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Research article

Fluidized bed co-combustion of hydrothermally treated paper sludge with two coals of different rank

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ABSTRACT

Fluidized bed co-combustion of raw paper sludge (Raw-PS) and hydrothermally treated paper sludge (HTT-PS) with either low (Lo-Coal) or high reactivity coal (Hi-Coal) was investigated. The paper sludge was treated in a pilot-scale hydrothermal reactor at 197 °C and 1.9 MPa for 30 min. South African bituminous and Thai subbituminous coals were selected as representative of Lo-Coal and Hi-Coal, respectively. A 110-mm bubbling fluidized bed combustor was used in this study. During the steady combustion tests the nominal temperature was 858 °C, the fluidization velocity was 0.5 m/s, and the excess air was varied as 20%, 40%, and 60%. Both single fuel combustion and co-combustion were tested. Co-combustion tests were conducted by feeding the sludge at mixing ratios of 30% and 50% (mass basis) with coal. The main focus of this study was on NO_x emissions and unburned carbon performance. Results showed that at 30% mixing ratio using HTT-PS instead of Raw-PS could reduce NO_x emission by 3–6% and 9–17% in the case of Lo-Coal and Hi-Coal, respectively, and the loss of unburned carbon could be decreased by 15–18% and 36–53% for Lo-Coal and Hi-Coal, respectively. The particle size distribution of fly ash of all samples was similar regardless of the excess air variation. On the whole, the hydrothermally treated paper sludge showed better performance for co-combustion with coal and would be a better choice compared to the original raw paper sludge.

1. Introduction

Paper sludge is one of the problematic waste materials in pulp and paper industry [1]. Because it contains a large amount of water, dewatering of sludge is rather difficult [2]. The paper sludge mostly comes from the primary clarifier and it mainly consists of discarded woody fibers [3,4]. Another portion of the paper sludge comes from the wastewater treatment facility and it is called secondary sludge, which has a very high water content [3]. Landfilling is the most common way to dispose of paper sludge [5,6]. This method involves many practical problems such as the production of a leachate that can contaminate ground water. In addition, transportation of the paper sludge, which consists of two-thirds water, to the dumping area is expensive. Internal utilization of this waste would be more appropriate.

Co-combustion of waste sludge with coal can be implemented in-house in conventional coal-fired power plants without significant modifications and major investments [7,8]. It can reduce the coal demand as well as exploit the waste efficiently through energy recovery. Fluidized bed combustion (FBC) technology is one of the most suitable combustion technologies that can realize this strategy [9]. It is well-known that FBC is characterized by excellent fuel flexibility and combustion stability. Thus, a wide range of fuels, including biomass and waste, can be burned in fluidized boilers with high efficiency. In particular, coal can be partially and conveniently substituted by waste biomass or sludge in FBC systems [10].

Co-firing paper sludge with coal has been investigated by thermogravimetric analysis [11,12] as well as fluidized bed combustion tests [7,8,13,14]. The main obstacle to the practical utilization of the paper sludge for co-combustion applications is its high water content. The water in the paper sludge reduces the net energy released during the combustion process because of water evaporation. Thus, only a limited amount of wet sludge can be used for co-firing with coal to maintain the energy output. Moreover, evaporated water will increase the volume of the flue gas affecting the design of both the combustion chamber and the post-combustion equipment. Due to this limitation, an efficient waste upgrading process is desirable. In our previous study, the subcritical hydrothermal treatment (HTT) was proposed for upgrading the

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paper sludge, by improving its dewaterability and fuel properties. The feasibility of this treatment was demonstrated at the pilot-scale level [15].

In this study, the FBC of raw paper sludge (Raw-PS) and hydrothermally treated paper sludge (HTT-PS) and their co-combustion performances with two different types of coals was investigated. The two coals had a different rank, being representative of low and high reactivity coals. First, the effect of the HTT on the NO_x emissions was studied. CO emissions were also reported along with their influence on the NO_x emissions. Second, the unburned carbon (UC) performance of the Raw-PS and HTT-PS was compared. The effect of mixing Raw-PS and HTT-PS on UC performance during the co-combustion tests was also studied and the combustion efficiency was evaluated. Finally, the fly ash particle size distribution was analyzed.

2. Experimental

2.1. Fuel samples

2.1.1. Raw and hydrothermally treated paper sludge

Raw paper sludge (Raw-PS) was provided by the Siam Kraft Industry Co., Ltd., Thailand. The HTT of the sludge was performed in Thailand in the framework of the collaboration between Tokyo Institute of Technology and the Siam Cement Public Company Limited. The Raw-PS was treated by a 1-m^3 cylindrical batch-type hydrothermal reactor at 197 °C and 1.9 MPa for 30 min. After the treatment was finished, the residual steam was discharged. Then, the hydrothermally treated paper sludge (HTT-PS) was extracted through drain valves and it was further dewatered by a 1.5 kW centrifugal decanter and naturally dried. The details of the pilot-scale HTT can be found in our previous study [15]. The received samples were fluffy (density of 300–350 kg/m^3) and this characteristic was problematic for the feeding system of the FBC apparatus, leading to the difficulty to obtain the desired and stable combustion conditions. Therefore, both Raw-PS and HTT-PS were densified by a 5.5 kW pelletizer. The pelletized Raw-PS and HTT-PS were crushed by a lab-scale ball-milling machine. Then, the sludge was sieved at the nominal particle size of 0.3–4 mm. After the sample preparation process, Raw-PS and HTT-PS had the density of 803 and 847 kg/m^3, respectively. Solid fuel properties of the prepared Raw-PS and HTT-PS, including the proximate (ASTM D7582), ultimate analysis (ASTM D3176), and the heating value (ASTM D5865), were analyzed and reported in Table 1.

