ARTICLE IN PRESS

Waste Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Partial oxidation of sewage sludge briquettes in a updraft fixed bed

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ARTICLE INFO

Article history:
Received 29 July 2015
Revised 26 January 2016
Accepted 29 January 2016
Available online xxxx

Keywords:
Biochar
Burning rate
Combustion
Fixed bed
Ignition front
Sewage sludge

ABSTRACT

The fixed bed reaction of sewage sludge briquettes was investigated to evaluate the potential applications to gasification, combustion, or production of biochar as soil ameliorator. The reaction had two distinctive stages: ignition propagation and char oxidation. The ignition front of the sludge briquettes propagated at a lower speed, which significantly increased the stoichiometric ratio of overall combustion reaction and peak temperatures. The ignition front also had irregular shapes due to the channeling effects. During the char oxidation stage, the sludge ash agglomerated because of the slow reaction rate and increased CO_2 formation. Because of low energy content in the product gas, the large briquettes were not favorable for syngas production. In addition, the low burning rates and ash agglomeration could cause problems in the operation of a grate-type furnace for combustion. However, the char accumulated above the ignition front had similar properties with that from pyrolysis under inert atmosphere. Therefore, the fixed bed reaction under partial oxidation conditions can be applied to produce biochar as soil ameliorator from the sludge briquettes without external heat supply.

1. Introduction

Sewage sludge is a residue of wastewater treatment, which must be disposed of by environmentally and economically sound methods. After ocean dumping and landfilling were banned, the main disposal method in industry has been through energy recovery that converts inorganic elements into inert ash, while cleaning product gas at the same time (Rulkens, 2008). The ash can be utilized for production of construction materials and cement (Monzo et al., 2003; Cheeseman and Virdi, 2005). However, the high moisture content imposes a significant difficulty on the energy recovery process. Even after mechanical dewatering, the sludge typically contains over 80% moisture content (Rulkens, 2008), which increases the bulk density and lowers the energy content. Therefore, it is preferable to dry the sewage sludge. This can increase the heating value of the sludge to 12–15 MJ/kg, although a significant amount of energy is consumed for evaporation of the moisture. In addition, drying the sewage sludge is particularly difficult because of a large fraction of bound water present inside. The conventional drying methods are direct and indirect heating using hot gas or steam combined with mechanical agitation (Chen et al., 2002). Pretreatment by thermal hydrolysis can improve the dewaterability of the sludge by destroying the organic cell structures and converting bound water into free water (Neyens and Baeyens, 2003). Ma et al. (2011) showed that the mechanical dewatering by centrifuge with pressure filtration after thermal hydrolysis at 180 °C reduced the moisture content of the sludge to 33 wt%, compared to around 80% without the pretreatment. The drying process can be combined with pelletization or briquetting for easy handling and feeding of the sludge.

The main method for energy recovery from the sewage sludge by thermal treatment is incineration in a dedicated facility or co-combustion in an existing fossil fuel-fired furnace such as a coal-fired power plant or cement kiln (Fytilim and Zabaniotou, 2008). Alternatives to combustion are pyrolysis and gasification. Pyrolysis converts the volatile matter in the sludge into condensable heavy compounds (bio-oil) and light gases. For example, Trinh et al. (2013) acquired a bio-oil yield of 41 wt% on a dry ash-free basis with a higher heating value (HHV) of 25.5 MJ/kg at 575 °C using a centrifuge reactor. The remaining solid fraction (char) can also be used as fuel, but its HHV was low (6.1 MJ/kg) due to the high ash content. A recent development is to use char from biomass, also known as biochar, as soil ameliorator to enhance the plant growth (Méndez et al., 2012) or as low quality adsorbent for heavy metals (Chen et al., 2014). Gasification converts the sludge into combustible gases called syngas for use as fuel or chemical feedstock. Dogru et al. (2002) showed that dried sewage sludge with a particle size of 5 × 10 × 35 mm and density of 314 kg/m^3 can be gasified by air to produce syngas having a HHV of 3.5–4.0 MJ/Nm^3 in a 5 kW

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http://dx.doi.org/10.1016/j.wasman.2016.01.040
0956-053X/

downdraft fixed bed. The heating value of syngas was increased by the use of hot air, at a lower stoichiometric ratio, and for a smaller particle size (Pérez et al., 2012; Werle, 2015).

For thermal conversion of solid biomass fuels, fixed bed configurations are commonly used (Werther and Ogada, 1999; Yin et al., 2008). Its applications include combustion in a grate-type furnace and gasification for synthetic gas production. During the fixed bed reaction, volatiles released from biomass particles by pyrolysis are ignited by heat transfer from existing flames and furnace walls. The ignition front then propagates to the adjacent fresh particles by heat transfer (Saastamoinen et al., 2000). This is followed by oxidation and gasification of char above the ignition front, which have relatively low reaction rates. In a grate-type furnace, the oxidation of residual char often has a distinctive period after the ignition front reaches the bottom of the bed (Ryu et al., 2007a).

