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Research article

Experimental investigation of synergistic behaviors of lignite and wasted activated sludge during their co-combustion

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ABSTRACT

To explore the feasibility of co-combustion of lignite and wasted activated sludge (WAS) and examine their synergistic effects, combustion of lignite–WAS blend at a mass ratio of 90:10 in a horizontal tube furnace was conducted. Results showed that the synergistic effects occurred between lignite and WAS during their co-combustion because the actual conversion ratio of combustible substances (CR) was higher than the theoretical prediction. Effects of furnace temperature and O_2 concentration of inlet atmosphere on CR were also determined. High furnace temperature and O_2 concentration of the inlet atmosphere resulted in high CR. In the early combustion stage, the furnace temperature played a major role. In the middle stage, the furnace temperature and O_2 concentration of the inlet atmosphere exhibited a combined effect. In the late state, the O_2 concentration of the combustion atmosphere played a key role. Scanning electron microscopy (SEM) photos indicated that the micro appearance of solid particles and their changing trends during the combustion of lignite–WAS blend were similar to those of lignite because of the high proportion of lignite (90%) in the blend. However, when compared to the case of lignite, the solid particles of the lignite–WAS blend were smaller, rougher, and looser in structure as the combustion progressed. In the solid combustion products of blend, carbon (C), oxygen (O), and chlorine (Cl) contents exhibited different evolution behaviors. The C content first increased and decreased, the O content first decreased and increased, and the Cl content continuously decreased to zero.
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1. Introduction

Municipal wastewater sludge contains large amounts of salts, nutriments, heavy metals, pathogens, and organic pollutants that significantly harm both humans and the environment if not treated properly. Energy utilization of sludge has received widespread attention because this process solves the environmental problems caused by sludge and enables efficient use of energy from sludge. The current methods for the energy utilization of sludge mainly include co-combustion with coal [1–4], anaerobic digestion to generate methane [5], low-temperature pyrolysis to produce fuel oil [6], gasification to prepare combustible gas [7], and coal sludge slurry preparation [8]. Co-combustion of sludge with coal is a preferred method of sludge handling because it significantly reduces sludge volume, completely eliminates pathogenic organisms, thermally destroys organic and toxic ingredients, and substantially minimizes odor. As the calorific value of dried sludge is comparable to that of lignite, this method is preferable because the energy content of the sludge is effectively used.

Dong et al. [2] conducted the co-combustion of tannery sludge and bituminous coal in a 220 t/h fluidized bed boiler; they reported that tannery sludge exhibited higher reactivity than bituminous coal. Thus, co-combustion would benefit coal ignition. However, the fraction of tannery sludge should be limited to avoid the reduction of combustion temperatures and increase of nitrogen oxides (NO_x) and some trace elements over their emission limits. By contrast, Coimbra et al. [9] pointed out that the co-combustion of primary and secondary pulp mill sludge with bituminous coal at a sludge fraction of 10% (on air-dried basis) is a feasible management option for sludge, which also reduces CO_2 and NO_x emissions. Under accurate control and appropriate sludge fraction conditions, the co-combustion of sludge with coal is a secure outlet and generates income through energy recovery.

Different conclusions were drawn on whether any synergistic effects exist between the coal and sludge during co-combustion. Yang et al. [10] conducted co-combustion tests of dried sewage sludge pellet and coal gangue on a tube furnace, and synergistic effects were observed on ignition performance, desulfurization, denitrification and trace element retention. Liao et al. [11] performed the co-combustion of semi-anthracite coal and paper mill sludge by thermogravimetric analysis. The researcher detected the synergistic effects between the two materials during their co-combustion process. Hu et al. [12] also reported

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similar results during the co-combustion of paper mill sludge and municipal solid waste. However, Chen and Wu [13] found that char yield was linearly related to the biomass blending ratio during the co-combustion of rice husks and coal, which indicated that the synergistic effects between the two materials did not occur. Gil et al. [14] studied the co-combustion of biomass (pine sawdust) with coal, and no significant interactions between biomass and coal were detected. A more detailed discussion of the burning performances of coal–biomass blends can be found in the overview [4]. The existence of synergistic effects between individual components depends on individual component types, component fractions, and combustion conditions.

Lignite is distributed widely in China, mainly in Inner Mongolia, Sinkiang, and Yunnan. With its wide distribution and large reserves, lignite is the most important primary energy and chemical material. In the present study, lignite from Sinkiang district and a wasted activated sludge (WAS) from a municipal wastewater treatment plant were selected. The combustion experiments of lignite, WAS, and their blend were conducted in a horizontal tube furnace. The synergistic effects between the WAS and lignite were studied in the following aspects: conversion ratio of combustible substances (CR); micro appearance of solid particles; and changing trends of carbon (C), oxygen (O), and chlorine (Cl) contents in the solid particles. The results can provide theoretical basis for the industrial application of lignite and the energy utilization of sludge.

