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Combustion behaviors and kinetics of sewage sludge blended with pulverized coal: With and without catalysts

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ABSTRACT

The combustion behaviors of sewage sludge (SS), pulverized coal (PC), and their blends were studied using a thermogravimetric analyzer. The effect of the mass ratio of SS to PC on the co-combustion characteristics was analyzed. The experiments showed that the ignition performance of the blends improved significantly as the mass percentage of SS increased, but its combustion intensity decreased. The burnout temperature (T_b) and comprehensive combustibility index (S) of the blends were almost unchanged when the mass percentage of SS was less than 10%. However, a high mass percentage of SS (>10%) resulted in a great increase in T_b and a notable decrease in S . Subsequently, the effects of different catalysts (CaO, CeO₂, MnO₂, and Fe₂O₃) on the combustion characteristics and activation energy of the SS/PC blend were investigated. The four catalysts promoted the release and combustion of volatile matters in the blended fuels and shifted their combustion profiles to a low temperature. In addition, their peak separating tendencies were obvious at 350–550 °C, resulting in high peak widths. All the catalysts improved combustion activity of the blended fuel and accelerated fixed carbon combustion, which decreased the ignition temperature and burnout temperature of the fuels. CeO₂ had the best catalytic effects in terms of the comprehensive combustion performance and activation energy, followed closely by Fe₂O₃. However, the rare-earth compounds are expensive to be applied in the catalytic combustion process of SS/PC blend at present. Based on both catalytic effects and economy, Fe₂O₃ was potentially an optimal option for catalytic combustion among the tested catalysts.

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1. Introduction

Sewage sludge (SS) is a by-product of the treatment process of urban wastewater (Liu et al., 2015a; Ma et al., 2014; Syed-Hassan et al., 2017). It releases a fetid odor and contains many harmful substances, including heavy metals, pathogenic organisms, parasitic ovum, and poorly biodegradable organic compounds (Magdziarz and Werle, 2014; Xie and Ma, 2013). These properties and the increase in SS production limit the traditional methods of sludge disposal, such as landfill and agricultural use, which may lead to the serious pollution of air, soil, and water (Chen et al., 2015a). Dried SS can produce a certain amount of heat due to its high content in organic substances and is considered as a potential biomass resource. The SS incineration, a waste to energy (WTE)

technology, can reduce the utilization of fossil fuels and the environmental pollution. Meanwhile, this technology can not only dramatically minimize odor and sludge volume, but also thermally destroy toxic organic components in SS (Kijo-Kleczkowska et al., 2015). Therefore, the incineration for SS has become a critical thermal disposal technology.

However, the separate combustion of SS is unstable because of its low calorific value and high ash content (Ding and Jiang, 2013; Lin et al., 2015; Zhang et al., 2017). Some researchers have found that the issue can be settled by adding coal for co-combustion (Chen et al., 2015b; Folgueras et al., 2003; Kijo-Kleczkowska et al., 2016; Liao and Ma, 2010; Magdziarz and Wilk, 2013; Otero et al., 2007, 2008; Xiao et al., 2010). The co-disposal of SS in utility boiler not only reduces operation cost, but also lowers pollutant emission using well-equipped flue gas cleaning facilities (Chen et al., 2015b; Du et al., 2014). In turn, the addition of some organic sludge to coal can improve the combustion efficiency. For example, Liao and Ma (2010) studied the combustion behaviors and kinetics of paper mill sludge blended with semi-anthracite coal. The results indicated that the addition of paper sludge into coal lowered the

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Nomenclature

T_i	ignition temperature [°C]	$\Delta t_{1/2}$	time zone of $(dw/dt)/(dw/dt)_{\max}$ [min]
T_b	burnout temperature [°C]	S	comprehensive combustibility index [$\%^2/(\text{°C}^3 \text{ min}^2)$]
T_m	peak temperature [°C]	$(dw/dt)_{\max}$	maximum mass loss rate [%/min]
C_i	ignition index [%/min ³]	$(dw/dt)_{\text{mean}}$	average mass loss rate [%/min]
C_b	burnout index [%/min ⁴]	R	universal gas constant [8.314 J/(mol K)]
t_i	ignition time [min]	$f(\alpha)$	reaction mechanism function
t_{\max}	peak time [min]	m_0	initial mass of the sample [mg]
t_b	burnout time [min]	m_f	final mass of the sample [mg]
α	conversion degree	m_t	mass of the sample at time t [mg]
t	reaction time [min]	A	pre-exponential factor [min^{-1}]
T	absolute temperature [K]	E	activation energy [kJ/mol]
$k(T)$	rate constant		

ignition temperature of blended fuel. Chen et al. (2015b) investigated the interactions between chemicals wastewater solid (RS) and lignite in the process of co-combustion under different blending ratios. The results showed that the comprehensive combustion performance of the blends increased as the mass percentage of RS in the blends increased.

