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Characteristics and interactions between coal and carbonaceous wastes during co-combustion

Ashak Mahmud Parvez, Tao Wu*

Key Laboratory of Clean Energy Conversion Technologies, The University of Nottingham Ningbo China, Ningbo 315100, China

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ABSTRACT

This work focuses on the combustion characteristics of an Australian coal, a suite of carbonaceous materials, and their blends. A drop in both ignition temperature and burnout temperature was observed when carbonaceous wastes were blended with coal at different proportions (10 wt% and 30 wt%). The ignition index values of coal/polystyrene and coal/oat straw blends increased by 78% and 52%, respectively when the blending ratio increased from 10 wt% to 30 wt%. Similarly, 2.6 times increase in combustion index was also observed in coal/oat straw blend due to a large increase of mass loss rate contributed by the devolatilisation of oat straw. The significant drop in both peak and burnout temperatures for all the blends studied in this research demonstrated that there were strong interactions during the co-processing of coal with carbonaceous materials, which could be quantified by the root mean square interaction index (RMSII). It was found that coal/oat straw and coal/polystyrene blends had the highest RMSII values, which indicated the presence of strong interactions between coal and oat straw/polystyrene in the blends during co-combustion.

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1. Introduction

Co-processing of biomass with coal is a cost-effective and environmentally benign approach to mitigate the emission of gaseous pollutants of CO₂, SO₂ and NO_x from fossil fuel combustion [1–3], and is commonly adopted by coal-firing power plants in western countries as an option to reduce carbon emissions [4]. It is estimated that [5], the substitution of 10% of coal with biomass for the generation of electricity at coal-fired power stations would result in approximately 150 GW biomass power capacity, which is 2.5 times of the biomass power capacity installed nowadays worldwide. At coal-fired power stations, there are two commonly used approaches to replace a portion of coal with biomass, *i.e.* direct and indirect methods [6,7]. In terms of direct co-firing process, renewable fuel and coal are burned together in the same furnace where milling process is conducted together or separately. On the other hand, indirect co-firing is based on thermal conversion of renewable to gaseous or liquid fuel and the co-firing of this converted fuel together with the base fuel [6,7]. Direct co-firing based on co-milling is normally preferred due to its advantages such as high efficiency (36–44%) [8], low retrofitting costs [9], flexibility in biomass supply [10], **etc.** However, co-firing also presents technical challenges associated with slagging [11,12], deposition and corrosion in boiler [13,14], poor handleability [15], adverse impacts on electrostatic precipitation and potential poisoning of SCR catalyst [8], **etc.** Hence, more research is necessary in order to maximise the benefits as well as to overcome the challenges.

Although coal is originated from carbonaceous materials, its pyrolysis, combustion and gasification characteristics are significantly different from other carbonaceous materials, such as biomass and municipal solid wastes. Thus, to minimise the detrimental effect of co-firing on utility boilers, it is essential to understand how combustion characteristics is affected by the blending of different carbonaceous wastes with coal especially when a variety of carbonaceous wastes are to be used to replace a large portion of coal in pulverised fuel boilers [4,16–18].

Over the past two decades, much work has been conducted to understand combustion characteristics of different fuels using thermogravimetric analyser (TGA) [19–23], aiming at a better understanding of possible interactions with respect to combustion behaviours

* Corresponding author.

E-mail address: tao.wu@nottingham.edu.cn (T. Wu).

[22,24–27], ash residue [28–30] and emission issues [28,29,31,32]. However, co-processing still presents some technical challenges in industrial applications due to the change in the type of carbonaceous wastes to be co-fired and the variation in their thermochemical properties. To date, many researchers have investigated the interactions between coal and biomass during co-combustion [4,16,22,27,29,32] and other carbonaceous wastes [21,22,33], but controversial results on the presence of interactions were reported. Recently, due to the significant amount of tyre and waste electrical and electronic equipment (WEEE) generated annually, there are some studies on the co-firing of coal and tyre scraps being reported [21,22,34]. However, not much effort has been made so far to understand the interactions during co-combustion of coal and tyre scraps, which is the same for non-metallic part of waste printed circuit boards (NMPCBs), one of the main components of WEEE, and for waste Polystyrene. Therefore, there is still a need to study the co-combustion behaviours when coal is co-fired with these carbonaceous wastes, which are of significant potential to be used as alternative fuels, and to understand the interactions between samples during co-combustion.

In this paper, the ignition and combustion behaviours of coal, a suite of carbonaceous wastes and their blends were studied using thermogravimetric analysis. The influence of blending on combustion characteristics was examined. The interactions between coal and carbonaceous materials during co-firing were also investigated in detail. The degree of interaction was quantified.

2. Experimental

2.1. Sample preparation

In this work, an Australian coal (AC) and oat straw (OS) were selected as the coal and biomass samples. Other carbonaceous wastes studied include non-metallic part of printed circuit boards (NMPCBs) and waste tyre (tyre) together with waste polystyrene (PS) as a representative of plastic waste.

All the samples were air-dried prior to size reduction. Samples were grounded to <106 μm (Endecott 106 μm sieve) following standard milling procedures (CEN/TS 15443:2006). Blends were prepared at different mass ratios (coal:carbonaceous material), *i.e.*, 10 wt% and 30 wt%, which are comparable to typical co-firing applications [22,35].

2.2. Sample characterisation

Proximate analysis of the samples was conducted following the standard practice (GB/T212-1991) [36]. Carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents were measured using a CHNS/O Element Analyser (PE2400, USA) following the standard testing procedure described in the manual. Calorific values of all the samples were determined using a calorimeter (IKA C 200, Germany).

2.3. Combustion characteristics

Thermogravimetric measurements of the coal and carbonaceous wastes were carried out using STA 449/F3 Jupiter thermal analyser (NETZSCH Geraetebau GmbH, Germany). The experiments were performed at a heating rate of 20 K/min from 50 °C to the maximum temperature of 1000 °C. Prior to each test, samples were further grounded manually to smaller sizes to eliminate diffusion effects. About 5 mg of sample (accuracy up to 0.01 mg via PerkinElmer AD 6 auto-balance) was loaded into a ceramic crucible for each test. This slow heating rate and small amount of sample would help further minimise heat and mass transfer effects in combustion process. Each test was repeated to ensure that the relative error between the experiments was less than 4%.

2.4. Performance indices

In this study, several parameters, *i.e.* ignition temperature (T_{ig}), peak temperature (T_p) and burnout temperature (T_b) were adopted to assess the combustion behaviours of the blends [21,22]. Ignition index (D_i) as expressed in Eq. (1) was also used to measure ignition performance of fuels [21].

$$D_i = \frac{R_{max}}{t_{max} \cdot t_{ig}} \quad (1)$$

where, R_{max} (%/min) and t_{max} represent the maximum combustion rate and corresponding time (min), respectively, while t_{ig} stands for ignition time.

Combustion index (S_c), which represents the combustion characteristics of a fuel, is illustrated below [37–39].

$$S_c = \frac{R_{max} \cdot R_{mean}}{T_{ig}^2 \cdot T_b} \quad (2)$$

where, R_{max} , R_{mean} , T_{ig} and T_b are maximum mass loss rate, average mass loss rate, ignition temperature and burnout temperature, respectively. Normally, greater values of D_i and S_c mean better ignition and combustion performance, respectively.

However, Eq. (2) is not suitable for the prediction of combustion performance for blends that consist of individual components with significantly different properties. Hence, combustion performance of blends can be evaluated using a new combustion index (S_{CB}) [37], which is expressed as follows:

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