the reactor to a series of refrigerated water cooled condensers. The vacuum was to adjust the gas/vapor residence time. For safety purpose, a microwave detector (MD-2000, Digital Readout) was used to monitor microwave leakage.

Firstly, 500 g of SiC particles were put in the quartz reactor to form a layer of absorbent bed. Then, the reactor was placed in the oven cavity. After connecting the inlet and outlet quartz tubes, the oven was turned on for the heating process. When the temperatures of the absorbent bed reached a designed level, the biomass samples were semi-continually dropped onto the hot SiC bed, while the microwaves oven cycles on and off every 15 seconds in order to improve the biomass heating, and maintain the set temperature of the absorbent bed. Samples of the gas product were collected during the process, while the liquid fraction and char samples were collected at the end of the experiment. The solid and liquid fraction yields were calculated from the weight of each fraction, while the gas yield was calculated by differences based on the mass balance.

2.3. Experimental design

A 2^3 factorial central composite experimental design (CCD), with 3 repetitions at the central point, was used to estimate the effects of the main variables. For each biomass, a total of 11 experiments were carried out. For wood sawdust experiments, the independent variables studied were: temperature (x_{1a}, °C), feedstock loading (x_{2a}, g), and absorbent particle size (x_{3a}, grit). In order to evaluate different effects, in addition to temperature, other independent variables were studied for corn stover experiments: temperature (x_{1b}, °C), biomass particle size (x_{2b}, mm), and vacuum degree (x_{3b}, mmHg). The dependent output variables were the yields of bio-oil (y_1, %), gas fraction (y_2, %) and char (y_3, %), the moisture content of the bio-oil (y_4, %) and the yield of syngas (y_5, %). Table 2 presents the code and values of the independent variables. Statistica 8.0 (StatSoft. Inc.) was used to analyze the experimental data statistically.