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Oxy-fuel co-combustion of sewage sludge and wood pellets with flue gas recirculation in a circulating fluidized bed

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ABSTRACT

Oxy-fuel co-combustion of waste sludge and biomass with flue gas recirculation was conducted to observe the combustion characteristics and enrichment of CO_2 using a 30 kWth circulating fluidized bed. The combustion reaction was accelerated and the ignition time was shortened by increasing the blending ratio of wood pellets and oxygen mixing ratio. The best combustion performance was observed at a 30% blended biomass ratio, with 23% oxygen mixing rate as oxy co-combustion with respect to heat recovery and enrichment of CO_2; this study included experiments with ranges of 0 to 70% for the blending ratio and 21 to 30% for the oxygen mixing ratio. With flue gas recirculation at 60%, the oxy-fuel co-combustion of sludge with biomass was optimized in high enrichment of CO_2 (over 90%) with less pollutant emissions, specifically 0.91% CO and 14 ppm NO.

1. Introduction

As renewable energy resources, waste sludge and biomass are considered to be potential alternative fuels. Since dumping waste sludge into the ocean was prohibited by the implementation of the London Convention in Korea, over 10 million tons of waste sludge has accumulated over several years due to lack of appropriate disposal [28]. Appropriate treatment of this waste sludge would require technological development instead of landfilling. Waste sludge contains many combustible components, which could be converted into valuable energy resources after pretreatment processes such as thermal drying [30,49]. Pretreatment processes would also increase the calorific value of sewage sludge and increase heat recovery efficiency [26,27,31,37]. For this reason, dried sewage sludge combustion technology, using different combustion types, has been applied as a waste to energy (WtE) technology [30,46]. Furthermore, the energy conversion efficiency of sewage sludge can be increased by co-combustion with other types of renewable biomass.

Recently, fluidized bed combustion has been widely applied as a method for incinerating sewage sludge to recover heat energy. Van de Velden et al. [45] applied a heat recovery system to sewage sludge incineration using bubling fluidized bed (BFB). According to the study, heavy metal distributions were different by sampling points of the waste stream in heat recovery system. Li et al. [31] demonstrated heat recovery from wet sewage sludge by integrating BFB drying and circulating fluidized bed (CFB) incineration technique. Due to large moisture content of sewage sludge, the integrated system used heat from a CFB combustor to dry sewage sludge and use it as an input to the combustor [31]. Although, BFB combustion has been well-proven technology for the treatment of sewage sludge, CFB combustion has the significant advantage of being able to use a wide range of fuels including sewage sludge. In addition, it demonstrates excellent performance for both heat and mass transfer, due to the turbulence between the fluidized material and solid fuels creating temperature uniformity [7,46]. Co-combustion of sewage sludge with coal has been studied by various researchers ([2,33,49,52]).

Plants using CFB for waste sludge combustion are operated with excess air, which causes high CO_2 emissions. Among carbon capture and storage (CCS) technologies, oxy-fuel combustion is regarded as a superior technology for reducing short-term CO_2 emissions. It substitutes air during combustion with an O_2/CO_2 mixture to increase CO_2 purity in flue-gas [5,40]. Other benefits include a reduction in NO_x generated during combustion, resulting from a lower net gas emission volume due to CO_2 injection as a substitute for N_2 [41]. These benefits can reduce plant operating costs by decreasing the requirement for air pollution control devices [8,34]. Many papers report attempting oxy-fuel co-combustion of various solid fuels using CFB technology [9,23,29]. Current research has advanced to the level of developing pilot plants [2,10]. For oxy-fuel combustion, flue gas recirculation (FGR) systems would be essential to enrich the CO_2 concentration in

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flue gas for recovery by CCS technology [11]. FGR would reduce the input volume of both the feed gas and flue gas [35], because the flue gas emitted from the combustion process would be reintroduced into the system under the riser of the fluidized bed. The recycled flue gas would change combustion conditions such as burnout time, flame temperature, and heat flux [17,43]. There were numerous researches of co-combustion of sewage sludge combustion using CFB combustor. However, most researches were focused on co-combustion of coal with sewage sludge, and those were conducted in air conditions. In addition, researches on FGR systems were mainly focused on the oxy-fuel combustion of coal, and there has been little research conducted regarding the oxy-fuel combustion of waste sludge and biomass using CFB technology.

In this study, oxy-fuel co-combustion was applied to sewage sludge combustion using the 30 KWth CFB. Wood pellets were used as an auxiliary fuel to increase heat recovery from sewage sludge combustion. Experimental tests comparing various fuel mixing and oxygen injection rates were conducted to optimize various design factors such as CO_2 concentration, pollutant emission, temperature gradient, and temperature gap under different combustion conditions. During the study, the effects of recycled flue gas on oxy-fuel co-combustion were observed by changing FGR rate with respect to combustion temperature and flue gas composition.

