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Research paper

Characteristics of biochar and bio-oil produced from wood pellets pyrolysis using a bench scale fixed bed, microwave reactor

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ABSTRACT

Microwave pyrolysis of wood pellets was investigated in a pilot scale fixed bed microwave reactor at various biomass loadings and microwave power levels. A fixed proportion of biochar (10% of biomass loading) was used as a microwave absorber in each test conditions. Effect of biomass loading and the power level on the product yields and on the characteristics of biochar and bio-oil products were examined. While the bio-oil yield decreased when the biomass loading was increased from 1500 g to 3500 g, the biochar and gaseous product yields increased with the biomass loading. However, the microwave power level shows an opposite trend. Biochar exhibited good higher heating value (31 MJ/kg) and possessed a fine pore size (< 1 nm), which can be used as a fuel or a source of porous carbon. Higher heating value of bio-oil was found in the range 12–14 MJ/kg. Kinematic viscosities of bio-oils were estimated in the range 1.8–6.1 mm^2/s at 40 °C that is similar to the viscosity requirement for the gas turbine applications. Moisture content in bio-oils was found in the range of 57.3–69.3%, which is higher than the upper limit of water content (30% wt.). Only a few chemicals, including furfural, phenol, 3-Methyl-1,2-Cyclipentanedione, 3-Methylphenol, and 4-Methylguaiacol were found in the bio-oils because of the high moisture content. Results of product characterization of biochar and bio-oils confirm that both microwave power level and biomass loading does not have any significant impacts. Further research can be carried out to find out the measures to reduce the moisture content in the bio-oil.

1. Introduction

Production of fuel oils, gases, and other chemicals using the renewable feedstock can be a stepping stone to achieve a low carbon economy in the world. Biomass is an abundant renewable resource that has significant potential to be used as feedstock for the energy generation and production of chemicals. Biomass encompasses all living plant matters that exist on the surface of the earth, including the organic wastes derived from plants, humans, animals, and marine life. Biomass is considered to be a renewable resource because it is regenerated at the same rate as it is being used. Renewability and domestic availability are major advantages of using biomass as an energy source; however, the energy density is relatively low compared to the conventional fossil fuels [1]. Biomass can be burned directly to generate power or produce heat [2]. It can also be converted to biofuels by physicochemical, biochemical, and thermochemical processes [2,3].

Bio-oils are produced using a pyrolysis process, which thermally decomposes biomass in a temperature range of 200–600 °C and in an inert environment, and then releases volatile and semi-volatile compounds [4]. Fast pyrolysis is usually deployed to produce bio-oil, which is carried out at high temperature in the temperature range of 400–650 °C and characterized by its fast heating and quenching processes [5–7]. The bio-oil consists of a large number of chemical compounds [8]. While some of the chemical compounds can be used as a source of energy that replaces conventional fuels, many other chemicals can be used for the food, pharmaceutical, and packaging industries. Such chemicals generated using renewable source would prefer over the petrochemical-based chemicals. Biochar is a carbon-rich solid residue left out after a pyrolysis process, which has a wide range of applications including power generation, soil amendment-adsorbent of organic compounds [9], waste management [10], and immobilizing heavy metals [9]. The microporous structure of biochar and high pore surface area not only makes it suitable for industrial applications but also increases the rate of carbon sequestration in soil, reducing the greenhouse gas emissions [11]. Recently, the use of biochar has escalated in microbial fuel cells, direct carbon fuel cells, and building supercapacitor [12].

While the fast pyrolysis process that heats up the biomass rapidly at

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high temperature is deployed to produce bio-oil [5–7], a slow or low-temperature pyrolysis process, hydrothermal carbonization, and gasification process can produce a dark carbon-rich residue called biochar [12]. The products of the pyrolysis process depend on many parameters such as the type of biomass, moisture content, particle size, reaction temperature, heating rate, reaction time, type and flow rate of carrier gas, catalyst, and reactor design [11]. Conventionally, heat is transferred to a surface of biomass to raise the temperature of biomass that initiates the primary pyrolysis reactions forming volatiles and char. The hot volatiles then moved toward the cooler part of solids, causing heat transfer between hot volatiles and cooler portions of the biomass [7]. However, because of several advantages over the conventional heating, such as non-contacting heating, energy transfer rather than heat transfer, volumetric heating, selective heating abilities, quick start-up and stopping, higher heating rate, heating from the inferior portion of biomass, and higher level of safety and automation [13], the use of microwave heating is considered as one of the prominent techniques to pursue a pyrolysis process. Microwave heating effect is a result of absorption of microwave radiation that causes molecular motion by migration of ionic species and/or rotation of dipolar species [13]. Thus, a higher absorption of the microwave would lead to a more heating effect. The absorption of the microwave depends on the material property that is termed as a dielectric loss. On one hand, a material with high dielectric loss factor absorbs more microwaves and produces a good heating effect, on the other, materials with less dielectric loss value does not produce heating effects. Thus, one can expect different chemical compositions in bio-oils produced from microwave and conventional pyrolysis because the microwave heating mechanism is completely different than what it is in the conventional method, which may alter the temperature of the overall process and can inhibit secondary reactions of pyrolysis products [14].

