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Blending effect of sewage sludge and woody biomass into coal on combustion and ash agglomeration behavior

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ABSTRACT

The co-combustion of sewage sludge and woody biomass is a key issue in coal power plants. Different combustion and ash behaviors of sewage sludge and woody biomass cause unpredictable operating concerns. In this study, the combustion and ash agglomeration behavior of blended fuel of sewage sludge and woody biomass (BSW) were investigated while coal co-combusted with it. Thermogravimetric analysis (TGA) revealed that adding a high amount of BSW into the coal lowered volatilization, ignition, and burn-out temperature. The char combustion reactivity of coal differed from that of BSW. The shrinking core model (SCM) and volumetric reaction model (VRM) were used to fit the char combustion reactivity of coal and BSW. In the case of ash agglomeration behavior, BSW addition led to increasing particle agglomeration at fouling temperatures. In particular, phosphorus composition influenced particle growth, which was verified using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM–EDX) analysis. Furthermore, the ash mixture ratio of BSW and coal changed the intensity of the phosphorus-bearing mineral phase from X-ray diffraction (XRD) analysis, and finally influenced the melting temperature of the ash.

1. Introduction

Renewable fuels such as sewage sludge and biomass have been solely combusted or co-combusted in boilers to generate electrical power [1–4], because their usage is an effective way to reduce CO_2 emissions during thermo-chemical conversion reactions. However, there are practical problems in using sewage sludge and biomass as fuels.

First, sewage sludge not only possesses low energy density because of high moisture content, but also contains large amounts of salts, nutrients, heavy metals, and organic pollutants [5], and therefore emits highly undesirable air pollutants compared with biomass and coal. Another issue is its high ash content, resulting in high ash fouling and slagging phenomena inside and at downstream of the boiler [6]. Secondly, biomass can be an indigenous energy source for a country, and its use can reduce the import cost of coal [7]; low NOx and SOx emissions during the combustion reaction are an additional advantage. However, several issues persist, such as high moisture, low energy density, farming cost, low ash melting temperature, and corrosion, among others. Several researchers have previously investigated the synergetic effect of sewage sludge and biomass co-combustion to solve reactivity, pollutant emission, and ash related problems [8–10].

Nonetheless, the synergetic effect of sewage sludge and biomass co-firing is not yet clear, and the available amount of material is insufficient to satisfy energy demand. Fuel characteristics between sewage sludge and biomass differ. In particular, even though the fuel types are the same, the fuel characteristics (e.g., the amount of moisture, volatiles, fixed carbon, ash, and combustion reactivity) vary depending on the location from which they are generated. Further investigation is required to figure out their fuel and combustion characteristics.

One of the best ways to perfectly complement the aforementioned defects of sewage sludge and biomass is co-combustion with coal. Many studies have been carried out with respect to coal co-combustion with sewage sludge and biomass, respectively [6,11–19]. In particular, the majority of investigations have been performed on air pollutant emissions [11–14], combustion reactivity [15–17], and ash melting and mineral phase transformation [6,18,19]. Therefore, the investigation of combustion and ash agglomeration behavior of sewage sludge and

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biomass with coal is a key parameter for solving unpredictable hurdles and realizing the continuous and stable operation of coal combustion facilities. In the case of Korea, to reduce CO_2 emissions, since 2012 the government has enforced a restrictive policy on power generation companies that operate coal power plants with more than a 500 MW capacity. The CO_2 reduction ratio allocated from the government increases every year. Mainly, woody biomass has been blended for co-firing into the coal boiler to follow the government regulations. Furthermore, coal power companies have attempted to use sewage sludge as a renewable fuel resource. However, investigations into the blending effect of sewage sludge and woody biomass during co-firing with coal regarding their combustion characteristics and ash particle agglomeration/transformation are rare. In our previous research [20], we attempted to develop a hybrid sludge fuel (HSF) applying for a coal combustion system. In fact, to commercialize the HSF fabrication process, the cost of the bioliquid and pre-treatment process needs to be lowered. To find a more practical and effective method for the application of sewage sludge and woody biomass, it is necessary to investigate the blending effect of sewage sludge and woody biomass for coal co-firing boilers.

In this work, sewage sludge generated from a waste water treatment plant and wood sawdust wasted from tree felling were blended. Their combustion and ash agglomeration characteristics were clarified during co-combustion with coal. The combustion characteristics of the employed fuels were evaluated using thermogravimetric analysis (TGA) during non-isothermal conditions. Char combustion reactivity was experimentally researched during isothermal combustion conditions, and representative char reaction models such as the shrinking core model (SCM) and the volumetric reaction model (VRM) were then compared with experimental char combustion behavior. Depending on the addition ratio of the blended fuel of sewage sludge and woody biomass (BSW) into the coal, ash agglomeration behavior and mineral phase transformation were verified as well. In particular, the crucial chemical component for the change of ash agglomeration and melting temperature was identified during the addition of BSW.

