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The effect of hydrothermal treatment on attrition during the fluidized bed combustion of paper sludge

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ABSTRACT

A combination of experimental techniques was employed to test primary fragmentation and char particle attrition by abrasion during fluidized bed (FB) combustion of raw paper sludge (Raw-PS), hydrothermally treated paper sludge (HTT-PS), and a subbituminous coal (Sub-C), for comparison. The hydrothermal treatment (HTT) was conducted by a pilot-scale reactor at 197 °C (1.9 MPa) for 30 min. The results showed that all three samples extensively underwent primary fragmentation. Char attrition tests under inert conditions showed that Sub-C intensely experienced particle rounding off at the beginning, but after that it became very strong against mechanical abrasive attrition, followed by HTT-PS and Raw-PS, respectively. The oxidative char attrition tests showed that Sub-C exhibited an initial low amount of carbon elutriation rate followed by an attrition enhancement effect at later stages of burn-off, whereas for the Raw-PS and HTT-PS attrition was always lower than under inert conditions due to extensive postcombustion of fines. HTT-PS always produced a lower amount of elutriated carbon than Raw-PS and this indicates better combustion performance as well as lower unburned carbon emission. Finally, the Primary Ash Particle Size Distribution (PAPSD) of the three fuels was determined, showing that the paper sludge would contribute much more than coal to the ash bed inventory in a full-scale FB combustor.

1. Introduction

Fluidized bed combustion (FBC) is a viable technology used worldwide for energy recovery from burning fossil fuels, biomass, waste, or their combination [1,2]. It offers several advantages like simple design, compact furnace, fuel flexibility and efficient mass and heat transfer [3]. Furthermore, FBC is environmentally acceptable since it generates a relatively low amount of noxious gases due to its low and well-distributed temperature in the furnace [3,4]. According to a report from International Energy Agency, between 1985 and 2010 the FBC plants capacity has increased ten times [5]. In 2013, more than 70 circulating fluidized bed boilers above 300 MWe have been under operation all over the world [5].

A variety of alternative fuels including biomass and waste such as rice husk [6], wood [7], and sludge [8] have been successfully burned in fluidized bed (FB) combustors. In an intensive energy industry such as pulp and paper production, FB boilers have been used for either generating process steam or producing electricity. Fuels that are burned in FB boilers are generally fossil fuels mixed with biomass/waste that is produced from the paper production process itself. Waste from the wood preparation process, e.g., woodchips, can be easily used as biomass fuel in the FB boiler. On the other hand, paper sludge that is a mixture of pulp and wastewater sludge is very problematic [9]. It has a very high water content and poor fuel properties [10]. A subcritical hydrothermal treatment (HTT) has been proposed to upgrade the fuel properties of paper sludge including dewaterability [11]. The upgraded paper sludge can be properly used as an alternative solid fuel in pulp and paper industries in FB boilers.

A series of combustion/co-combustion experiments had been performed to promote a practical utilization of using the upgraded paper sludge instead of the original sludge in pulp and paper industry [12–14]. In our latest study [14], steady FB combustion/co-combustion of both original (Raw-PS) and upgraded (hydrothermally treated) paper sludge (HTT-PS) with either low or high reactivity coal was investigated. Results showed that NO_x emissions could be reduced by using HTT-PS instead of Raw-PS in co-combustion applications. Unburned carbon loss of the HTT-PS was 72% lower than that of the Raw-PS at 20% excess air combustion condition. This improvement helped decreasing the loss of carbon in the FB co-combustion (with 30% share of

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sludge) by approximately 18% and 35% in the case of low and high reactivity coal, respectively.

Alternative solid fuels such as paper sludge and other biomass fuels have high volatile matter content. This differentiates the combustion process from burning conventional fossil fuels in the FBC with regards to aspects such as a solid fuel and volatile matter segregation along and across the furnace [15,16], combustion reactivity [17], and particle attrition rate [18]. Among these issues, particle attrition is of particular importance in FBC since it directly affects the loss of carbon through elutriation. Further investigation of this phenomenon is a key to obtain more information and understandings on the carbon loss results found in our steady FBC campaign with this fuel [14].

Studies on fuel particle attrition in FB reactors including primary fragmentation during devolatilization, char particle attrition by abrasion, secondary fragmentation, and percolative fragmentation have been carried out on several biomass and waste fuels [17,19–22]. On the basis of a comprehensive study on combustion and attrition of different kinds of biomass char during FBC, Scala et al. concluded that primary and secondary fragmentation were dependent on the type of biomass and these phenomena strongly affected the average particle size and particle size distribution of the fuel in the FB [20]. Two different types of sewage sludge were also subjected to attrition tests during FBC, and it was found that the different preprocessing that the sludge underwent moderately affected fragmentation and attrition by abrasion [21]. On the whole, these previous studies indicated that the attrition behavior during FBC was significantly dependent on the type of fuel and its origin.

This paper aims to investigate the effect of HTT on the attrition propensity of paper sludge. Raw-PS and HTT-PS, and a subbituminous coal (for comparison) were subjected to a combination of attrition tests. Firstly, primary fragmentation during devolatilization was studied. For each fuel, Sauter mean diameter evolution, fragmentation probability and particle multiplication factor were determined. The resulting char particles were also morphologically and porosimetrically characterized. Secondly, mechanical (inert) and oxidative attrition tests were carried out on fuel char particles to study the abrasion resistance of the materials and the resulting carbon elutriation rate during FBC. Finally, the primary ash particle size distribution of the fuels was determined.

