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Combustion behavior of corncob/bituminous coal and hardwood/bituminous coal

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ABSTRACT

The combustion performance of two typical herbaceous and woody samples (corncob and hardwood) and bituminous coal is evaluated using a thermal analysis technique. The biomasses show better ignition performance, volatile matter release performance and comprehensive combustion performance than those of the bituminous coal. With increasing the heating rates, the performances of corncob, hardwood and biomass/coal blends get obviously improved. The dominant mechanisms associated with combustion kinetics for corncob and most corncob/coal blends at pre-peak and post-peak are described by the Avrami–Erofeev equations (n = 3 or n = 4). The dominant mechanisms associated with combustion kinetics for hardwood and hardwood/coal blends at pre-peak are described by the Avrami–Erofeev equations (n = 3 or n = 4) or Z-L-T equation (n = 2). The dominant mechanisms associated with combustion kinetics for hardwood and hardwood/coal blends at post-peak are described by the Avrami–Erofeev equations (n = 3 or n = 4). The dominant mechanisms of combustion for bituminous coal during the pre-peak and post-peak period are determined to be the reaction order equations. Some significant synergistic interactions are detected between Chinese bituminous coal and corncob or hardwood, especially for all corncob/coal blends at heating rate of 90 °C/min and 80Cc20C blend at heating rate of 70 °C/min during the co-combustion.

1. Introduction

Biomass is a renewable energy source that can provide crucial environmental and economic benefits, and biomass residues are readily available in large quantities [1]. Corn (maize) is an important crop among all agricultural grains in the world, especially in the North America, Asia, and Europe [2,3], and then the amount of its byproducts such as corn straw and corncob is enormous. Wood residues mainly consist of waste from forest harvesting and lumber mills. Compared with coal, burning biomass directly cannot give very high energy output due to the high moisture content and low calorific value [4]. Combustion of biomass blended with coal is an effective technique for application with biomass [5,6]. Also, reactivity of coal is improved by blending with biomass [7,8]. Power generations from coal/biomass blends are increasingly gaining importance as the biomass is considered to be carbon neutral, and reduction in net CO_2, SO_x and NO_x emissions [9,10]. Most of the developed and developing countries are considering co-firing as an attractive option by providing incentives [9]. Due to the abundant supply of corncob, a lot of research attention is mainly focused on exploring the new techniques of converting corncob to biomass energy forms [11,12], or utilizing directly the heat from corncob combustion [13]. Trninic et al. [14] reveal the detailed kinetics about corncob pyrolysis, and emphasize the possibilities of a common kinetic model for the pyrolysis of most agricultural byproduct. Aho et al. [15] investigate the quality of deposits during grate combustion of corn stover and wood chip blends. Wang et al. [16] reveal that there are interactions during co-pyrolysis of corncob and lignite blends, which increase overall tar yields and decrease overall gas yields compared with those obtained from pyrolysis of unblended feedstocks. A host of literatures specially address wood combustion behavior. According to Amaral et al., Araucaria biomass (softwood) has a higher lignin content of 34.9%, higher than the 23.3% of the Amazon biomass (hardwood), which would lead to higher CO_2 emission of Araucaria biomass than Amazon biomass during the combustion process [17]. The combustion emission behavior of pine (softwood) and eucalyptus (hardwood) in a fireplace and a stove are also detected [18]. An irreversible second order reaction is adopted to describe the combustion kinetics of wood in a fluidized bed [19]. The combustion

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kinetics parameters of beech and fir wood are also determined with a unified mechanism [20]. Aghamohammadi et al. investigate the combustion emission of five typical wood biomass (mixed tropical wood residue, bamboo, oil palm trunk, Acacia and rubber wood) in South East Asia, and reveal that the DTG curves of all wood samples present four overlapping peaks [21]. Yorulmaz et al. apply the Coats-Redfern method in both main combustion stages to investigate the thermal kinetics of waste wood samples (untreated pine, plywood and particleboard) [22].

A slice of investigations have also been conducted concerning co-combustion of biomass and coal [23–27]. Based on TG analysis, co-combustion kinetics of bituminous coal and pine sawdust blends are also been studied by the Coats–Redfern method with two-scheme models [23]. Varol et al. and Moon et al. detect that there are certain synergistic effect between lignite and biomass (oak wood chips, wood pellets) during their co-combustion [25,28]. Zhou et al. also highlight that ignition property and thermal reactivity of coal gangue could be enhanced by the blending of biomass (soybean stalk and pine sawdust) [8]. Combustion parameters (ignition index and combustibility index) of a pulverized coal blending with pine wood are highlighted, and then the kinetics parameters are detected based on a double parallel reactions random pore model [29]. The combustion behavior and kinetics of various biomass chars (forest residues, wood), lignite and their blends are revealed, which combustion performance of the blends shows certain deviation from the weighted average of the individuals [1,27,30].