2. Experimental method and apparatus

2.1. Fuel preparation

Many Korean coal power plants import Indonesian low rank coal as a feedstock. One of these Indonesian low rank coals, namely SUEK, was chosen for this work. The sewage sludge from a waste water treatment plant was first dried for applying in experimental sample. The sewage sludge and wood sawdust were blended at a certain weight ratio (at the dry basis, 6:4) for the fabrication of BSW, before it was added into the coal sample. The BSW and coal samples were pulverized in a fan-type disk mill and then separated below 300 μm using an electromagnetic sieve shaker. All the samples were dried at 105 °C for 12 h prior to the combustion and ash agglomeration experiments. To evaluate the effect of BSW addition to the coal during combustion and ash agglomeration/transformation, the mixture ratios of SUEK and BSW were set to 95%:5%, 85%:15%, and 70%:30%, respectively.

2.2. Experimental instrument and analysis technique

The basic properties of the experimental fuels were investigated using proximate analysis (TGA-701 thermogravimeter), ultimate analysis (TruSpec elemental analyzer for C, H and N and SC-432DR sulfur analyzer for S), and caloric value (Parr 6320EF calorimeter). The detailed fuel characteristics are illustrated in Table 1. SUEK has a higher carbon content and lower oxygen content than BSW, resulting in a different heating value. In addition, the amount of ash chemical components in SUEK and BSW differs. The majority of ash chemical components detected from X-ray fluorescence (XRF) analysis (ZSX Primus analyzer) are indicated in Table 2.

To study the combustion characteristics of the fuels during non-isothermal and isothermal conditions, thermogravimetry (TG) and differential thermogravimetry (DTG) analysis were conducted using a Q500 TA instrument. During the non-isothermal combustion, a heating rate of 10 °C/min and an air flow rate of 100 ml/min were employed up to 900 °C. To identify the char combustion reactivity, the raw sample was first pyrolyzed from room temperature up to 1000 °C at a heating rate of 10 °C/min under N_2 atmosphere, and then the temperature was retained for 20 min. The atmospheric gas was switched from N_2 to air at a flow rate of 100 ml/min. The isothermal char combustion was conducted for 30 min.

To identify key ash chemicals in particle agglomeration and transformation, the agglomeration tests were conducted through several heating processes and separations. The raw samples separated below 300 μm were first put into an alumina crucible and ashed in a muffle furnace at 800 °C for 10 h. Each prepared ash sample (0.4 g) was injected into the muffle furnace for agglomeration tests. After raising up to the desired temperature (900 and 1000 °C, respectively), the ash sample in the alumina crucible was fed into the muffle furnace. The ash sample was heated for 3 h, and then removed from the muffle furnace. The ash agglomeration behavior was verified using an electromagnetic shaker with a sieve size of 300 μm. The agglomeration tendency was measured based on the weight ratio of the residue ash on the sieve and total input ash. The ash samples were separated on the sieve for 6 min. A detailed schematic diagram of the experimental procedure for identifying ash agglomeration behavior is depicted in Fig. 1. A simple calculation equation for agglomeration tendency is shown as follows:

$$\text{Degree of agglomeration (\%)} = \frac{m_{residue}}{m_{total}} \times 100 \quad (1)$$

where $m_{residue}$ is the weight of the residue ash on the sieve, and m_{total} is the weight of the total input ash for the agglomeration test. To investigate the relationship between the agglomeration behavior and mineral phase transformations of the experimental ashes, X-ray diffraction (XRD) analysis (Ultima III analyzer) and ternary phase diagram were taken into account.

2.3. Reaction model of the char combustion

Kinetic studies of coal, sewage sludge, and biomass during combustion have been conducted by many research groups [17,21–23]. In this work, two different representative reaction models, the SCM and the VRM, were employed to compare experimental char combustion behavior. The SCM for combustion assumes that the reaction takes place on the external surface of a spherical solid particle [24].

The SCM assumes that the reaction initially occurs at the external surface of the char and then the reactant gas gradually diffuses the gas film and ash layers. The reactant gas reacts on the unreacted core surface which keeps on shrinking, but always exists during the reaction progress [25–27].

$$3[1-(1-X)^{1/3}] = k_s t \quad (2)$$

where k_s, X, and t mean the reaction rate constant of the SCM, the carbon conversion, and the reaction time, respectively; k_s depends on temperature and gaseous reactant concentration.

When modeling the char combustion reaction, it can be assumed that the pseudo-homogeneous kinetic equation is applied [28]. Therefore, the simple pseudo-homogeneous VRM for the solid substrate was occasionally employed to investigate the overall reaction rate of char combustion. Typically, the VRM assumes that the char particle reacts homogenously with the reactant gas and the particle size keeps constant, whereas the density decreases during the reaction [29,30].

$$-\ln(1-X) = k_v t \quad (3)$$

where k_v, X and t mean the reaction rate constant of VRM, the carbon conversion, and the reaction time, respectively. The reaction rate