2. Materials and methods

2.1. Samples

Raw paper sludge (Raw-PS) was provided by the Siam Kraft Industry Co., Ltd., Thailand. The HTT of the sludge was done in Thailand under the collaborative research between Tokyo Institute of Technology and the Siam Cement Public Company Limited. A pilot-scale hydrothermal reactor was used to treat Raw-PS at the temperature of 197 °C and pressure of 1.9 MPa as the optimal condition for 30 min. Then, the hydrothermally treated paper sludge (HTT-PS) was dewatered and dried. The detailed procedures of the pilot-scale HTT can be found in our previous study [11]. Since the received samples were fluffy, the feeding of the fuel in the fluidized bed combustor was rather difficult to control [14]. Thus, the Raw-PS and HTT-PS were pelletized and then crushed by lab-scale ball milling machine. After that, they were sieved at the nominal size between 3 and 4 mm. The subbituminous coal (Sub-C) was also crushed and sieved at the same size range. From this point, they were further utilized according to each experiment described later. The fuel properties of the samples are shown in \Table 1.

2.2. Particle attrition tests

2.2.1. Apparatus

The fluidized bed experiments were performed at the Institute for Research on Combustion (IRC) in Naples, Italy, under the collaborative research with Tokyo Institute of Technology. An atmospheric bubbling fluidized bed made from stainless steel (AISI 312) shown in Fig. 1 was utilized in this study. It has 40 mm internal diameter and 1 m height. A 22 mm thick perforated plate with 55 holes (0.5 mm in diameter) disposed in a triangular pitch is used as a gas distributor. Heat is supplied to fluidization column and preheating section by two semicylindical (2.2 kW) electric furnaces. A chromel-alumel thermocouple placed 40 mm above the distributor is used to measure the temperature of the bed and it was controlled at the desired temperature by a PID controller. The freeboard is kept unlagged to minimize postcombustion of fine particles. The flow rate of gases fed into the fluidized bed was controlled by two high-accuracy digital mass flow meters. Bed material consisted of 180 g of silica sand with the nominal size of 300–400 μm and a minimum fluidization velocity is 0.05 m/s at 850 °C. The fixed bed height was 0.1 m (aspect ratio H/D = 2.5).

Table 1
Fuel properties (dry basis).

sample	proximate analysis (%)			ultimate analysis (%)					heating value (MJ/kg)	
	FC	VM	Ash	C	H	N	S	O	HHV	LHV
Raw-PS	8.6	59.5	31.9	33.4	4.3	2.9	0.7	26.9	12.0	11.1
HTT-PS	8.3	55.6	36.1	33.2	4.1	1.9	0.6	24.1	12.3	11.4
Sub-C	41.7	51.9	6.4	64.0	4.6	0.6	0.0	24.4	25.3	24.3

Raw-PS: raw paper sludge; HTT-PS: hydrothermally treated paper sludge; Sub-C: subbituminous coal; FC: fixed carbon; VM: volatile matter; HHV: higher heating value; LHV: lower heating value.

2.2.2. Primary fragmentation tests

For primary fragmentation experiments, the basket-equipped configuration shown in Fig. 1A was utilized. The top of the fluidized bed was left open to the atmosphere. The samples were put into the stainless steel circular basket which was inserted into the hot fluidized bed column. The gap between the column and the basket was kept minimal to prevent the loss of small fragmented particles during the test. The basket was able to retrieve both fragmented and non-fragmented particles. With a mesh of 0.8 mm the bed materials could easily pass through the basket leaving only the products from the fragmentation test for further analysis. Table 2 presents the experimental conditions of this test. The sand bed was fluidized with nitrogen at 0.8 m/s. The experiments were carried out by injecting five single fuel particles, nominal diameter of 3–4 mm, into the bed kept at 850 °C from the top of the column and keeping them in the bed for about 3 min. During the devolatilization, the basket rested on the distributor. Then, after the devolatilization was completed, the resulting char was retrieved from the basket. The number and size of the particles including fragmented and non-fragmented char were analyzed. The experiments were repeated six times with a total number of particles of 30 for statistical purpose. The resulting char particles and their surfaces were observed by a scanning electron microscope (SEM, FEI Inspect S). The char was also subject to porosimetric analysis, carried out in a Micromeritics AutoPore IV apparatus for pore sizes ranging from 3 nm to 120 μm.

2.2.3. Char particle abrasion tests

The second configuration shown in Fig. 1B was used in the char abrasion tests. The top of fluidized bed reactor was assembled by a two-exit brass head equipped with a three-way valve. By switching this valve, it was possible to direct the flue gas alternately through two sintered brass-made removable filters. Batches of samples could be fed to the reactor by a hopper connected to the upper part of the freeboard. The exhaust gases, O_2 and CO_2 concentrations, were measured on-line by a paramagnetic analyzer and two NDIR analyzers. The CO_2 data from the analyzer was used to calculate carbon conversion according to method provided by Scala et al. [23]. In these experiments, char had to be first prepared from the original samples. The char was obtained by using a method similar to that used during the primary fragmentation