Little information is available to the co-firing in a wide scope of heating rates and blending ratios. Many investigations are intensely regarding combustion characteristics and kinetics of pure biomass and pure coal. Furthermore, much of the work is invariably highlighted concerning the co-combustion kinetics parameters for biomass and coal only based on simple order reaction models no involving the description of mechanism. Comprehensive analysis of combustion behavior and kinetics difference what are all about between herbaceous and woody samples and their blends with bituminous coal, is still not found. Also, majority of researches are addressed on softwood such as pine residuals. Although interaction of coal and biomass during co-pyrolysis has been widely explored [16,31], limited data are available on the occurrence of synergistic effects or inhibiting effects of coal and biomass during co-combustion.

This paper presents co-combustion behavior and kinetics of two typical herbaceous and woody samples (corncob and hardwood) and bituminous coal for a wide range of heating rates and blending ratios. The main purpose of the current study is to address the influence of heating rates, blending ratios and sample kinds on combustion behaviors (ignition index, volatile matter release index and comprehensive performance index) and kinetics (apparent activation energy and mechanism functions), which are base on two main stages around maximum burning rate. The synergistic effects or inhibiting effects of coal and biomass during co-combustion are evaluated based on the TG behavior of samples. Comparison of combustion characteristics between corncob/coal blends and hardwood/coal blends is explored. The Arrhenius parameters are analyzed to assess if there are any compensating effects.

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 combustion experiments. The corncob and hardwood briquette samples were provided by University of Oakland, and Chinese pulverized bituminous coal were selected, then the biomass samples were crushed to 0.2 mm–0.6 mm. The samples were sieved by using use a standard screen (80 meshes). The biomass/coal blends were shaken thoroughly in a box with biomass mass percentages of 20, 40, 60 and 80%, respectively. The initial mass of each sample was maintained at 10 mg ± 0.5 mg. The sample was placed into a platinum crucible. The combustion processes were performed with heating rates of 10, 30, 50, 70 and 90 °C/min, respectively. To ensure reproducibility, the experiments were repeated three times. The results indicate that a good reproducibility is maintained for each run because the relative deviation was generally within ±1.0%. The proximate analyses of the samples were also tested and listed in Table 1. The heating values were calculated using the method in the Ref. [32].

2.2. Characterizations of combustion performance

Ignition index (D_i), volatile matter release index (D_v) and the comprehensive performance index (D_c) are often applied to evaluate combustion performance of different fuels.

D_i represents the ignition performance of fuels, which reflects how difficultly or easily and how fast or slowly the fuel gets ignited. It is expressed as below [1,36,37].

$$D_i = \frac{DTG_{max}}{T_i \cdot T_p} \quad (1)$$

where, DTG_{max} is the maximum combustion rate (mg·min^{-1}), T_p the corresponding temperature of maximum combustion rate DTG_{max} (°C), T_i the ignition temperature (°C) corresponding to the temperature at which the combustion profile separates from the pyrolysis one [38], which is determined by the method in the Ref. [36].

D_v represents the general release performance of volatile matter in fuel, D_c, the comprehensive characteristics. They can be determined by the equations as below [1,4,39–42]:

$$D_v = DTG_{max} \Big/ \left(T_p \cdot T_v \cdot \Delta T_{1/2}\right) \quad (2)$$

$$D_c = DTG_{max} \cdot DTG_m \Big/ \left(T_i^2 \cdot T_b\right) \quad (3)$$

where, DTG_m is the average combustion rate (mg·min^{-1}), T_v the initial release temperature of volatile matter (°C), which refers to

Table 1
Proximate and ultimate analysis of samples.

Samples	Proximate analysis (wt.%)				Ultimate analysis (wt.%) [33–35]					HHV (MJ/kg)
	M_{ar}[a]	V_{ar}	A_{ar}	FC_{ar}	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	
Corncob	8.28	71.16	2.70	17.86	49.00	5.40	44.20	0.40	0.00	17.36
Hardwood	6.29	77.52	0.91	15.28	50.20	6.20	43.50	0.10	0.00	18.66
Bituminous coal	2.72	22.42	29.16	45.70	68.42	3.91	1.32	12.69	0.70	19.43

[a] ar indicates the abbreviation of 'as received basis' (wet basis).