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Mechanical stability and combustion characteristics of hydrochar/lignite blend pellets

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ABSTRACT

In the present study, hydrochar/lignite pellets were prepared and their fuel qualities including tensile strength, combustion characteristics and ash-related problems were investigated. The results showed that addition of hydrochar to lignite increased tensile strengths of lignite pellets, especially when the hydrochar fraction exceeded 50% in the blends. The main binding forces within hydrochar/lignite pellets were similar to those of hydrochar pellets; the lignite particles were merely interlocked within the matrix of the hydrochar structure. Obvious interactions were observed between hydrochar and lignite during blend pellet combustion and as a result, enhanced thermal efficiency and decreased air pollutant emissions were expected during hydrochar/lignite pellet combustion compared to lignite pellet combustion. The ash from hydrochar/lignite pellets had similar chemical composition to that from lignite pellets, indicating that the utilization and disposal of blend pellet ash would be similar to lignite pellet ash. Furthermore, hydrochar addition to lignite decreased slagging inclination of blended pellets. Based upon calculated slagging index (SI) values, ash from hydrochar/lignite blend pellets was within a low slagging inclination range when the hydrochar fraction in the blend pellets was higher than 50%.

1. Introduction

The concerns about depletion of fossil energy as well as increasing environmental pollution caused by large-scale utilization of fossil fuels have challenged the world to find a new and better way to meet the fast growing energy demands. Among these efforts, renewable biomass/coal co-firing in coal-fired plants has received increasing attention because this approach can accommodate varying amounts of available biomass and does not require large investments in new-stand-alone biomass plants [1–3].

Conventional pulverized biomass/coal co-firing introduces several constraints, including low energy density of pulverized biomass and emissions of high dust levels [4]. To overcome these challenges, the use of biomass pellets is a preferred alternative due to their improved fuel quality – including increased energy density, and uniform shape and size. In addition, increased energy efficiency and reduced pollutant emissions have been reported from combustion of biomass pellets as compared to pulverized biomass [5]. When combined, raw biomass and coal do not pelletize well, and are therefore not suitable for high-quality pellet fabrication. During the pelletization process, it is thought that extractives within biomass materials reduce the binding sites between adjacent biomass particles [6–8]. As for coal, the forces between coal particles are very weak due to lack of functional groups on the surface, resulting in poor pelletization [9,10]. In general, the use of additional binders or severe pelletizing conditions are necessary to achieve desirable mechanical strengths of solid fuel pellets [6,11]. However, some binders decrease the energy density of pellets and may be harmful to the environment [11]. In addition, biomass feedstocks generally contain high contents of alkali and alkaline earth metals (AAEMs), which cannot be removed by pelletization. Hence, ash-related problems including slagging and fouling, which are often encountered during combustion of pulverized biomass/coal, are still present during combustion of biomass/coal pellets as they represent simple physical mixtures of biomass and coal [12–16]. Furthermore, due to large differences in fuel quality between biomass and coal, there is no interaction between these constituents during combustion of the mixed pellets [17].

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Hydrochar, the solid biofuel produced from hydrothermal carbonization of biomass feedstock, has improved fuel qualities compared to raw biomass, such as homogenized physico-chemical properties and decreased ash content [18]. In view of the wide diversity among different biomass resources, the resulting raw biomass/coal blend pellets may have different fuel properties, creating challenges for effective pellet applications [11]. However, with the use of hydrochars for preparation of pellets in place of raw biomass, such technical problems can be overcome because of their homogenized properties, regardless of the type of biomass feedstocks used for energy generation. Furthermore, significant synergistic interactions have been observed between pulverized hydrochar and coal during co-processing. As a consequence, increased thermal efficiency and reduced pollutant emissions are achieved compared to raw biomass/coal co-processing [19,20]. Furthermore, ash-related problems encountered during biomass combustion are expected to be mitigated when using hydrochars, due to their reduced AAEM and ash contents compared to raw biomass. Hydrochar has been reported to exhibit significantly improved pelletizing performance compared to raw biomass, and hydrochar pellets have higher mechanical strength than raw biomass pellets [6]. Therefore, fuel pellets made of hydrochar and coal blends are desired because of their improved mechanical strength and combustion properties and there is no need for binder addition or severe pelletization conditions.

Many investigations have been reported in the literature regarding the preparation and use of raw biomass (woody biomass) pellets and raw biomass/coal mixed pellets [6,17,21–23]. Among these reports, woody biomass is generally used for pellet preparation instead of abundant agricultural residues. In addition, the combustion behavior of biomass pellets has rarely been studied compared to their mechanical durability and very little information about mixed hydrochar/coal pellets is available [24–27]. In the present study, for the first time, hydrochars produced from non-woody biomass (coconut fiber and shells) were used to prepare fuel pellets with coal. Important fuel qualities of the resultant hydrochar/coal blend pellets were investigated from multiple perspectives including mechanical strength, combustion characteristics and slagging and fouling inclinations. The present study is part of our ongoing attempt to develop value-added utilization of highly abundant, non-woody waste biomass.