Microwave pyrolysis is a thermochemical process that uses microwave heating to decompose biomass in the absence of oxygen to produce non-condensable gases, liquid bio-oil, and solid biochar [15,16]. A significant amount of work in microwave assisted pyrolysis has been established to produce biochar and bio-oil. A detailed review of microwave assisted pyrolysis on the production of biochar and bio-oil can be found in the literature [7,17–20]. These reviewers confirmed that microwave assisted pyrolysis could be deployed to different feedstock such as sawdust, switchgrass, coffee hulls, coffee grounds, wheat straw, corn stalk, corn stover, sugarcane, rice straw, rice husk, sugarcane bagasse, sugarcane peel, bamboo, peanut shells, sewage sludge, glycerol, and waste oil. However, the product yields and product characterization could depend on many process parameters. For instance, in the fluidized bed reactor system, large size particles are not preferred as they tend to settle down to the bottom of the bed, resulting in the inefficient heat transfer and slower thermal processing [21]. Very fine particle size is often desired to reduce negative effects on bio-oil production using conventional pyrolysis. Fine particle size is, however, not necessary in the microwave pyrolysis [19,22]. Characteristics of biochar and bio-oils also depend highly on the type of raw biomass and pyrolysis conditions [24,25]. Characterizing bio-oil and biochar both chemically and physically will provide a better understanding of the pyrolysis process that could help further in the development of biomass waste to energy and to other value-added products [26].

There are a few studies on the pyrolysis of wood pellets using microwave heating technique [4,21,27–29]. These studies are, however, limited to a low sample load below 400 g. While the use of wood pellets improves the homogeneity of feedstock for the pilot-scale microwave pyrolysis reactor, it also helps the pellet industries to open their market and become the feedstock supplier for the bio-oil producers. In addition, only a few scientific publications [23,30,31] on a large-scale microwave assisted pyrolysis were reported so far. While Miura et al. [23] and Zhao et al. [30] have hung the sample inside the reactor, Salema et al. [31] adopted a fixed bed reactor design in which they tested corn stalk briquettes with the maximum loading of 1500 g and conducted a preliminary study using a small fraction of the total biomass loading capacity at the partial power level of the total designed power of 3000 W. However, this study aims to investigate more on the reactor developed by Salema et al. [31] that could help to explore further the microwave pyrolysis process in a scaled-up fixed bed reactor.

In the earlier numerical simulation study of the heating behaviour of pellets under multimode microwave system, Salema and Afzal [32] found biomass loading has a significant impact on the microwave absorption and on the electric field intensity, which then affects the overall pyrolysis process and the characteristics of biochar and bio-oil. Salema at al [31]. then further investigated the effect of biomass loading and power level in a scaled-up microwave pyrolysis reactor in which they examined the quantitative as well as qualitative characteristics of bio-oil and biochar. They performed the tests using 75 g of biochar as a microwave absorber, which is equivalent to 15% and 7.5% at 0.5 kg and 1 kg of biomass loading, respectively. While they adopted power level only in the range of 30–50% of total designed capacity (3000 W), they ran each test for 2 h. As the microwave heating process is a quick one, it may not require such a long operation. So, it is essential to know if the test can be done relatively with less operation time that could potentially save the energy supplied to the system. At the same time, it is also required to test the developed reactor to know if it can handle higher biomass loadings.

This study, thus, reports microwave assisted pyrolysis process in a bench scale fixed bed reactor using wood pellets. Commercially available wood pellets with a higher bulk density were pyrolyzed to reduce biomass pre-processing time and ensure a smooth supply of feedstock. Experiments, keeping the same fraction of microwave absorber (10%) at different biomass loadings and same residence time of 1 h, were carried out at different power levels. Only the characteristics of biochar and bio-oil were examined. The results of this work would be useful to further scale up the microwave assisted (MW) pyrolysis system and develop a modular design using a fixed bed reactor system.

2. Materials and methods

2.1. Materials

Locally available standard pellets manufactured by the Eastern Embers Premium Wood Pellets were used as a feedstock. The wood pellets were made up of 100% softwood and were manufactured from spruce sawdust at the pellet plant located in Shubenacadie, Nova Scotia. The average moisture content of the raw wood pellets was found to be 6.85%.

2.2. Experimental set-up

A bench scale fixed reactor-based microwave technology as shown in Fig. 1 was deployed to conduct experiments. The reactor consists of a top cover with necessary holes for temperature measurement probes and nitrogen supply, a bottom cover with a tube for volatile gas collection, a perforated plate inside the reactor that holds the loaded biomass sample and allows volatiles to pass through, and a cylindrical reactor made up of stainless steel with inner diameter 35.5 cm and length 53.3 cm. The detailed reactor design was explained by Salema et al. [31]. The fixed bed reactor is connected with a microwave generator, purchased from the Muegge GmbH, Germany, of capacity 3000 W that generates microwave radiation of frequency 2.45 GHz. The microwave generator consists of a power supply (MX3000D-152 KL), a magnetron head (MH3000S−250BB), a 3-stub-tuner (MW2009A-260ED), and a waveguide (WR 340). Nitrogen, using a nitrogen generator of VWR model CA26000-014 that converts the pressurized air into nitrogen of purity 97.5%, was supplied from the top of the reactor. The supplied nitrogen flux from the top of reactor flushed out the generated volatiles from the bottom of the reactor. The volatiles leaving from the bottom of the reactor was connected with a water-cooled gas