Table 1
Fuel analysis.

	Raw paper sludge (Raw-PS)	Hydrothermally treated paper sludge (HTT-PS)	South African coal (Lo-Coal)	Thai coal (Hi-Coal)
Proximate analysis (%, as received)				
Moisture	9.5	8.2	7.3	28.0
Ash	28.9	33.2	10.3	4.6
Fixed carbon	7.8	7.6	54.4	30.1
Volatile matter	53.8	51.1	28.0	37.4
Total combustibles	61.6	58.7	82.4	67.5
Proximate analysis (%, dry ash free)				
Volatile matter	87.4	87.1	34.0	55.4
Ultimate analysis (%, dry ash free basis)				
Carbon	49.0	51.9	77.6	68.3
Hydrogen	6.3	6.4	4.5	4.9
Nitrogen	4.2	3.0	1.4	0.6
Sulfur	1.0	1.0	0.7	0.0
Oxygen*	39.4	37.8	15.9	26.1
Heating value (MJ/kg, dry basis)				
HHV	12.0	12.3	26.7	25.3
LHV	11.1	11.4	25.8	24.3

*Calculated by difference; Lo-Coal: low reactivity coal; Hi-Coal: high reactivity coal.

2.1.2. Low and high reactivity coals

In this study, two different types of coals were utilized. The South African bituminous coal (Lo-Coal) that contains a low amount of volatile matter (30%) is considered as a low reactivity coal whereas the high volatile matter (50%) subbituminous coal (Hi-Coal) provided by the Siam Kraft Industry Co., Ltd., Thailand is representative of high reactivity coals. The coal properties are also presented in Table 1. The nominal particle size of coal was 1.18–4 mm.

2.2. Bubbling fluidized bed combustor

The fluidized bed co-combustion experiments were performed at the Institute for Research on Combustion (IRC) in Naples, Italy, under a collaboration research activity with Tokyo Institute of Technology. An atmospheric stainless-steel bubbling fluidized bed combustor was used in this study (Fig. 1). The internal diameter of the reactor is 110 mm with the height of 2.7 m. It is electrically heated by eight semi-cylindrical ovens with an approximate total power of 20 kW. Air was preheated to 600 °C and utilized as the fluidizing gas. Four chromel-alumel thermocouples were placed at the different heights to monitor the temperature of the column. The same type of thermocouple

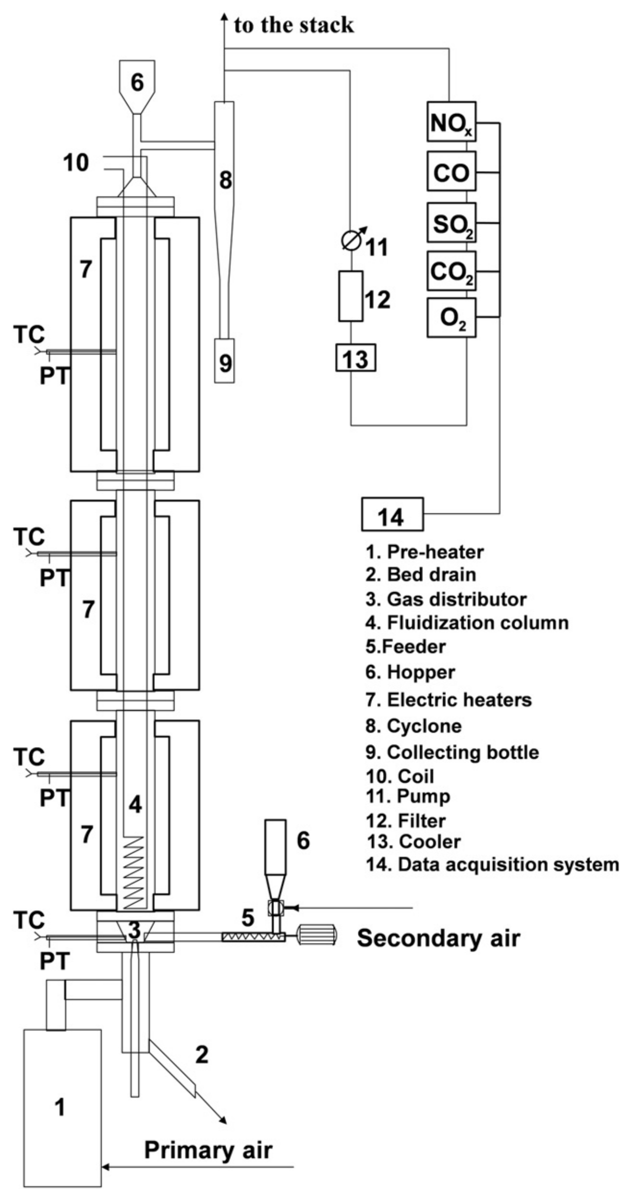

Fig. 1. Scheme of the 110 mm ID stainless-steel fluidized bed combustor.