The reaction characteristics in a fixed bed are affected by the fuel properties, particle size, and air flow rate (Ryu et al., 2006, 2007a). The fuel properties, such as the heating value and volatile matter content, determine the amount of combustible fractions released during pyrolysis and their enthalpy of reaction. The particle size and size distribution influence the void ratio, distribution of air within the bed, and pressure drop. The airflow rate determines the amount of oxygen available and the degree of convective heat transfer of the fuel particles. With an increase in the air flow rate, the reaction characteristics are categorized into oxygen-limited, reaction-limited, and convective cooling regimes (Shin and Choi, 2000). Despite numerous experimental studies on different fuel particles, it is often difficult to predict the reaction characteristics of a new fuel due to the complicated physical and chemical interactions involved.

This study investigated the fixed bed reaction of dried sewage sludge treated by the thermal hydrolysis, drying, and briquetting processes. In Moon et al.'s study (2015) using a small heated reactor with a sample weight of 10 g, the sludge powder after the hydrothermal treatment was found to promote the release of gases during pyrolysis and to increase the yield and heating value of syngas during steam gasification, compared to the untreated sludge. The present study is for sludge briquettes in which larger particle sizes lead to different heat/mass transfer and reaction characteristics. The focus was on identifying the fundamental reaction characteristics in an updraft fixed bed at low air flow rates to evaluate the potential applications of the sludge briquettes to combustion, gasification, and biochar production. In a batch-type lab-scale reactor, the sludge briquettes were burned at air flow rates ranging between 74.5 and 596 kg/m^2 h. The reaction characteristics were compared to those of wood pellets. Wood pellets represent high-value biomass with a uniform particle size, a low ash content and high energy content. Therefore, it can be considered as the reference material for better understanding on the reaction characteristics of the sludge briquettes by comparison. The detailed measurement of temperature, gas composition, and mass loss rate were used to determine the quantitative parameters of the reaction characteristics. The char formed during the ignition propagation stage was collected by quenching with nitrogen, and its properties were compared to those of char obtained from pyrolysis.

2. Experimental

2.1. Materials

The samples used in this study were sewage sludge and wood, both in densified forms. Table 1 lists the fuel properties of the samples. The sludge was originally collected from the dewatered cake of a municipal sewage treatment facility in Korea. It was then treated by thermal hydrolysis at 20 bar and 200 °C, dried, and briquetted into a spheroid shape (20 × 20 × 10 mm). Details of the process have been presented elsewhere (Moon et al., 2015). The moisture content of the sludge was 5.73%, which resulted from efficient drying after thermal hydrolysis that removes the bound water under high pressure and moderate temperature. The ash content was significantly high (36.27%), which lowered the HHV (14.28 MJ/kg). The wood pellet was a commercial product produced from pine and spruce sawdust. Compared to the sludge, the wood pellets had a very low ash content (0.17%) and high HHV (18.38 MJ/kg).

Table 1
Fuel properties of dried sewage sludge briquette and wood pellet samples.

		Sewage sludge briquette	Wood pellet
Proximate analysis (wt%)	Moisture	5.73	7.99
	Volatile matter	50.76	78.37
	Fixed carbon[a]	7.24	13.47
	Ash	36.27	0.17
Ultimate analysis (wt%)	C	51.00	48.32
	H	7.37	5.64
	O[a]	33.16	45.98
	N	6.59	0.05
	S	1.88	0.01
HHV (MJ/kg)		14.28	18.38
Particle type (mm)		Spheroid: 20 × 20 × 10	Cylinder: 5 × 5 × 25

[a] By difference.

2.2. Fixed bed reactor

Fig. 1 shows the schematic of the lab-scale fixed bed reactor. It consisted of a cylindrical reactor, load cells, air supply, and gas cleaning system. The reactor (ID 300 mm × height 700 mm) was made of SUS310 and had a refractory lining (thickness 50 mm). A perforated plate was placed inside the reactor to support the bed of fuel particles and distribute air uniformly. A total of 10 K-type thermocouples measured the temperature inside the bed along the center line starting from the level of the perforated plate (T0) with a uniform spacing of 50 mm (up to T9). Three load cells (HBM, PW6D) were installed below the reactor to monitor the weight of the fuel. The fuel bed had an initial height of 300 mm, which required a sample weight of 15–17 kg. The air was supplied from a compressor with flow rates ranging between 74.5 and 596 kg/m^2 h. The fuel particles were ignited at the top of the bed by kerosene. The product gas from the reactor passed through two condensing systems, operating at 10 °C using water and −20 °C using acetone. After tar and water were separated, the non-condensable gas was passed through an electrostatic precipitator to remove particulates. The cleaned gas was sampled to measure the gas composition by (i) an on-line analyzer (A&D System, A&D 900) for continuous monitoring, and (ii) a gas chromatograph (Perkin–Elmer, Clarus 680 GC), every 9 min for detailed analysis including O_2, CO, CO_2, H_2, CH_4, and heavier hydrocarbons.

In addition, separate tests were carried out for comparison of the properties of char formed from pyrolysis and fixed bed combustion. The details of the pyrolysis system are reported elsewhere (Lee et al., 2013). For a sample weight of 220 g, the pyrolysis reactor was heated to 530 °C at a heating rate of approximately 10 °C/min under a nitrogen atmosphere. The char formed during the fixed bed combustion was collected after quenching the bed with nitrogen after the thermocouple, T1, reached 600 °C at an air flow rate of 149 kg/m^2 h.

Please cite this article in press as: Kim, M., et al. Partial oxidation of sewage sludge briquettes in a updraft fixed bed. Waste Management (2016), http://dx.doi.org/10.1016/j.wasman.2016.01.040