INVESTIGATING SYNERGISTIC INTERACTION OF BAMBOO AND TORREFIED BAMBOO WITH COAL DURING COCOMBUSTION

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Abstract. To investigate if there is synergistic interaction between bamboo with coal, or between torrefied bamboo with coal during cocombustion, bamboo and torrefied bamboo separately were respectively uniformly mixed with coal and the weight percentage of bamboo or torrefied bamboo in the mixture were 10%, 20%, 30%, and 40%. The combustion behaviors of blends were characterized using thermogravimentric analyzer at heating rates of 10°C/min, 20°C/min, 30°C/min, and 40°C/min. Results showed that the combustion process of bamboo and coal combustion was separated during cocombustion, and the higher temperature zone corresponding to coal combustion had a higher activation energy. Cocombustion of torrefied bamboo and coal had a combustion zone. Combustion characteristics gradually increased with increase in heating rates and decrease in mixing ratios. Theoretical combustion characteristics obviously shifted to higher temperatures, indicating synergistic interactions between bamboo/torrefied bamboo and coal. Cocombustion of torrefied bamboo and coal was more feasible with a stabler combustion process. The results might be helpful to promote bamboo resources as a blend fuel for co-firing application with coal.

Keywords: Bioenergy, bamboo, torrefied bamboo, synergistic interaction, cocombustion

INTRODUCTION

Energy crisis and environment degradation have driven many industries to use renewable resources for energy products. Biomass materials have therefore gained increasing attention in regard to energy utilizations (Idris et al 2012). Cocombustion is regarded as one of the most advantageous ways of using biomass and waste for replacement of fossil fuels for energy

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conversion (Sahu et al 2014). Biomass/coal cofiring in existing coal-fired boilers can accommodate varying amounts of available biomass and does not require large investments in new, stand-alone biomass plants (Liu et al 2013). Celaya et al (2015) investigated cocombustion characteristics of brewer's spent grains and Illinois No. 6 coal. Based on the analysis of evolved gases, they found the presence of both potential additive and synergistic interactions on a molecular level. Otero et al (2008) studied the kinetics of the combustion of coal, two different sewage sludge and their blends by simultaneous thermogravimetric analysis. It was found when the weight percentage of sludge in the blend was less than or equal to 10%, the effects on coal combustion were hardly noticeable in terms of weight loss. Wu et al (2011) found that the fuel burnout, NO and SO_2 emission in cocombustion of coal and solid recovered fuel were decreased with increase in contents of solid recovered fuel. Kwong et al (2007) investigated cocombustion performance of coal with rice husks and bamboo. Compared with coal combustion, the combustion temperature decreased and energy output reduced during the process of cofiring. The reason was that the decrease in the heating value with the increase ratio of biomass in the mixture. They also found that in the range of 10-30% biomass blending ratios, gaseous pollutant emissions, such as carbon dioxide, carbon monoxide, nitrogen oxides, and sulfur dioxide were reduced and found the minimum energy-based emission factors.

Even though there has an increasing interest in the cocombustion of coal and biomass, the diversity in combustion characteristics of biomass make difficulties to handle raw biomass for fuel (Parikh et al 2007). Torrefaction has been regarded as a valid way to improve the properties of raw biomass for thermal conversion, such as the field of cofiring with coal (Joshi et al 2015). Torrefaction of biomass results in a fuel more similar to coal. It has gained increasing attention in terms of a deeper understanding of the fundamental reaction mechanisms and the engineering of novel reactor designs (Peduzzi et al 2014). Yang et al (2015) torrefied three types of biomass with different components. They found lignin made the main contribution to the solid fuel yield. The reactivity of cellulose and hemicelluloses in each biomass was affected by the biomass species and the component weight ratio of the biomass. Chen et al (2015) investigated the torrefaction characteristics of a microalga (*Chlorella vulgaris* ESP-31) residue in inert (N_2) and noninert (CO_2) atmospheres at temperatures of 200-300°C with the duration of 15-60 min. They found that the enhancement factor of higher heating value, energy yield, and atomic H/C and O/C ratios vs torrefaction severity index had a linear relationship. The solid and energy yields of the residue torrefied in CO_2 were lower than in N_2 because the thermal degradation in the former was more active. Toscano et al (2015) torrefied tomato peels and found mass yield, energy yield, and energy densification varied in the ranges of 94.7-69.9%, 98.0-86.0%, and 1.04-1.23, respectively. Torrefaction made the material increasingly hydrophobic with increase in torrefaction temperature.

