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Evaluation on the oxy-fuel combustion behavior of dried sewage sludge

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HIGHLIGHTS

- The oxy-fuel combustion behavior of dried sewage sludge was detected.
- The comprehensive performance indices of sewage sludge were determined.
- Dominant combustion mechanisms around two main peaks were evaluated.
- Kinetic compensation effects were revealed in key burning stages of sewage sludge.

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ABSTRACT

The combustion behavior of sewage sludge under oxy-fuel condition was evaluated based on a thermal analysis technique. At heating rates of 20–80 K min^{-1}, the ignition temperatures of the sewage sludge were between 250 and 300 °C under air and three O_2/CO_2 atmospheres (oxygen contents of 21%, 30% and 40%). The burning process of the sewage sludge in air was very similar to 30%O_2/70%CO_2 atmosphere. The ignition and burnout temperatures of the sewage sludge decreased with increasing oxygen contents in O_2/CO_2 atmospheres. The average comprehensive performance indices of the sewage sludge in 40% O_2/60%CO_2 atmosphere were about 2 times more than that in 21%O_2/79%CO_2 atmosphere. Moreover, the ignition and comprehensive performance indices of the sample sharply rose up with increasing heating rates. The ignition and comprehensive performance indices of the sewage sludge in 30%O_2/70%CO_2 atmosphere at 80 K min^{-1} were about 4 times and 6 times more than that at 20 K min^{-1}. The kinetic parameters in four combustion stages around two peaks were evaluated based on the Coats–Redfern method coupled with Ozawa–Flynn–Wall equation. There were certain kinetic compensation effects for both main combustion stages and different oxygen contents in oxy-fuel.

1. Introduction

The growing global urbanization of society coupled with the increasing population and industrialization is resulting in sewage sludge regarded as the residue largely produced from municipal waste water treatment [1]. There are more than 20 million tons of sewage sludge being produced annually in China [2]. In Europe, the production of dry sewage sludge from multi-process treatment is in average 90 g per person per day [3]. Utilization of waste sludge as a renewable energy resource is a feasible way to manage the continuously increasing waste sludge generation in order to fulfill vital environmental standards [4]. Pyrolysis, gasification, combustion are main thermal treatment technologies for the municipal sewage sludge. The advantages of thermal processes include the large reduction in volume, the thermal destruction of toxic organics and the recovery of the energy of organic sources in the sludge. One of the most promising options is combustion [5,6], which can also reduce the dependency on fossil fuels. Especially in highly developed countries, the combustion technique of the municipal sewage sludge is increasingly common way for its management.

Mechanical dewatering process can make the moisture content of the sewage sludge be reduced to about 75–80% [7–9]. Ogada and Werther [10] observed that dewatered sludge combustion in a semi-pilot scale bubbling FBC reactor had distinctive phenomenon compared with coal combustion due to lots of moisture and volatiles in the dewatered sludge. Thermal drying characteristics for dewatered sludge have been addressed in previous works [11–14]. The combustion kinetics of sewage sludge pellets under

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Nomenclature

a	conversion degree
A	the pre-exponential (s^{-1})
D	combustion index
E_a	apparent activation energy (J mol^{-1})
m	mass; empirical constant in integral function
n	reaction order
R	the universal gas constant (J mol^{-1} K^{-1})
T	temperature (K/°C)

Greek letter

β	heating rate (K min^{-1})

