Journal of the Taiwan Institute of Chemical Engineers 70 (2017) 236–243

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

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

Microwave torrefaction of sewage sludge and leucaena

Yu-Fong Huang, Hsuan-Te Sung, Pei-Te Chiueh*, Shang-Lien Lo

Graduate Institute of Environmental Engineering, National Taiwan University, 71, Chou-Shan Rd., Taipei 106, Taiwan, ROC

ARTICLE INFO

Article history:
Received 26 June 2016
Revised 22 October 2016
Accepted 27 October 2016
Available online 3 December 2016

Keywords:
Microwave torrefaction
Sewage sludge
Leucaena
Biochar
Bioenergy

ABSTRACT

This study attempted to investigate and compare sewage sludge and leucaena torrefaction using a single-mode microwave oven. To discuss reactivity, product characteristics, and energy recovery, microwave torrefaction of the two feedstocks was carried out at various microwave power levels. Besides, thermal properties of raw feedstocks and torrefied products were observed by the deconvolution of derivative thermogravimetric profiles. The volatile matter contents of the two biomass feedstocks were substantially reduced at relatively low microwave power levels. Because of high heating value and fuel ratio as well as low atomic H/C and O/C ratios, the biochar could replace coal. Compared with sewage sludge, microwave torrefaction of leucaena produced thermally stable biochar at lower microwave power levels, which means that the microwave heating performance of leucaena is better. Compared with conventional torrefaction, mass and energy yields of microwave torrefaction were lower, which could be attributable to the more severe reaction accomplished by microwave heating. The atomic H/C and O/C ratios of leucaena biochar were close to those of anthracite, so combustion or gasification of the biochar could form less smoke. After microwave torrefaction at relatively high microwave power levels, a high HHV (dry ash-free basis) of sewage sludge biochar was found.

1. Introduction

Renewable energy has recently attracted more interest because of high worldwide energy demand, unstable and uncertain petroleum sources, and concern over global climate change [1]. One of the promising renewable energy options is bioenergy. Biomass, including wood, crop and forest residues, and municipal and industrial wastes [2], is a sustainable carbon-neutral resource for the production of biofuels and biomaterials [1,3]. Biomass wastes can be regarded as a cheap and relatively abundant source of bioenergy [4]. The bioenergy generated from biomass wastes and residues has gained more importance among the different sources of renewable energy [5], because these biomass feedstocks do not compete with food crops and directly or indirectly cause land-clearing [2].

Untreated biomass has high moisture content, low energy densities, and hydrophilic nature, and it is bulkier with poorer handling and transportation characteristics and is more tenacious to make it difficult to comminute into small homogeneous particles, resulting in complicated and expensive storage and transportation [6–9]. Besides, the high oxygen content of biomass results in a large amount of smoking during combustion [9]. All of these drawbacks have given rise to the development of new technologies for biomass modification in order to ensure that its use as an energy source is environmentally friendly and economically efficient [7,10]. One way to modify the chemical and physical properties of biomass is a thermal processing step known as torrefaction [6,10,11]. Torrefaction is a low-temperature (200–300 °C) thermal pretreatment of biomass operated at atmospheric pressure in the absence of oxygen [11–13], so it is also known as mild pyrolysis [6,7,9,14]. In addition to increasing energy density and decreasing moisture and oxygen content, torrefaction has a great effect on the grindability and reactivity of biomass [7], and the torrefied biomass becomes hydrophobic due to the formation of non-polar unsaturated structures [11].

Most biomass torrefaction researches and applications use conventional electric heaters, whereas there is an alternative method called microwave heating. Microwave heating which is also referred to as dielectric heating [15,16] has been attracting increasing interest in recent years [17]. Compared with conventional heating, microwave heating provides various advantages such as higher heating efficiency and power density, better heat transfer and process control, more uniform heat distribution, and faster internal heating [15,18–20]. Microwave heating can reach high temperatures in a fraction of the time of conventional heating [21]. The unique features of microwave heating can be used to improve processes, modify selectivities, or perform reactions that do not occur by conventional heating [22]. According to the aforementioned

---

* Corresponding author. Fax: +886 2 2392 8830.
E-mail address: ptchueh@ntu.edu.tw (P.-T. Chiueh).

http://dx.doi.org/10.1016/j.jtice.2016.10.056

advantages, the combination of microwaves with torrefaction will be a promising technique.

Sewage sludge disposal would be one of the most complex environmental problems [23,24]. In fact, the organic content in sewage sludge can be utilized as a biomass resource for the production of energy [25,26]. Leucaena is a fast growing tree with high biomass production, so it has a high potential for bioenergy production and can be an alternative to the use of traditional biomass feedstocks [27,28]. Both sewage sludge and leucaena feedstocks are abundant and representative biomass resources, although their compositions and characteristics are very different. This study attempted to investigate and compare the microwave torrefaction outcomes of the two feedstocks, such as reaction performance and process applicability. The reactivity, product characteristics, and energy recovery of microwave torrefaction were discussed to evaluate the benefits and potential applications of this technique.