Bamboo is seen as a promising energy crop because of its high growth rate and a number of major fuel characteristics such as low ash content, alkali index, or heating value (Rousset et al 2011). The total area of bamboo resource in China is about six million hectares and they have been used to make various industrial products (Jiang 2007). Due to special shape of bamboo, the processes of manufacture have produced abundant wastes and the wastes have great potential as a bioenergy resource of the future. The quality and properties of bamboo as a potential biomass source differ within various bamboo species (Fryda et al 2014). In this research, *Phyllostachys praecox* was torrefied with a temperature of 300°C and a residue time of 2.0 h in the nitrogen atmosphere. The characteristics of cocombustion of bamboo/torrefied bamboo and coal were investigated. On the other hand, whether there have synergistic interactions between them also studied. The results from this research will be very helpful to promote bamboo resources as a blend fuel for co-firing application with coal.

MATERIALS AND METHODS

Materials

Phyllostachys praecox (*Cv. ventricousinternode*) samples of 4 yr old were taken from a bamboo plantation located in Zhejiang Province, China. The MC of the raw bamboo was about 8.1%. Bamboo tubes with the length of 200 mm (longitudinal) were dried at temperature 105°C until their mass stabilized. Torrefied bamboo samples were prepared using a digitally muffle furnace (Aremco Products) in the nitrogen environment with a torrefaction temperature of 300°C and a residue time of 2.0 h. After torrefaction, they were immediately placed in the desiccator and cooled to room temperature.

Standard coal was obtained from China Coal Research Institute. Bamboo, torrefied bamboo, and coal were pulverised to fine particle about 250-425 μm in diameter using with a Wiley mill. Bamboo powder and torrefied bamboo powder were respectively uniform mixed with coal powder. The weight percentages of bamboo or torrefied bamboo in the mixture were 10%, 20%, 30%, and 40%. They were dried at temperature 105°C until their mass stabilized.

Testing Combustion Characteristics

Combustion characteristics were analyzed in terms of global mass loss using constant heating rate/conventional TGA Q 500 thermogravimetic analyzer (TA Instruments, America). Samples were evenly and loosely distributed in an open pan with an initial weight of about 5-8 mg. Temperature variation was controlled from room temperature (30 ± 5°C) to 1000°C with 10°C/min, 20°C/min, 30°C/min, and 40°C/min of heating rates under 60 mL/min of air flows. Three replicates for each TGA experiment were performed.

Kinetics

The fundamental rate equation used in all kinetics studies is generally described as:

$$\frac{d\alpha}{dt} = k f(\alpha) \qquad (1)$$

where k is the rate constant and $f(\alpha)$ is the reaction model, a function depending on the actual reaction mechanism. Eq 1 expresses the rate of conversion, $d\alpha/dt$ at a constant temperature as a function of the reactant conversion loss and rate constant. In this study, the conversion rate α is defined as:

$$\alpha = \frac{(w_0 - w_t)}{(w_0 - w_f)} \qquad (2)$$

where w_t, w_0, and w_f are time t, initial, and final weight of the sample, respectively. The rate constant k is generally given by the Arrhenius equation:

$$k = A \exp\left(\frac{-E_a}{RT}\right) \qquad (3)$$

where E_a is the apparent activation energy (kJ/mol), R is the gas constant (8.314 J/K mol), A is the preexponential factor (min^{-1}), and T is the absolute temperature (K). The combination of Eqs 1 and 3 gives the following relationship:

$$\frac{d\alpha}{dt} = A \exp\left(\frac{-E_a}{RT}\right) f(\alpha) \qquad (4)$$

For a dynamic TGA process, including the heating rate, $\beta = dT/dt$, into Eq 4, Eq 5 is obtained as:

$$\frac{d\alpha}{dT} = \left(\frac{A}{\beta}\right) \exp\left(\frac{-E_a}{RT}\right) f(\alpha) \qquad (5)$$

Eqs 4 and 5 are the fundamental expressions of analytical methods to calculate kinetic parameters on the basis of TGA data. Activation energy values were calculated using a custom program designed within Microsoft Office Excel 2007 (Microsoft Corp., Redmond, WA).

Synergistic Analysis

To investigate whether synergy occurred between bamboo, torrefied bamboo, and coal during combustion process, the theoretical value of weight loss was calculated based on measured value of pure bamboo, torrefied bamboo, and coal.

$$Y_{\text{calculated}} = X_{\text{bamboo}} \times Y_{\text{bamboo}} + X_{\text{coal}} \times Y_{\text{coal}} \quad (6)$$

where, $Y_{\text{calculated}}$ is the theoretical value of weight loss of the mixture, X_{bamboo} is the percentage of bamboo or torrefied bamboo in the blends, Y_{bamboo} is the measured value of weight loss of bamboo or torrefied bamboo, X_{coal} is the percentage of coal in the blends, and Y_{coal} is the measured value of weight loss of coal.