Meanwhile, many studies also indicated that the thermal reactivity of SS or coal improves by adding various additives (Abbasi-Atibeh and Yozgatligil, 2014; Fang et al., 2016; Folgueras and Diaz, 2010; Fu et al., 2016; Huang et al., 2018; Li et al., 2007; Liu et al., 2015b, 2015c; Ma et al., 2006; Wang et al., 2014; Zhang et al., 2014; Zou and Zhao, 2017). For example, Li et al. (2007) reported that metal oxides (CuO, Fe₂O₃, and ZnO) decrease the ignition temperature of high ash coal and accelerate the combustion rate and burnout of fixed carbon. Abbasi-Atibeh and Yozgatligil (2014) showed that K-based catalyst has a high char reactivity and decreases the burnout temperature of lignite. Liu et al. (2015b, 2015c) conducted a detailed analysis of the synergistic effects of Fenton's reagent and conditioner CaO on product distribution in SS pyrolysis; their results demonstrated that the two conditioners promote the direct conversion of tar molecules to gaseous products. Fang et al. (2016) showed that MgO, Al₂O₃, and ZnO contribute to the decrease in the initial temperature and activation energy of paper sludge in pyrolysis. However, most of literature focuses on the co-combustion of SS and coal or the effect of catalysts on SS or coal at present. The research about the effect of catalysts on the co-combustion characteristics of SS/coal blends is relatively rare. Thus, further research is still necessary.

In this study, the combustion behaviors of sewage sludge (SS), pulverized coal (PC), and their blends were analyzed by thermogravimetric analysis. Based on many literature studies on combustion or pyrolysis of coal or biomass (Abbasi-Atibeh and Yozgatligil, 2014; Cai et al., 2017; Fang et al., 2016; Gong et al., 2010a, 2010b; Li et al., 2007; Ma et al., 2006), CaO, CeO₂, MnO₂, and Fe₂O₃ were selected as the catalysts, and the effects of 5% catalysts on the combustion of SS/PC blends were investigated. Subsequently, the kinetic parameters during co-combustion were calculated using the Coats–Redfern integral method to analyze catalytic combustion.

2. Material and methods

2.1. Sample preparation

In this study, SS was collected from secondary sedimentation tank of the Qinghe municipal wastewater treatment plant in Beijing, China. The coal type was bituminous coal from Shanxi Province, China. Before the experiments, SS and coal samples were dried in an air drying oven at 105 °C for 24 h, after which they

are crashed, ground, and sieved to obtain particles with a size less than 75 μm. The particle size distributions of SS and PC are characterized by a CILAS 1180 laser particle size analyzer. The mass percentages of dried sludge in the blends were set as 0%, 5%, 10%, 15%, 20%, 30%, 50% and 100%, which were named PC, 5SS95PC, 10SS90PC, 15SS85PC, 20SS80PC, 30SS70PC, 50SS50PC and SS, respectively. Then 5% catalysts (CaO, CeO₂, MnO₂, and Fe₂O₃) was mixed with the 10SS90PC blend. The final samples were stored in desiccators and designated as Ca–10SS90PC, Ce–10SS90PC, Mn–10SS90PC, and Fe–10SS90PC.

The proximate analysis and ultimate analysis of SS and PC were determined by TGA2000 according to GB/T212–2008 and Vario EL cube according to ASTM D5373–08 and GB/T214–2007, respectively. The calorific values were measured by HKRL–4000B according to GB/T213–2008. The ash components of SS and PC were tested by XRF.

2.2. Thermogravimetric analysis

The combustion experiments were conducted on a NETZSCH STA 449 F3 thermogravimetric analyzer (Germany) with a sensitivity of 10^{−7} g. During the experiments, the initial weight of the sample was about 6 mg to reduce the heat and mass transfer limitations between the solid particles. The samples were heated from room temperature to 900 °C in air atmosphere with a flow rate of 80 mL/min at a heating rate of 20 °C/min. Each run was repeated at least three times under the same conditions to decrease experimental error. The schematic diagram of experimental apparatus was shown in Fig. 1.

2.3. Determination of combustion characteristic parameters

The ignition temperature (T_i , °C), burnout temperature (T_b , °C), and peak temperature (T_m , °C) were directly obtained from the mass loss (TG) and mass loss rate (DTG) curves according to previously described methods (Lin et al., 2015).

In addition, the ignition index (C_i , %/min³), burnout index (C_b , %/min⁴), and comprehensive combustibility index (S , %²/°C³ min²) were also used to evaluate the combustion performance of all the samples (Li et al., 2011; Zhang et al., 2015a). These parameters could be calculated by Eqs. (1)–(3).

$$C_i = \frac{(dw/dt)_{\max}}{t_i t_{\max}} \quad (1)$$

$$C_b = \frac{(dw/dt)_{\max}}{\Delta t_{1/2} t_{\max} t_b} \quad (2)$$

$$S = \frac{(dw/dt)_{\max} (dw/dt)_{\text{mean}}}{T_i^2 T_b} \quad (3)$$

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