



## A study on torrefaction of sewage sludge to enhance solid fuel qualities



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### ABSTRACT

Torrefaction is a treatment which serves to improve the properties of biomass in relation to thermochemical processing techniques for energy generation. In this study, the torrefaction of sewage sludge, which is a non-lignocellulosic waste was investigated in a horizontal tubular reactor under nitrogen flow at temperature ranging from 150 to 400 °C, for torrefaction residence time varying from 0 to 50 min. The torrefaction kinetics of sewage sludge was studied to obtain the kinetic parameters. The torrefied sewage sludge products were characterized in terms of their elemental composition, energy yield, ash content and volatile fraction. The energy and mass yields decreased with an increase in the torrefaction temperature. From an elemental analysis, the weight percentage of carbon in the sewage sludge increased with an increase in the torrefaction temperature. On the other hand, the weight percentages of hydrogen and oxygen tended to decrease. The gaseous products from torrefaction of sewage sludge were also analyzed. From this work, it was found that the compounds with oxygen were emitted at a temperature lower than that for hydrocarbon gases and the temperatures of 300–350 °C were the optimum torrefaction temperatures for sewage sludge.

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### 1. Introduction

The global problems associated with the intensive use of fossil fuels have increased interest in the use of renewable fuels worldwide where biomass is widely available at low cost. However, a pre-treatment process is required to convert biomass into a hydrophobic solid product with an increased energy density (Uslu et al., 2008). Raw biomass is generally characterized by its high moisture content and volatility, and by its lower higher heating value (HHV) and energy density levels compared to fossil fuels (Werther et al., 2000). Biomass has some disadvantages when used as fuel, such as its low HHV, high moisture content, hygroscopic nature, smoke emission during combustion, its heterogeneous and uneven composition, and transport difficulties (Uemura et al., 2011). Existing technologies to convert biomass to energy include thermochemical and biochemical processes (Goyal et al., 2008). The thermochemical conversion process is the most common technique, which include combustion, pyrolysis, gasification, and liquefaction (Uemura et al., 2011; Zhang et al., 2010). The treatment of biomass at lower temperatures ranging from 200 to 300 °C under an inert atmosphere was known to be effective for

improving the energy density and shelf life of the biomass (Uemura et al., 2011; Zhang et al., 2010; Arias et al., 2008). This treatment is referred to as 'torrefaction', and it has been widely applied to wood and grass biomass over the past few years. The main improvements of torrefied biomass include reduced moisture and an increased energy density; a reduced oxygen-to-carbon (O/C) ratio, which increases the HHV; the strong fibers of the biomass becoming brittle, which improves grindability by reducing the cost and energy required for grinding; and the ignitability and reactivity is improved, which enhances the efficiency during gasification or pyrolysis (Chen and Kuo, 2010; Bridgeman et al., 2008). During this process the OH radicals of the polymer breaks away forming H<sub>2</sub>O and some carbon compounds enters into reactions forming CO<sub>2</sub> and CO. Though this process involves significant loss in mass, the energy released in the above reaction is relatively small. Furthermore, H<sub>2</sub>O and CO<sub>2</sub> do not carry away any chemical energy from the biomass. Thus, the biomass experiences a greater loss in mass and smaller loss in energy resulting in a net increase in energy density of the biomass even on dry basis (Dhungana et al., 2012). Torrefaction can be incorporated into a combined drying, torrefaction, and pelletization process, with both economic and energy efficiency benefits (Bergman et al., 2005a). However, this process requires a separate plant, the input of the process energy, and the production of gaseous and volatile streams, entailing

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capital costs, operating costs, and emission control efforts. A balance between these associated costs for fuels which are more grindable and have higher HHV is therefore critical for the future of torrefaction and requires thorough analysis and extensive, reliable data (Bridgeman et al., 2008).

One of the materials which can be converted into fuel is sewage sludge (SS) (Atienza-Martinez et al., 2013). SS is a waste generated from wastewater treatment plants. During the last 2 decades, developments in municipal wastewater treatment strategies are characterized by a continuous effort to improve the quality of the effluent by upgrading existing treatment plants and designing and implementation of new more effective plants (Magdziarz and Werle, 2014). Municipal wastewater treatment can be considered as a continuous activity also in the future. It is organizationally, technically, and economically hardly possible to prevent or strongly reduce the amount of municipal wastewater. This means that the produced amount of sewage sludge will not change significantly in the future (Rulkens, 2007). In its dry form, SS could be considered a special type of renewable fuel, due to the high quantity of organics of sufficiently high calorific value, similar to that of brown coal (Werther and Ogada, 1999). There is therefore increased interest in utilization of SS, resulting also from limited reserves of fossil fuels, limited global security of energy supplies and environmental and climatic regulations on CO<sub>2</sub> emissions.