To further compare the interaction within different blends, deviations between measured and theoretical values were calculated in Eq 3:

$$\text{Deviation}(\%) = (Y_{\text{measured}} - Y_{\text{calculated}}) / Y_{\text{calculated}} \times 100\% \quad (7)$$

where Y_{measured} is the measured value of weight loss of the mixture and $Y_{\text{calculated}}$ is the theoretical value of weight loss.

RESULTS AND DISCUSSION

Combustion Process and Characteristics

Figures 1 and 2 showed the cocombustion processes of bamboo, torrefied bamboo, and coal with 20% of biomass weight in the mixture and different heating rates. Cocombustion processes of other biomass percentages such as 10%, 30%, and 40% were not showed because they were similar with that of 20% of biomass weight in the mixture. As shown in Figure 1, there were two main combustion zones during cocombustion of bamboo and coal. The combustion processes of lower and higher temperature zones corresponded to combustion of bamboo and coal, respectively. The separated combustion zones indicated the higher reactivity and lower combustion efficiency of bamboo (Khan et al 2009). The main weight losses of blends occurred at the higher combustion temperature zone.

Compared with cocombustion of bamboo and coal, that of torrefied bamboo and coal (Figure 2) only had a main combustion zone at higher temperature, which might be due to the loss of moisture and volatile loss, and some thermal decomposition of hemicelluloses, cellulose, and lignin of bamboo during torrefaction process. Liu et al (2013) found the start temperature of thermal decomposition of bamboo (*P. praecox*) was about 157°C, this can be as a reference for

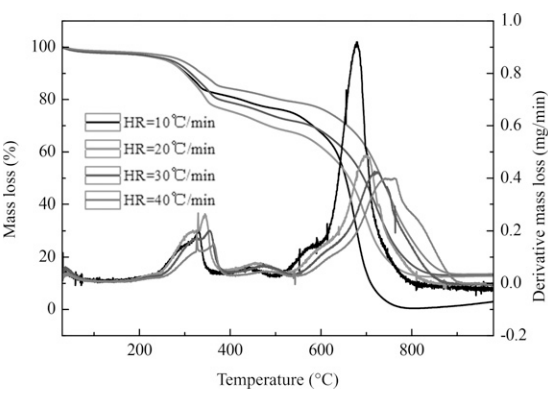

Figure 1. TGA of blends from 20% bamboo and 80% coal at different heating rates.

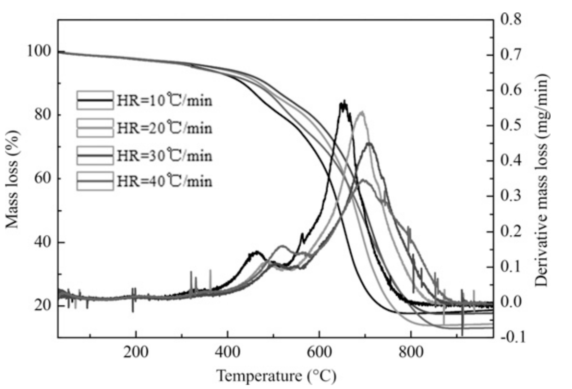

Figure 2. TGA of blends from 20% torrefied bamboo and 80% coal at different heating rates.

Table 1. Combustion characteristics of blends with bamboo and coal during cocombustion.

			First combustion zone			Second combustion zone				
Bamboo dose (%)	Heating rate (°C/min)	T_i (°C)	Temperature range (°C)	T_{peak} (°C)	R_{max} (mg/min)	Temperature range (°C)	T_{peak} (°C)	R_{max} (mg/min)	T_b (°C)	Total burnout (%)
10	10	235	235-361	330	0.14	486-806	651	0.75	806	83.1
	20	239	239-381	345	0.15	509-868	696	0.68	868	87.8
	30	242	242-383	355	0.15	512-882	706	0.51	882	85.6
	40	246	246-394	363	0.12	516-923	678	0.44	923	87.7
20	10	232	232-360	329	0.20	504-848	680	0.92	848	98.9
	20	237	237-387	344	0.26	532-874	700	0.48	874	87.5
	30	240	242-396	354	0.20	538-904	724	0.42	904	86.9
	40	243	243-404	363	0.15	540-928	764	0.40	928	86.5
30	10	227	227-367	327	0.20	510-852	680	0.92	852	99.2
	20	232	232-387	344	0.26	529-868	699	0.49	868	87.5
	30	236	236-397	355	0.20	538-917	720	0.42	917	86.8
	40	242	242-406	365	0.15	557-924	760	0.40	924	86.6
40	10	172	172-375	328	0.46	513-828	656	0.36	828	90.8
	20	188	188-391	346	0.26	528-876	702	0.53	876	88.0
	30	201	201-397	357	0.38	555-889	705	0.32	889	85.1
	40	208	208-406	360	0.21	560-922	734	0.40	922	87.6