2. Experimental methods

2.1. Fuel properties

For this experiment, waste sludge from a sewage treatment plant in Korea was used as the primary fuel, and wood pellets were used as an auxiliary fuel. The properties of each component of the fuel are shown in Table 1. The volatile fractions in waste sludge and wood pellets were 45.11 and 74.47%, respectively. The ash fractions in the waste sludge and wood pellets were 35.35 and 0.29%, respectively. Due to the higher ash fraction in the sewage sludge, the fraction of organic compounds such as carbon, hydrogen, and oxygen, which were primarily involved in the combustion reaction, was lower than that of the wood pellets. The fractions of nitrogen and sulfur in the dried sewage sludge were 4.43 and 0.43%, whereas these elements were not detected in the wood pellets. The calorific values of dried sewage sludge and wood pellets were 3010 and 4260 kcal/kg, respectively. Based on the calorific values of waste sludge, the following blending ratios of wood pellets to waste sludge were chosen: 0, 30, 50, and 70%. 100% wood pellet fuel was not tested in this study, because its burning speed was too fast, causing local combustion to occur in front of the feeder; moreover, it generated a blockage, making the feeder difficult to operate continuously. The feeding rates of different fuel components were decided based on calculation of the calorific value and elemental components of the sewage sludge and wood pellets.

2.2. Operation of the 30 kWth CFB

The combustion tests were conducted in a CFB system consisting of a riser, cyclone, down-comer, and loop-seal. The riser had an inner diameter of 0.15 m and a height of 6.4 m. The CFB was surrounded by heating material in order to deliver the required combustion heat to the fuel during air and oxy-fuel combustion. The reactor was preheated to 873 K using a fast circulating fluidized bed. The O_2 injection rate in the oxy-fuel atmosphere that was fed into the riser was varied from 21 to 30%. The flue-gas recirculating rate was varied from 0 to 60% during oxy-fuel co-combustion. The operating conditions and stability of the CFB system were continuously observed by a data acquisition system to provide real-time analysis. During experiments, the temperature of the riser was measured at 0.356, 0.581, 1.004, 2.404, 3.804, 5.204, and 6.339 m above the distributor, by a series of thermocouples. The concentrations of O_2, CO_2, CO, and NO in the flue gas were continuously monitored after the bag filter by a portable gas analyzer. Fig. 1 shows a schematic diagram of the 30 kWth CFB oxy-fuel combustion system.

Table 2 shows the properties of the fluidizing material in the CFB system. Sand, with a diameter of 315 μm and a density of 1461 kg/m^3 was used as the fluidizing material. As calculated by a previous study, a superficial velocity of over 2.5 m/s was required to operate the CFB [23]. Based on the findings of a previous study, a solid circulating rate of 15 kg/m^2·s and superficial velocity greater than 2.5 m/s were selected for use in this study [20].

3. Results and discussion

3.1. Combustion characteristics of oxy-fuel co-combustion

The theoretical O_2 demand of the combustion system can be calculated by stoichiometric methods using fuel elemental analysis. Complete combustion would be achieved when sufficient O_2 is supplied. The excess O_2 ratio can be defined as the difference between the theoretical O_2 demand and the actual amount of O_2 in the combustion system. Using fuel elemental analysis to calculate the excess O_2 ratios of waste sludge and wood pellets showed that the ratios vary depending on the input oxidant composition and the blending ratio of wood pellets. The excess O_2 ratios and combustion conditions for each experiment are shown in Table 3. For air combustion and 21% oxy-combustion, the same excess O_2 ratio was calculated. However, the excess O_2 ratio increased as the oxygen injection rate increased. Table 3 shows the O_2 ratio for the oxidants used in these experiments. As shown in the table, blending wood pellets into the fuel increased both the heating value and the excess O_2 ratios.

Both the heating value of the fuel and the excess O_2 ratio directly affect the temperature inside the reactor and the flue gas composition ([4,33,53]). To compare these combustion characteristics, the temperature gap between the riser and flue gas temperature was measured as shown in Fig. 2. With air combustion, the temperature gap decreased as the ratio of wood pellets increased. Generally, the solid fuel combustion process begins with the moisture in the fuel evaporating from within the fuel particles. After this, volatile matter is released and combusts, with the combustion of char immediately following in multiple steps [9]. As shown in Table 1, the volatile content of the fuel increased as the blending ratio of wood pellets increased, which expedited the char combustion. Therefore, increasing the ratio of wood pellets to waste sludge increases combustion efficiency as well as

Table 1
Properties of the solid fuels.

Properties		Sewage sludge	Wood pellet	Properties		Sewage sludge	Wood pellet
Proximate analysis (wt%)	Moisture	7.32	8.68	Element analysis (wt%)	Carbon	28.14	48.59
	Volatile	45.11	74.47		Hydrogen	4.74	6.08
	Fixed carbon	12.25	16.56		Nitrogen	4.43	–
	Ash	35.32	0.29		Oxygen	23.9	42.03
Calorific value (kcal/kg)		3010	4260		Sulfur	0.43	–

Detection limit of N and S: 0.5%.