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Oxygen enriched co-combustion characteristics of herbaceous biomass and bituminous coal

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ABSTRACT

The oxy-fuel co-combustion behavior of two different herbaceous biomass species (beetroot and switchgrass) with bituminous coal was investigated by thermal gravimetric analysis (40 °C/min). The effects of sample kinds, oxygen concentrations and blend ratios on the co-combustion characteristics were obtained. The results showed that the incorporation of the beetroot or switchgrass could improve the combustion characteristics of the bituminous coal. The ignition temperatures (T_i) of the blends were very close to the pure beetroot and switchgrass. The T_i values of the pure beetroot and beetroot/coal blends were lower than those of the pure switchgrass and switchgrass/coal blends. The T_i values and T_b values of blends and their parent samples decreased with increasing the oxygen concentration. The comprehensive performance indices of blends and their parent samples increased with increasing the oxygen concentration. A significant interaction was detected between the bituminous coal and the beetroot or switchgrass during the oxy-fuel co-combustion.

1. Introduction

With the boom of the global economy and population, the energy demand increases continuously. Biomass has been predicted to be an important contributor to future sustainable energy systems and sustainable development in both industrialized and developing countries [1–4]. Lignocellulosic biomass, which consists of three major constituents: cellulose, hemicellulose, and lignin [2,5], has attracted growing attention as a promising alternative. A wide variety of biomass materials, including herbaceous and woody materials, agricultural residues and energy crops are used [6]. Switchgrass, a perennial warm-season grass, is desirable as a potential biofuel in direct combustion systems because of its excellent burn quality, ease of management, and high yield [7]. Beet root residue is a by-product from beet sugar production, and it is abundant especially in the US, but they are currently being wasted or used for lower-value products [8]. Due to the high volatile matter and moisture content, burning biomass alone cannot give very high energy output compared with coal combustion [9–11]. Co-combustion of biomass and coal in an effective method is of significant importance to both environmental protection and resource sustainable development [11–16]. Co-firing is a popular and convenient option for existing power stations to generate renewable electricity, because of its relative ease of implementation and low risk [10]. Existing power plants may continue to be used with very few modifications [6,17], and the biomass addition to coal would improve the combustion efficiency because of the lower CO concentrations and higher char burnout level in co-firing [11,14,15,18].

The co-combustion of wood and coal, could improve burn-off rate and ignition performance [19–21]. The incorporation of tobacco residue could improve the combustion characteristics of high-ash anthracite coal, especially the ignition and burnout characteristics compared with the separate burning of tobacco residue and coal [22]. Further reduction in CO_2 emissions can be achieved by oxygen enriched combustion of these blends [9], both techniques are being considered as methods of enhancing the efficiency of CO_2 capture from power plant for subsequent sequestration. Increasing the oxygen mole fraction, particles of all fuels burned more intensely [23]. The combustion rate of coal powder rose and burnout time decreased with oxygen concentration increasing [24]. Coal burnout can be improved by blending biomass in CO_2/O_2 mixtures [25]. The ignition performance of bituminous coal blending with palm shell was improved, and with oxygen concentration increasing, the ignition temperature decreased gradually [26]. Most researches related to the co-combustion characteristics of coal and biomass are performed under air atmosphere, and usually selected biomasses mainly include wheat straw, corn straw and sawdust. Furthermore, analysis associated with the oxygen-enriched combustion are mainly focused on pure biomass or pure coal [27–29]. The use of bituminous coal with herbaceous biomass briquettes such as beetroot and switchgrass, and an assessment about the effect of various parameters, like

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blending ratio and oxygen concentration, on oxygen enriched co-combustion characteristics are still scarce.

This paper presents oxygen enriched co-combustion characteristics of the bituminous coal and herbaceous biomass (beetroot and switchgrass) for a wide range of blending ratios and oxygen concentrations. The main purpose of the current study is to explore the influence of oxygen concentrations, sample kinds, and biomass ratios on co-combustion behaviors, such as ignition temperature, burnout temperature, volatile matter release index and comprehensive performance index.

2. Methods

2.1. Experimental facility and test samples

A thermogravimetric analyzer (TGA/SDTA851, Mettler Toledo) with a precision of 0.001 mg was used to conduct the co-combustion experiments. Chinese pulverized bituminous coal, beet root and switchgrass particle were selected, then the biomass samples were crushed to 0.2–0.6 mm. The beetroot and switchgrass residues were provided by University of Oakland. From these materials, a series of biomass/coal blends were prepared and homogenized with biomass weight percentages of 20, 40, 60 and 80 wt.%. The initial mass of each sample was maintained at 10 mg ± 0.5 mg, and the total flow rate of nitrogen and oxygen was set at 100 ml/min, in which oxygen flow rate was taken as 21, 40, 60, 80, 100 ml/min, respectively. The experiments were conducted at atmospheric pressure and temperature ranging from 50 to 800 °C. The heating rate was maintained at 40 °C/min. The weight loss (TG curve) and derivative weight loss (DTG curve) were recorded as a function of temperature and time during the heating run. Proximate analyses of the parent samples and their blends were performed in the analyzer, the detailed measuring methods were reported in Refs. [30,31].