T_i, ignition temperature; T_b, burnout temperature; R_{max}, the maximum of weight loss.

the explanation of bamboo with coal. Liu et al (2014) found that about 51% of volatile matters in bamboo was pyrolyzed during torrefaction process with a temperature of 300°C and a residue time of 2.0 h. These matters owned higher reactivity, causing bamboo easier to be ignited. Torrefaction therefore decreased the reactivity of bamboo, resulting in having a continuous/overlapping combustion zone with coal during cocombustion of torrefied bamboo and coal.

The cocombustion characteristics of bamboo and torrefied bamboo with coal were showed in Tables 1 and 2, respectively. In Table 1, the ignition temperature gradually increased with increase in heating rates and decreased with

Table 2. Combustion characteristics of blends with torrefied bamboo and coal during cocombustion.

			The main combustion zone				
Fuel	Heating rate (°C/min)	T_i (°C)	Temperature range (°C)	T_{peak} (°C)	R_{max} (mg/min)	T_b (°C)	Total burnout (%)
10% bamboo/90% coal	10	505	505-835	680	0.82	835	85.3
	20	540	540-873	705	0.59	873	82.8
	30	555	555-894	720	0.52	894	87.4
	40	565	565-919	764	0.43	919	85.0
20% bamboo/80% coal	10	511	511-836	654	0.56	836	82.3
	20	540	540-866	694	0.54	866	86.1
	30	559	559-894	708	0.45	894	82.5
	40	580	580-915	695	0.36	915	87.1
30% bamboo/70% coal	10	520	520-840	658	0.51	840	77.4
	20	555	555-875	668	0.45	875	88.0
	30	570	570-896	684	0.36	896	86.2
	40	575	575-912	735	0.40	912	85.2
40% bamboo/60% coal	10	525	525-821	641	0.49	821	83.2
	20	532	532-884	680	0.42	884	86.5
	30	589	589-891	666	0.33	891	89.4
	40	590	590-906	662	0.31	906	87.1

T_i, ignition temperature; T_b, burnout temperature; R_{max}, the maximum of weight loss.

the rising of bamboo contents in the blends. The first combustion zone started at about 172-246°C and stopped at 361-406°C with peak temperature (T_{peak}) around 327-365°C and 0.14-0.38 mg/min of R_{max} to different heating rates and mixing ratios. The second combustion zone of different samples started at 486-560°C and stopped at 806-928°C with T_{peak} around 651-724°C and 0.36-0.92 mg/min of R_{max}. For each sample, cocombustion characteristics including start, peak, and stop temperature increased with increase in heating rates during second combustion zone. Burnout temperature of all samples also increased with increase in heating rates, such as from 806°C to 923°C for blends of 10% bamboo and 90% coal, from 848°C to 928°C for blends of 20% bamboo and 80% coal, from 852°C to 924°C for blends of 30% bamboo and 70% coal, and from 828°C to 922°C for blends of 40% bamboo and 60% coal. The total weight loss of all samples were more than 80% during cocombustion of bamboo and coal.

Compared with the blends of bamboo and coal, Table 2 showed cocombustion of all blends of torrefied bamboo and coal had obviously higher ignition temperatures due to a lower reactivity of torrefied bamboo. This also resulted in combustion zone overlap during cocombustion of torrefied bamboo and coal. Therefore, torrefied bamboo/coal blends combusted at a continuous temperature zone, starting from 505°C to 590°C

Table 3. Kinetic parameters from cocombustion of bamboo and coal.

