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Consequences of sludge composition on combustion performance derived from thermogravimetry analysis

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ABSTRACT

Wastewater treatment plants produce millions of tons of sewage sludge. Sewage sludge is recognized as a promising feedstock for power generation via combustion and can be used for energy crisis adaption. We aimed to investigate the quantitative effects of various sludge characteristics on the overall sludge combustion process performance. Different types of sewage sludge were derived from numerous wastewater treatment plants in Beijing for further thermogravimetric analysis. Thermogravimetric–differential thermogravimetric curves were used to compare the performance of the studied samples. Proximate analytical data, organic compositions, elementary composition, and calorific value of the samples were determined. The relationship between combustion performance and sludge composition was also investigated. Results showed that the performance of sludge combustion was significantly affected by the concentration of protein, which is the main component of volatiles. Carbohydrates and lipids were not correlated with combustion performance, unlike protein. Overall, combustion performance varied with different sludge organic composition. The combustion rate of carbohydrates was higher than those of protein and lipid, and carbohydrate weight loss mainly occurred during the second stage (175–300 °C). Carbohydrates have a substantial effect on the rate of system combustion during the second stage considering the specific combustion feature. Additionally, the combustion performance of digested sewage sludge is more negative than the others.

1. Introduction

Sewage sludge produced in wastewater treatment plants (WWTPs) is currently a problem because elevated amounts of sludge are generated with increasingly stringent wastewater treatment requirements (Wang et al., 2012b). European statistics indicated that the dry weight of sewage sludge production is nearly 90 g per capita per day (Davis, 1996), and the implementation of wastewater management regulations has caused approximately 10 million tons of additional sewage sludge generated yearly since 2005 (Werle and Wilk, 2010). About 30 million tons of sewage sludge is produced in China (Khan et al., 2013). Sewage sludge that is not properly disposed will lead to other environmental issues, such as greenhouse gas emissions (Wang et al., 2012a).

Dried sewage sludge contains a high quantity of organic matter and has a substantial calorific value. Sewage sludge is recognized as an alternative feedstock for power generation via combustion and can be used for energy crisis mitigation (Garcia et al., 2013; Werther and Ogada, 1999). This emerging practice can facilitate the substantial reduction of for-disposal sewage sludge amount because detrimental substances are removed when sewage sludge is used for power generation. Thus, energy recovery through sludge combustion is no longer a possibility, but rather an obvious reality. The sludge combustion process (SCP) has been extensively studied. However, information is still lacking on the combustion performance of sewage sludge and its connection with sludge composition. Sewage sludge contains a variety of complex components, and each constituent shows specific burning features unlike single-solid fuels, such as coal (Viet et al., 2013). Previous studies on SCPs have only addressed small components of a comprehensive technical scheme (Ogada and Werther, 1996); (Francisca Gómez-Rico et al., 2005). Designing and operating an industrial-scale SCP still requires reliable information on feedstock characteristics, which has been historically obtained from semi-empirical tests. This lack of data often presents a problem in the scale-up stage because the contributions of all complex constituents in real sewage sludge to SCP efficiency are not considered in experience-based models.

Thermogravimetry (TG) and differential thermogravimetric (DTG) analyses are widely applied in the comparative evaluation of varying thermal processes in the combustion system (Su et al.,

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2013). These methods can rapidly examine multiple combusting indices (e.g., maximum combustion rate, ignition temperature, and burnout temperature). In particular, TG can monitor the sample mass of substance as a function of temperature and/or time, whereas DTG is an approach performed by detecting the rate of mass loss. These two approaches have been used recently in thermal degradation of biomass samples (Eero, 1981; Jakab et al., 1997; Meszaros et al., 2007; Sebestyén et al., 2011; Shafizadeh, 1968; Varhegyi et al., 1988; Villanueva et al., 2011; Wilson et al., 2011), investigations of sewage sludge pyrolysis (Dumpelmann et al., 1991; Magdziarz and Werle, 2014), and combustion (Font et al., 2001; Magdziarz and Wilk, 2013), as well as co-combustion of sewage sludge and other substances (Otero et al., 2002; Park and Jang, 2011; Yu and Li, 2014). Operation parameters of SCPs, such as temperature and atmosphere conditions, were also evaluated using both TG and DTG approaches (Calvo et al., 2013; Manara and Zabaniotou, 2012). The dynamic connection between sludge characteristics and SCP performance using TG and DTG techniques should be explored. However, little research has been conducted from this perspective at a comprehensive scale.

We aimed to investigate the relevant effects of sewage sludge composition on SCP performance and the consequences of such effects. The most significant constituent for SCP performance was also estimated to provide a reference basis for the future design and operation of SCPs.