There are several works about torrefaction of lignocellulosic biomass (Uemura et al., 2011; Arias et al., 2008; Deng et al., 2009; Li et al., 2012; Chen and Kuo, 2010; Bridgeman et al., 2008) but torrefaction of non-lignocellulosic biomass, such as SS, has been studied to a lesser extent (Dhungana et al., 2012; Atienza-Martinez et al., 2013; Ábrego et al., 2013). So, this study focuses on the effect of the operational conditions of SS torrefaction on the properties of the products obtained. Different torrefaction temperatures and torrefaction residence times were tested in a lab-scale horizontal tubular reactor.

## 2. Experimental

### 2.1. Materials

SS obtained from wastewater treatment plant in Cheonan, Korea was used as the raw material in this study. After collection, each sample was homogeneously mixed and dried at 105 °C for 24 h. Table 1 shows the properties of the SS sample used in this study. The moisture content of the raw SS was 82.2%, with 2.6% ash content. The HHV of the dried sample was determined to be 19.86 MJ/kg. Most of the compositions of “others” in Table 1 are inorganic components.

**Table 1**  
The properties of the SS sample.

|                                    |        |       |
|------------------------------------|--------|-------|
| Elements (wt. %) <sup>a</sup>      | C      | 46.93 |
|                                    | H      | 6.83  |
|                                    | N      | 7.40  |
|                                    | O      | 23.23 |
|                                    | S      | 0.54  |
|                                    | Cl     | 0.07  |
|                                    | Others | 15.0  |
| Moisture (%) <sup>b</sup>          |        | 82.2  |
| Volatile fraction (%) <sup>b</sup> |        | 15.2  |
| Ash (%) <sup>b</sup>               |        | 2.6   |
| HHV (MJ/kg, dry) <sup>a</sup>      |        | 19.86 |

<sup>a</sup> Dry basis.

<sup>b</sup> Wet basis.

### 2.2. Experimental device and procedure

The dried sample was ground for a homogeneous experimental condition. Each experiment was carried out with 20 g of sample at atmospheric pressure. In this study, a horizontal tubular reactor with an internal diameter of 150 mm and a length of 600 mm was used for torrefaction, as schematically shown in Fig. 1. A prescribed amount of each sample was weighed and put in a crucible. Nitrogen flushing was done until the concentration of oxygen in reactor was less than 1%. After flushing the reactor with nitrogen (2 l/min), the temperature of the reactor was raised to different desired temperatures ranging from 150 to 600 °C at a constant heating rate of 10 °C/min using an electric heater. When the torrefaction temperature and torrefaction residence time reached the required experimental condition, the heating reactor was immediately stopped and the carrier gas was shut down. The torrefied sample was then instantly removed and was weighed. In order to investigate the influence of the residence time, the experiments for the torrefaction residence time have also been performed at various residence times varying from 0 to 50 min for 250, 300 and 350 °C. In this experiment, the torrefaction residence time means the residence time after reaching the required temperature. All the other experiments are performed at 0 torrefaction residence time.

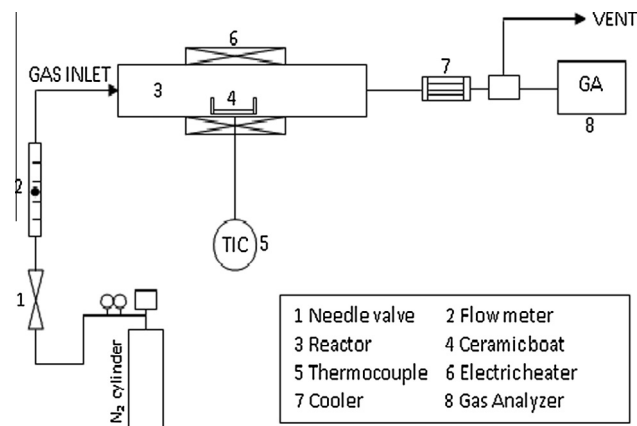
For each experiment, the moisture content, HHV, volatile fraction, and ash content were measured. The HHV was measured using a bomb calorimeter (Parr Instrument Co., Model 1672, Moline, IL, USA). The ash content was determined by the standard method developed by National Renewable Energy Laboratory (NREL) (Sluiter et al., 2008). Elemental analyses of the feedstock and torrefied sample were done by an elemental analyzer (Thermo Fisher Scientific Inc., Thermo FLASH 2000, Hudson, NH, USA). The emitted gas during the torrefaction of SS was measured using a gas analyzer (Greenline MK2, Eurotron Instruments, Chelmsford, UK).

The mass and energy yields are defined by Eqs. (1) and (2), as used by Bridgeman et al. (2008).

$$\text{Mass Yield } (Y_{\text{mass}}) = \frac{\text{mass after torrefaction}}{\text{mass of raw sample}} \times 100\% \quad (1)$$

$$\text{Energy Yield } (Y_{\text{energy}}) = Y_{\text{mass}} \times \frac{\text{HHV (torrefied sample)}}{\text{HHV (raw sample)}} \times 100\% \quad (2)$$

To obtain the kinetic parameters of torrefaction reaction, a thermogravimetric analysis (TGA) of the SS was also conducted using a thermogravimetric analyzer (TA Instruments, Q50, New



**Fig. 1.** Schematic diagram of the horizontal tubular reactor used in this work.

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