2.2. Characterizations of combustion performance

The volatile matter release index (D_v) and the comprehensive performance index (D_c) were often used to evaluate combustion performance of different fuels.

The D_v represents the release performance of volatile matter in fuel. The D_c represents the comprehensive characteristics including ignition and burnout. They can be determined by the equations as below [1,22,32–34]:

$$D_v = \frac{\mathrm{DTG}_{\max}}{T_p \cdot T_v \cdot \Delta T_{1/2}} \tag{1}$$

$$D_c = \frac{\mathrm{DTG}_{\max} \cdot \mathrm{DTG}_m}{{T_i}^2 \cdot T_b} \tag{2}$$

where, T_p is the corresponding temperature of maximum combustion rate $\mathrm{DTG}_{\max}$ (°C), T_v the initial release temperature of volatile matter (°C) namely the corresponding temperature at a mass loss of 0.1 mg min^{-1}, T_i the ignition temperature (°C), T_b the burnout temperature (°C), $\Delta T_{1/2}$ the temperature zone of DTG/DTG$_{\max}$ = 1/2 in the descending part and the rising part of DTG peak, (°C), DTG$_{\max}$ the maximum combustion rate (mg min^{-1}), DTG$_m$ the average combustion rate (mg min^{-1}). So it can be deduced that the higher the D_c value is, the better the ignition and burnout performances are; the higher the D_v value is, the more centralized the combustion region of char residues, the better the burnout performance is.

3. Results and discussion

3.1. Proximate analyses

The measured proximate analyses were listed in Table 1. The heating values in Table 1 were estimated by using the method reported in Ref. [35]. The ultimate analysis results for the parent samples [3,36–38] were also listed in Table 1.

3.2. Co-combustion behavior of the blends

A series of the TG and DTG curves of samples in different oxygen concentrations were obtained, but only partial results were presented due to the limited space. Figs. 1 and 2 illustrated the TG and DTG curves, respectively.

From Figs. 1 and 2, as for the burning profiles of bituminous coal compared to those of switchgrass and beetroot residues, it can be found that significant variations existed due to differences in the elemental and chemical compositions of these fuels. The bituminous coal required a higher temperature than biomass to release its volatile constituent, and it burnt slowly over the whole temperature range due to its lower volatile matter content and stronger bonds. It showed the obvious combustion profile with a main peak between 350 and 500 °C with a maximum weight loss rate at 400 °C. Moreover, the combustion of the volatile matters was inconspicuous. A net weight gain had been observed due to oxygen chemisorption before the onset of combustion around 270 °C, the literature [33] also reported a similar experimental result on oxygen-enriched combustion of biomass micro fuel. After drying, the DTG curves of beetroot, switchgrass and their blends with bituminous coal were separated into two stages, with the first one in the range of 200–350 °C and the second one in the range of 350–600 °C. The mass loss during the first stage was controlled by the combination of the total decomposition of hemi-cellulose and cellulose and

Table 1
Proximate and ultimate analysis of samples.

Samples	Proximate analysis (wt.%)				Ultimate analysis (wt.%)					HHV (MJ/kg)
	M_{ad}	V_{ad}	A_{ad}	FC_{ad}	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	
100C	2.72	22.42	29.16	45.70	68.42	3.91	1.32	12.69	0.70	19.427
20B80C[a]	4.89	50.10	14.47	30.54						18.497
40B60C	6.49	51.35	13.99	28.17						17.857
60B40C	6.57	66.14	8.96	18.33						16.723
80B20C	6.77	67.63	8.95	16.65						16.361
100B	9.37	71.88	2.30	16.45	40.75	5.92	45.73	1.31	0.19	17.005
20S80C[b]	5.49	49.80	19.58	25.13						16.497
40S60C	5.60	50.29	18.71	25.40						16.676
60S40C	5.99	68.13	12.39	13.49						15.295
80S20C	6.30	71.70	9.00	13.00						15.705
100S	7.58	76.25	3.20	12.97	42.04	4.97	35.44	0.77	0.18	16.449

[a] 20B80C refers to 20% beetroot/80%bituminous coal blend.
[b] 20S80C refers to 20% switchgrass/80% bituminous coal blend.