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Combustion characteristics of waste sludge at air and oxy-fuel combustion conditions in a circulating fluidized bed reactor

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HIGHLIGHTS

- Comparative combustion performance of waste sewage sludge in air and oxy-fuel conditions.
- Pressure drop and temperature distribution in air and oxy-fuel combustion.
- Comparison of ash composition in air and oxy-fuel combustion.
- Comparison of flue-gas composition in air and oxy-fuel combustion.

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ABSTRACT

Oxy-fuel combustion and circulating fluidized bed (CFB) technologies were applied to waste sewage sludge using a cold-bed and a 30 kWth CFB pilot test bed. In the cold-bed tests, the minimum fluidization velocity (u_{mf}) and the superficial velocity were determined as 0.120 m/s and 2.5 m/s, respectively. In pilot tests, the combustion characteristics of waste sewage sludge in oxy-fuel condition were very distinctive compared with that in air condition in terms of operation parameters such as the distribution of pressure drop and temperature, flue-gas temperature, and the composition of ash and flue-gas. Based on cold-bed and pilot bed tests, the oxygen injection rate was optimized in the range from 21% to 25% in oxy-fuel condition for waste sludge combustion to apply oxy-fuel combustion and CFB technologies with considering technologies for stable and economic operation.

1. Introduction

In recent years, the demand for renewable energy has increased worldwide, because the releases of greenhouse gases from fossil fuel will not be acceptable in the near future. As one of the renewable energy resources, the generation of waste sewage sludge in Korea has gradually increased over the years. Finally, it will reach over 10 million tons in 2015. Since ocean dumping was inhibited due to the London Convention, the combustion of waste sewage sludge has emerged as one of the alternative disposal options, with the added potential benefit of energy recovery technologies for waste to energy. Waste sewage sludge combustion has also been utilized in the paper and pulp industries. In most plants to combust such industrial waste sludge, fluidized bed combustion technology was adopted in order to produce superheated steam to convert into electricity or heat. Fluidized bed combustion (FBC) has been considered as a common technology for waste sewage sludge due to the fuel-like characteristics of waste sewage sludge composed of lots of organic components. There are lots of researches of combustion characteristics of waste sewage sludge using FBC technology. Ogada and Werther [1] studied combustion characteristics of dewatered sludge using laboratory and semi-pilot scale bubbling FBC reactor. They observed that sludge combustion had distinctive phenomenon compared with coal combustion due to lots of moisture and volatiles in the sludge. Sludge combustion undergoes series of reaction processes such as drying, de-volatilization, and char combustion. Time spans were different with each combustion process, which was indicated the location these processes occurred. Latva-Somppi et al. [2] compared the combustion characteristics from co-combustion of paper sludge with biomass using industrial BFBC and CFBC with fuel injection capacity of 10.8 ton/h and 10.4 ton/h, respectively. The bed temperature of BFBC was slightly