Subscripts and superscripts

b	burnout
c	comprehensive performance
i	ignition
m	mean
max	maximum
p	peak

air atmosphere in a laboratory-scale batch type stoker incinerator was evaluated by Lee and Bae [15]. The results presented their decomposition rate decreased and their activation energy increased as the moisture content of the sludge pellets increased. Dried sewage sludge 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 [6]. Therefore, dried sludge is preferred as the sludge is to be incinerated. Pre-drying of sewage sludge up to about 25% dry base content is required for conventional incineration [16]. Thermal analysis techniques have been widely in exploring combustion characteristics of sewage sludge [6,17–19] in air atmosphere, which are addressed with the influence of sewage sludge types and heating rates. Based on a thermal analysis technique, Magdziarz and Wilk [20] revealed combustion kinetics of sewage sludge in air atmosphere at heating rates of 10, 40 and 100 K min^{-1}, in which the kinetic parameters were calculated using KAS model. The thermal analysis techniques are advantageous for assessing quickly the fuel behavior such as the ignition and burnout temperatures, the maximum burning rate and reactivity temperature, the amount of ash and required combustion time. Thermal analysis is also the most common technique used for exploring the combustion kinetics of sample, in which sample mass may be small enough to prevent the effect of thermal diffusion in the sample on the kinetics [21]. Based on the TG technique, Wang et al. revealed that combustion characteristics of anthracite coal/pine wood were improved by the increase of heating rate, and that there was certain kinetics compensation effect for different heating rates [22]. Moreover, compared with conventional air combustion, oxy-fuel combustion technique can be available for producing a sequestration-ready high CO_2 concentration effluent gas [23–25] and deriving a higher boiler thermal efficiency with lower sensible heat loss [26]. Nitrogen oxides emission will be also diminished [27], and sulfur oxides can be more easily removed in O_2/CO_2 atmospheres [28]. Reducing the emissions should also be concerned for the combustion process of the sewage sludge. Bejarano and Levendis [23] pointed out that bituminous coal or lignite particles burned at higher mean temperatures in O_2/N_2 than in O_2/CO_2 environments with analogous oxygen contents. Arias et al. [29] highlighted that the oxygen concentration in O_2/CO_2 atmosphere should be 30% or higher to obtain similar or better ignition properties of bituminous coal and bituminous coal/biomass blends in comparison with air. Oxy-fuel combustion behaviors for coals, and coal/biomass blend or municipal solid waste (MSW) have been explored based on the TG technique [26,30–32]. However, it has received less attention for wastes, especially municipal sewage sludge. CO_2 has more density, higher heat capacity, and stronger radiativity than those of N_2. The replacement of N_2 by CO_2 will cause some negative effects on the combustion such as ignition performance and burning stability [33,34]; therefore, higher O_2 concentrations are usually considered in the oxy-fuel combustion to hold a similar combustion behavior. Based on a TG technique, Lai et al. [35] found that lignocellulosic materials from MSW in 70%CO_2/30%O_2 atmosphere achieved a similar combustion performance as 80%N_2/20%O_2. Tang et al. [36] addressed that NO_x and SO_2 emissions between 800 °C and 1000 °C reduced when replacement of N_2 by CO_2 in atmosphere during MSW combustion. Chen et al. [24] found that combustion rates and combustion performance indexes of petrochemical wastewater sludge in its oxy-fuel combustion increased with O_2 concentration increasing by using a TG technique. Jang et al. [37] pointed out that oxy-fuel combustion of waste sewage sludge in a circulating fluidized bed reactor with oxygen injection rate ranged from 21% to 25% would mitigate agglomeration, fouling and corrosion problems from waste sewage sludge combustion. However, comprehensive evaluation on oxy-fuel combustionperformance and kinetics of municipal sewage sludge including the effect of oxygen contents and heating rates with wide scope has not yet been reported so far. Actually, there have been very limited studies reported on oxy-fuel combustion technology to be applied any waste feedstock. Major waste feedstock for oxy-fuel combustion has done by wood biomass due to its abundance and convenient transporting. Moreover, much investigation about the combustion kinetics for solid fuels is only based on a combustion stage and only using one kinetic model such as Coats–Redfern (CR) approach.

This paper gives combustion behavior of typical Chinese municipal sewage sludge under air and oxy-fuel combustion conditions at heating rates of 20–80 K min^{-1}. The current work mainly aims to address the influences of oxygen contents (21–40%) and heating rates on combustion performance (ignition and comprehensive performance indices), and kinetics based on four main stages around maximum conversion rates of volatile matter and char. Also, the combustion behavior of the dried sewage sludge in O_2/CO_2 atmospheres is compared with that in air. The present work can provide available data for the effect of elevated levels of CO_2 on the combustion behavior of sewage sludge.

2. Methods

2.1. Experimental facility and test samples

A thermogravimetric analyzer (TGA/SDTA851, Mettler Toledo) with a precision of 0.001 mg was utilized to perform the experiments. The raw municipal sewage sludge sample after mechanical dewatering was collected from a municipal wastewater treatment plant (Beijing, China). The pH value of the sludge sample was 6.71 [11]; the contents of total nitrogen, total phosphorus, total potassium and organic matter of the sludge were 56.6, 49.1, 9.3 and 667.6 g kg^{-1}. The initial moisture content of the sewage sludge was about 82.6% (wet base), that was obtained by holding the sample in an oven (KUNTIAN; 101-00B, China) for about 12 h at 105 °C. The dried sewage sludge samples for combustion tests were