2. Materials and methods

2.1. Brief description of sludge samples

All sludge samples were collected from 10 municipal WWTPs in Beijing, China, in June 2012. Table 1 presents a summary of these samples. Three kinds of sewage sludge derived from WWTPs were used: primary sludge (PS) from the primary clarifiers, waste activated sludge (WAS) from secondary clarifiers, and digested sludge (DS) from anaerobic digesters. Sludge samples were freeze-dried immediately after retrieval. After lyophilization, the sludge samples were ground to 100 mesh and stored at 4 °C before further tests.

2.2. Composition analysis of sludge samples

A standard method was used to determine the compositions based on proximate analysis, i.e., moisture, volatiles, ash, and fixed carbon (D5142-04, 2002). Proteins in various kinds of sludge originated from different sources. The PS protein was from a protein-containing substance in wastewater that settled in the primary sedimentation tank. The WAS and DS proteins were from microbial metabolism. Protein content was analyzed using a Kjeldahl instrument (UDK152). Carbohydrates and lipids were determined using a colorimetric method (Dubois et al., 1956) and an ether extraction method (Ferraz et al., 2004), respectively. The weight fractions of major elements (C, H, O, N, and S) were analyzed by two elemental analyzers (EAI CE-440 Element Analyzer and PE-2400 II Element Analyzer), and the net calorific value (NCV) was measured using an automatic oxygen bomb calorimeter (IKAC2000).

Table 1
Description of sludge samples.

Sample no.	Sample source[a]	Capacity ($\times 10^4$ m^3/d)	Wastewater source	Treatment process[b]
1	WAS	7	Municipal	OD
2	WAS	7	Municipal	A^2/O
3	WAS	20	Municipal	OD
4	WAS	5	Industrial	CASS
5	WAS	5	Industrial	CASS
6	WAS	20	Municipal	Inverted A^2/O
7	WAS	20	Municipal	A^2/O
8	WAS	4	Municipal	UCT
9	PS	60	Municipal	A^2/O
10	WAS	60	Municipal	A^2/O
11	DS	60	Municipal	A^2/O
12	WAS	100	Municipal	General AS
13	WAS	8	Municipal	OD
14	WAS	8	Municipal	CASS

[a] Sludge samples from the same sewage treatment plant are: sludge nos. 1 and 2; sludge nos. 6 and 7; sludge nos. 9, 10, and 11.
[b] OD—oxidation ditch; A^2/O: anaerobic–Anoxic–Oxic process; CASS—cyclic activated sludge system; UCT: a type of improved A^2/O process, proposed by the University of Cape Town; AS—activated sludge process.

2.3. TGA approach of sludge samples and organic matter

TGA on real sludge samples and representative matter for sludge organics [i.e., bovine serum albumin (BSA), casein, glucose, starch, soybean oil, and lipids extracted from the sludge] were performed using a thermogravimetric analyzer (NETZSC STA-409PC). The weight of each sample was approximately 18 mg. The furnace temperature was increased from 40 °C to 850 °C at a rate of 10 °C/min with an air flux of 30 mL/min. The sample weight was monitored continuously as a function of temperature. Soybean oil and lipids extracted from the sludge were mixed with silicon dioxide to prevent splashing during combustion.

2.4. Determination of combustion characteristic index (CCI)

In this study, indicator CCI (mg^2 min^{-2} K^{-3}) represented the combined effect of four general combustion parameters (maximum combustion rate, average combustion rate, ignition temperature, and burnout temperature) and was used to evaluate the overall performance of SCP. Thus, CCI can be defined by the following equation according to a previous study (Wang et al., 2011):

$$\mathrm{CCI} = \frac{(d_w/d_t)_{\max}(d_w/d_t)_{\text{mean}}}{T_i^2 T_h} \tag{1}$$

where $(d_w/d_t)_{\max}$ (mg/min) is the maximum combustion rate, $(d_w/d_t)_{\text{mean}}$ (mg/min) is the average combustion rate, T_i (K) is the ignition temperature, and T_h (K) is the burnout temperature. The combustion performance improved with increasing CCI (Wang et al., 2011).

2.5. Statistics approach for correction analysis

Statistics analysis was performed to identify the quantitative relationships of individual sludge characteristic and combustion performance, and a representative approach of univariate linear correlations was used (Ou et al., 2014; Yoshiyuki and Yutaka, 2003) with IBM SPSS Statistics 19.0 software (SPSS Inc., Chicago, IL). The Pearson's product momentum correlation coefficient was referred to as R value and was used for linear estimation. The value of R is in the range −1 to +1. A value of −1 indicates a perfect negative correlation, whereas a value of +1 represents a perfect positive correlation. A value of 0 indicates the absence of correlation.

3. Results and discussion

3.1. Sludge composition

Table 2 presents detailed data on sludge composition of the samples. Volatile compounds (50–74%) are the main components of sludge, and the amounts vary with the samples collected. The proportion of volatile compounds was lowest in sludge no. 5 (~50%) and was highest in sludge no. 8 (~74%). Volatiles of sludge