During the actual combustion in a boiler or furnace, temperature and atmosphere are generally unevenly distributed in space. However, the temperature and atmosphere significantly affect combustion. Therefore, investigating the influences of temperature and atmosphere on the co-combustion properties of WAS with lignite is crucial.

Many studies have focused on the influence of oxygen content on the co-combustion properties of two materials under oxygen-enriched atmospheres [11,15]. However, local oxygen-lacking and oxygen-enriched areas likely appear in the boiler or furnace at the same time. In the present study, three atmospheric conditions, namely, oxygen-lacking, normoxic, and oxygen-enriched, were formed by allocating the inlet proportions of N_2 and O_2. The co-combustion characteristics of WAS with lignite under these three atmospheres were investigated. Considering the uneven distribution of temperature in the boiler or furnace during actual application, the influence of temperature on the co-combustion characteristics was also investigated in the present study. The results can contribute to our understanding of the local combustion performances in a boiler or furnace.

2. Experimental

2.1. Materials

Lignite was collected from Sinkiang district, and WAS was collected from a municipal wastewater treatment plant (MWTP) in Hangzhou city. 0.5 million tons of industrial and household wastewater of the city was treated by A/A/O technique in this MWTP every day. Lignite and WAS were dried at 105 °C for 24 h. The samples were ground and sieved to the desired size (less than 74 μm).

The proximate analyses were determined using drying oven and muffle furnace according to national standards of China (GB/T 212). The ultimate analyses were determined using an element analyzer (Vario EL III, Elementar, Germany) according to national standards of China (GB/T 476). The calorific values were determined using an automatic calorimeter (HYZDHW-4000, Huayuan, China) according to national standards of China (GB/T 213).

The compositions of the ashes of lignite and WAS were measured using an X-ray fluorescence analyzer (ARL Advant'X, Thermo, USA). The measurement was conducted in triplicate, and the results were presented as mean value. The error between each measurement result and the mean value was less than 10%.

2.2. Co-combustion equipment and methods

The combustion experiments of lignite, WAS, and their blend were conducted in a horizontal tube furnace system with a temperature-control precision of ± 3 °C, as shown in Fig. 1. Lignite–WAS blend was prepared using 10% dried WAS and 90% dried lignite.

In actual industrial application, the fuels are fed continuously into a boiler or furnace which is operated at a relative stable temperature, although the temperature shows some fluctuations of dozens of degrees centigrade. Thus, in the present study, the temperature of the tube furnace was first increased to the desired value, and the sample was pushed into the tube furnace (Fig. 1a) rather than the opposite, which was adopted by most thermogravimetric analysis because the sample was first placed in the combustion chamber and the temperature of the furnace was increased. When the appointed time was achieved, the sample was pulled out from the tube furnace to the cooling position (Fig. 1b).

Through the combusting and cooling processes, an atmosphere flow, which was formed by N_2 and O_2 controlled by an individual mass flowmeter, was fed into the quartz tube in the tube furnace. The sample was taken out and sealed for determination after being cooled down to room temperature.

A sample of approximately 2 g was used for each test, and the combustion times were 1, 5, 10, and 30 min. The influences of temperature and O_2 concentration of the atmosphere were studied. The temperatures considered were 800, 1000, and 1200 °C. Three atmosphere conditions, namely, oxygen-lacking, normoxic, and oxygen-enriched, were obtained by allocating the inlet proportions of N_2 and O_2 at ratios of N_2:O_2 = 90:10, 79:21, and 70:30, respectively. The total atmosphere flow was 1 L/min.

2.3. Weight loss analysis and conversion ratio of combustible substances during combustion

Weight loss analysis was conducted by determining the weight of solid products after different combustion times. The experiment was conducted in triplicate, and accordingly three parallel results were obtained for the weight of solid products obtained under each condition. The mean value of the three parallel results was used for combustion analysis. The error between each measurement result and the mean value was less than 8%.

The local conversion ratio of combustible substances (CR) can be obtained by the following formula:

$$\mathrm{CR} = \frac{(m_0 - m_t)}{m_0(1 - A_d)}, \tag{1}$$

where m_0 and m_t represent the initial and actual weight of the material, respectively, and A_d represents the ash yield of the material on a dry basis.

2.4. Structure and element composition evaluation of solid products

SEM observations for solid products from different combustion times were performed by a SIRION-100 field emission scanning electron microscope (FEI, Netherlands) equipped with an integrated energy dispersive X-ray spectrometer to analyze the elements and their contents.

3. Results and discussions

3.1. Characterization of materials

The proximate and ultimate analyses and the calorific values of lignite and WAS on dry basis are shown in Table 1. The ash (A_d) yields of lignite and WAS are 21.57% and 54.75%, respectively, and the fixed carbon (FC_d) yields of lignite and WAS are 45.78% and 4.96%, respectively.

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