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higher than that of CFBC. In addition, the temperature difference from bed region to freeboard region was higher in BFBC than that in CFBC because circulating material distributed the heat temperature efficiently along with CFBC reactor. Numerous researchers focused on the combustion of volatiles of waste sewage sludge. According to those researches, de-volatilization was occurred particular location such as flame zone and freeboard in which were occurred significant temperature difference in the reactor. Moreover, fluidization velocity and more even temperature distribution would be important for the homogenous combustion and heat recovery [3–6]. In addition, ash and metals emission in waste sewage sludge combustion would be important because waste sewage sludge contained significant portion of ash in which mostly consisted of heavy and trace metals. Along with this, researchers focused on emission characteristics of major elements such as Al, Ca, Na, K, Pb, Cd, Cr, Cu, and Ni from waste sewage sludge combustion using FBC reactor. Rink et al. [7] studied combustion characteristics of paper sludge using 300 kW fluidized bed combustion facility with bubbling fluidization mode. There were locally high temperature regions in the reactor using bubbling FBC. In this region, high temperature caused the melting process of refractory metals and alkali metals in waste sewage sludge with the formation of alkali-silicates in those temperature ranges. Char carbon concentration gradually decreased as oxygen concentration and bed temperature increased. Cenni et al. [8] studied behavior of metals Cr, Mn, Ni, Pb, Zn by co-firing of drying sewage sludge during pulverized coal combustion using 500 kW pulverized fuel combustion chamber. Metal contents in the ash increased as sludge mixing rate increased because the composition of flue-gas could affect the condensation temperature of metal species by blending rate of sewage sludge with coal. Corella and Toledo [9] studied behavior of six metals such as Cd, Ni, Cr, Zn, Cu, and Pb using BFBC pilot plant. Lopes et al. [10] studied heavy metal distribution from co-combustion of sewage sludge and coal using pilot BFBC. They observed that heavy metals were differently distributed by the ash types such as bottom ash and fly ash. Amand and Leckner [11] studied metal emission from co-combustion of sewage sludge with coal or wood using 12 MWth commercial CFB boiler. The amounts of ash and major elements increased as the sludge mixing rate increased. Barbosa et al. [12] studied chemical and ecotoxicological properties of ashes by the co-combustion of coal and sewage sludge. Co-combustion of sewage sludge occurred high concentration of metals in bottom ash and fly ash. In series of those researches, the composition of heavy metals in ash was unstable because the difference of temperature distribution in the BFBC reactor was higher than that in CFBC. Most researches focused on the combustion characteristics of BFBC or co-combustion of waste sewage sludge as second fuel in CFBC. The capacity of commercial FBC plants ranged from 100 to 200 tons of waste sewage sludge combustion per day. Those FBC plants have utilized excess air for combustion, and have generated lots of carbon dioxide which is one of the important greenhouse gases. Due to this global warming, CCS technology has been developed in order to reduce carbon dioxide from stationary emission sources primarily from the fossil fuels combustion. There are different types of carbon dioxide capture technologies, such as pre-combustion, post-combustion, and oxy-fuel combustion. Oxy-fuel combustion is in the demonstration phase and uses high purity oxygen in a combustion medium for coal fired power plants [13]. During oxy-fuel combustion, a combination of oxygen typically with a greater than 95% purity level and recycled flue gas are utilized for the combustion of the fuel. By recycling the flue gas, a gas consisting primarily of carbon dioxide is generated with a carbon dioxide concentration over 90%, which is ready for sequestration without stripping of the carbon dioxide from the gas stream [14]. Therefore, oxy-fuel combustion technology for newly constructed and retrofitted waste sewage sludge FBC plants would be necessary to generated high purity carbon dioxide in the flue-gas. In an earlier study, oxy-fuel combustion was demonstrated by the pilot test performance of a pulverized coal power plant. The earliest study of coal oxy-fuel combustion on a pilot scale was conducted for the Argonne National Laboratory (ANL) by the Energy and Environmental Research Corporation (EERC) in their 3 MWth pilot facility. The results of that study indicated that oxy-fuel combustion would be capable of being successfully applied as a retrofit to a wide range of utility boiler and furnace systems [15–17]. A pilot scale study conducted by the International Flame Research Foundation (IFRF) evaluated the combustion of pulverized coal in a mixture of O_2 and recycled flue gas with the primary consideration of retrofitting an existing boiler, while increasing the carbon dioxide concentration to above 90% for carbon dioxide capture [15]. A study by the IHI company demonstrated combustion characteristics such as the flame temperature as the function of oxygen concentration, NOx conversion rate, and SOx emission during oxy-fuel combustion in a 1.2 MWth test furnace [15,18]. A study by the Air Liquide and the Babcock & Wilcox (B&W) company demonstrated the combustion process based on O_2 enriched flue gas recirculation in order to provide an easy-to-implement option for multi-pollutant control, including carbon dioxide capture suitable for retrofitting an existing boiler. The test showed that the oxy-fuel combustion generated less NOx than air combustion. In addition, it showed the effective removal performance of SOx with wet flue-gas desulfurization (FGD) equipment and a significant reduction of mercury emissions [15]. CANMET has been developing oxy-fuel combustion technology by conducting many theoretical and practical studies. In a 0.3 MWth capacity pilot-scale combustor, the coal combustion behavior in various mixtures of oxygen and carbon dioxide were studied in order to demonstrate the effects of several factors on the combustion performance including the oxygen concentration, recycled ratio, and burner performance, etc. [15,19]. In addition, the CANMET organization designed a 0.8 MWth pilot plant for the demonstration and evaluation of the oxy-fuel CFB combustion process. The feedstock utilized in the tests included a pet-coke, a bituminous coal, and a sub-bituminous coal. Along with pulverized coal power plants, fluidized bed coal power plants with oxy-fuel combustion have been demonstrated by pilot test performance [20]. The VTT Technical Research Centre conducted a 0.1 MWth pilot test under air and oxy-fuel combustion conditions using seven different fuels including anthracite coal, bituminous coal, lignite coal, and 2 different types of biomass such as wood pellet and straw pellet. The flue gas emissions were measured and ash samples were collected in different tests in order to evaluate the combustion efficiency and emission performance. The primary flue gas emissions, such as carbon dioxide, CO, NO, and SO_2 were measured during all of the tests [21]. In addition, there were several on-going demonstration projects for oxy-fuel combustion by several institutes worldwide [22–24]. However, all of the pilot and demonstration projects were conducted primarily using coal fossil fuel to demonstrate the oxy-fuel combustion of coal-fired power plants because it has been most abundant fuel to be utilized for energy production. There have been very limited studies reported on oxy-fuel combustion technology to be applied any waste feedstocks. Major waste feedstock for oxy-fuel combustion has done by wood biomass due to its abundance and convenient transporting. Arias et al. [25] studied combustion characteristics of coal and biomass by comparing air and oxy-fuel combustion. The ignition temperature and burnout rate were different by blending rate of biomass with coal and oxygen injection rate in oxy-fuel combustion. According to Fryda et al. [26] deposition and fouling rate in oxy-fuel combustion were significantly different between coal and co-combustion of biomass with coal. In several researches, they observed that oxygen injection rate was significantly