2. Experimental

2.1. Materials

Coconut fiber (CF) and coconut shell (CS) were selected as representative non-woody biomass feedstocks for hydrochar production. The hydrochars were produced by typical hydrothermal carbonization of biomass at 250 °C; detailed procedures can be found elsewhere [18,28]. The hydrochars produced from CF and CS were labeled as CF-HC and CS-HC, respectively. The lignite sample was obtained from Pasar, Indonesia. Prior to pelletization, hydrochar and lignite were milled to less than 150 μm and dried at 60 °C for 24 h.

Pellets were prepared using a single pelletizer at room temperature. A detailed description of pellet preparation can be found in our previous work [6]. Briefly, the starting materials were loaded stepwise into the pelletizer die, and then compressed at a maximum pressure of 200 MPa (for hydrochar and hydrochar/lignite) or 320 MPa (for lignite). After holding 5 s at the maximum pressure, the pellet was obtained by removing the die backstop and applying pressure on the pellet to push it out of the die. The length/diameter of each pellet was approximately 0.9 and at least 5 pellets were made from each test sample.

2.2. Characterization

The carbon, hydrogen, nitrogen and sulfur contents were determined using an EA3000 Elemental Analyzer (Italy). Proximate analysis was carried out according to the Standard Practice for Proximate Analysis of Coal and Coke (GB/T212-2008) using a 5E-MAG6600 Automatic Proximate Analyzer (China). The higher heating value (HHV) of solid fuels was measured using a Kaiyuan 5E-KC5410 Express Calorimeter (China). The tensile strength of pellets was determined using a universal tester (Instron, USA). The microstructure and bonding behavior within pellets were analyzed by observing the fracture surface. This surface, which was prepared by manually breaking a pellet into two parts, was analyzed by scanning electron microscopy (SEM) using a JSM-5600LV microscope (JEOL, Japan).

Thermogravimetric analysis (TGA) was carried out with a Thermobalance TGA-7 instrument (Perkin Elmer, USA). Around 20 mg of each pellet was used for TGA combustion experiments, which were conducted in a temperature range from 25 to 850 °C, with a heating rate of 20 °C/min and an air flux of 150 ml/min.

Pellet ash was prepared at 750 °C according to ASTM D3174-12. For ash analysis, the ash was first digested in a mixed solution (2 ml 65% HNO_3, 2 ml 30% H_2O_2 and 0.5 ml 48% HF) at 180 °C for 30 min in a Hanon microwave digester (China). The digestion solution was then evaporated to dryness to remove the fluorides, and the resultant residues were dissolved in a 1:1 HNO_3 solution, and diluted to the desired volume using de-ionized water. Metal concentrations (K, Na, Ca, Fe, Si, Al, Ti and Mg) in the digestion solution were quantified using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Perkin Elmer 3000DV, USA).

3. Results and discussion

3.1. Characterization of raw materials

As shown in Table 1, the hydrochars CF-HC and CS-HC have similar chemical compositions. Compared to lignite, both hydrochars have higher volatile matter (VM), but lower fixed carbon (FC) and ash contents. The low ash content of the hydrochars (4.9% and 1.1% for CF-HC and CS-HC, respectively), is helpful in minimizing slagging, reducing soot formation, and facilitating ash disposal [12,13]. In addition, nitrogen and sulfur contents in solid fuels are key concerns because of their transformation into NO_x and SO_2 in the combustion process. The N/S contents in CS-HC (1.4% and 0.5% for N and S, respectively) are relatively higher than those of CF-HC (1.0% and 0.3% for N and S, respectively), but both hydrochars have substantially lower N/S compared to the lignite (1.7% and 0.8% for N and S, respectively). This implies that considerable environmental benefits can be achieved from co-combustion of hydrochar/lignite compared to lignite combustion

Table 1
Proximate and ultimate analysis of starting hydrochars and lignite.

	CF-HC	CS-HC	Lignite
Proximate analysis (db)			
Volatile matter (%)	67.9	73.2	48.9
Fixed carbon (%)	27.1	20.3	41.0
Ash (%)	4.9	1.1	10.3
Ultimate analysis (%) (daf)			
C	67.1	69.0	61.6
H	5.2	5.2	5.7
N	1.0	1.4	1.7
S	0.3	0.5	0.8
O (by difference)	26.4	23.9	30.2
Higher heating value (MJ/kg)	28.4	28.8	25.8