2. Material and methods

2.1. Materials

Sewage sludge was obtained from the Dihua Sewage Treatment Plant, Taipei, Taiwan. The as-received moisture content of the sewage sludge was approximately 85 wt%. The raw sewage sludge was air dried for several months and then dried in an oven at 105 °C for three days. Although the moisture could be nearly completely removed after oven drying, the sewage sludge would soon absorb and/or adsorb water molecules in the air because of its porous property. Leucaena wood was provided by the Kenting National Park, Pingtung, Taiwan. The raw leucaena wood was dried in an oven at 105 °C for 1 hr. Like sewage sludge, the dried leucaena showed a low moisture content, which was, however, a little higher than that of dried sewage sludge. This should be owing to the relatively high porosity of the dried leucaena sample. Before applying to microwave torrefaction and relevant experiments, sewage sludge and leucaena was dried, shredded, and ground into powder, and then it was sieved using a 50-mesh screen (0.297 mm opening).

2.2. Experimental apparatus

A single-mode (focused) microwave oven was used in this study. This microwave oven operates at a frequency of 2.45 GHz, and its maximum output power is 2000 W. A schematic diagram of the overall microwave heating system can be found elsewhere [29]. Both reaction tube (40 cm length, 5 cm outer diameter) and sample crucible (3 cm height, 4 cm outer diameter) are made of quartz. There was a three-stub tuner in charge of regulating the incident angle of microwaves to make sure that microwave peak is located at the center of reaction zone. At the end of microwave propagation pathway, a short-circuit plunger was set to adjust the wavelength phase of microwaves. During the experiment induced by microwave heating, both three-stub tuner and short-circuit plunger were adjusted to minimize reflected microwave power. The heat caused by the reflected microwave power was absorbed by a water load that was cooled down by a refrigerated circulator. Incident and reflected microwave power was measured by a power meter. The temperature of the biomass sample was measured by a thermocouple and an infrared thermometer. After passing through a condenser, the vapor produced during the experiment was divided into condensable (tar) and incondensable (gas) parts, and the flow rate of the gaseous product was measured by a digital flow meter.

2.3. Experimental details

The microwave power levels of 100, 150, 200, 250, 300, 350, and 400 W were applied for sewage sludge torrefaction, and 100, 125, 150, 200, and 250 W for leucaena torrefaction. The microwave power levels chosen for sewage sludge and leucaena torrefaction were different because of their different microwave torrefaction performance. After a preliminary study, it was found that, to reach the same reaction result, leucaena would need lower microwave power level than sewage sludge. This will be discussed later. The reaction cavity was purged with pure nitrogen gas at a flow rate of 25 ml/min to maintain its inert atmosphere. After sufficient purging, the power supply of the microwave heating system was turned on and switched to the prescribed microwave power level for the total operation time of 30 min. Reflected microwave power was controlled to be as low as possible during the entire experimental period by adjusting the three-stub tuner and the short-circuit plunger. The actual working microwave power level was determined by subtracting the reflected microwave power level from the incident level. When the prescribed processing time was reached, the power supply was turned off, the gas purging was stopped, and the tar and gas collectors were removed and sealed. After self-cooled down to the room temperature, solid residues (biochar) remained in the crucible were removed and then placed in a desiccator for hours. All of the experiments were performed in triplicate at least to obtain average values for the results. The maximum temperatures reached during the torrefaction of sewage sludge and leucaena at different microwave power levels are listed in Table 1. It can be seen that leucaena would need lower power level than sewage sludge to achieve the same maximum temperature.

2.4. Analytical methods

Proximate analyses of biomass samples and torrefied products were performed according to the standards D7582-12 and D3172-07a of the American Society for Testing and Materials (ASTM). Ultimate analyses were carried out by using a Perkin–Elmer 2400 II CHNS/O elemental analyzer. Higher heating values (HHV) were measured in a Parr 1341 adiabatic oxygen bomb calorimeter. Each sample (approximately 1 g) was dried at 105 °C in an oven for 24 h prior to heating value analysis. Thermogravimetric analyses (TGA) were carried out by using a TA Instruments SDT Q600 thermogravimetric analyzer with a nitrogen flow rate of 100 ml/min, and

Table 1
Maximum temperatures of microwave torrefaction.

	Sewage sludge						
	100	150	200	250	300	350	400
Maximum temperature (°C)	168 ± 19	217 ± 31	277 ± 14	310 ± 44	348 ± 36	376 ± 38	404 ± 50
	Leucaena						
	100	125	150	200	250		
Maximum temperature (°C)	232 ± 25	264 ± 12	310 ± 39	341 ± 46	367 ± 52		