Fuel	Heating rates (°C/min)	Temperature range (°C)	Linear function	Correlation coefficient value	E_a (kJ/mol)	A (1/min)
10% bamboo/90% coal	10	235-361	$y = -3{,}044.9x - 9.70$	$R^2 = 0.9966$	25.32	1.86E − 03
		486-806	$y = -10{,}473x - 2.02$	$R^2 = 0.9104$	87.10	1.39E + 01
	20	139-381	$y = -4{,}158.1x - 8.07$	$R^2 = 0.9985$	34.57	2.60E − 02
		509-868	$y = -9{,}811.3x - 3.33$	$R^2 = 0.9283$	81.60	7.04E + 00
	30	242-383	$y = -4{,}139.2x - 8.24$	$R^2 = 0.9994$	34.41	3.29E − 02
		512-882	$y = -9{,}337.5x - 4.08$	$R^2 = 0.9607$	77.60	4.74E + 00
	40	246-394	$y = -3{,}160.9x - 9.82$	$R^2 = 0.9974$	26.28	6.86E − 03
		516-923	$y = -8{,}995.3x - 4.33$	$R^2 = 0.9848$	74.80	4.75E + 00
20% bamboo/80% coal	10	232-360	$y = -3{,}652.1x - 8.95$	$R^2 = 0.9991$	30.36	4.75E − 03
		504-848	$y = -13{,}196x + 0.26$	$R^2 = 0.9233$	101.00	1.71E + 02
	20	237-387	$y = -3{,}817.6x - 8.63$	$R^2 = 0.9963$	31.74	1.37E − 02
		532-874	$y = -10{,}515x - 2.95$	$R^2 = 0.9393$	87.40	1.10E + 01
	30	242-396	$y = -3{,}555.7x - 9.01$	$R^2 = 0.9936$	29.56	1.31E − 02
		538-904	$y = -9{,}239.1x - 4.56$	$R^2 = 0.9501$	76.80	2.90E + 00
	40	243-404	$y = -3{,}333.7x - 9.64$	$R^2 = 0.9982$	27.72	8.72E − 03
		540-928	$y = -9{,}706.6x - 4.26$	$R^2 = 0.9708$	80.70	5.12E + 00
30% bamboo/70% coal	10	227-367	$y = -3{,}851.8x - 8.29$	$R^2 = 0.9974$	32.02	9.68E − 03
		510-852	$y = -11{,}880x - 1.03$	$R^2 = 0.9038$	98.80	4.25E + 01
	20	232-387	$y = -4{,}460.1x - 7.03$	$R^2 = 0.9989$	37.08	7.86E − 02
		529-868	$y = -7{,}579.6x - 5.60$	$R^2 = 0.9146$	63.00	5.58E − 01
	30	236-397	$y = -4{,}087.6x - 7.89$	$R^2 = 0.9965$	33.98	4.58E − 02
		538-917	$y = -7{,}763.6x - 5.75$	$R^2 = 0.9405$	64.50	7.38E − 01
	40	242-406	$y = -3{,}954.7x - 8.47$	$R^2 = 0.9973$	32.88	3.32E − 02
		557-924	$y = -8{,}578.4x - 5.38$	$R^2 = 0.9648$	71.30	1.58E − 00
40% bamboo/60% coal	10	172-375	$y = -4{,}826.3x - 5.81$	$R^2 = 0.9972$	40.13	1.45E − 01
		513-828	$y = -5{,}565.3x - 7.04$	$R^2 = 0.8829$	46.30	4.88E − 02
	20	188-391	$y = -4{,}103.3x - 7.61$	$R^2 = 0.9976$	34.11	4.07E − 02
		528-876	$y = -7{,}972.5x - 5.27$	$R^2 = 0.9079$	66.30	8.19E − 01
	30	201-397	$y = -4{,}875.9x - 6.14$	$R^2 = 0.9973$	40.54	3.14E − 01
		555-889	$y = -5{,}662.1x - 7.46$	$R^2 = 0.9206$	47.10	9.79E − 02
	40	208-406	$y = -3{,}990.3x - 8.07$	$R^2 = 0.9967$	33.18	4.98E − 02
		560-922	$y = -7{,}572.5x - 6.12$	$R^2 = 0.9472$	63.00	6.65E − 01

Table 4. Kinetic parameters from cocombustion of torrefied bamboo and coal.

Fuel	Heating rates (°C/min)	Temperature range (°C)	Linear function	Correlation coefficient value	*E*a (kJ/mol)	*A* (1/min)
10% torrefied bamboo/90% coal	10	505-835	$y = -16{,}898x + 4.1018$	$R^2 = 0.9890$	140.49	1.02E + 07
	20	540-873	$y = -11{,}536x - 1.9535$	$R^2 = 0.9666$	95.91	3.27E + 04
	30	555-894	$y = -10{,}905x - 2.8102$	$R^2 = 0.9853$	90.66	1.97E + 04
	40	565-919	$y = -10{,}502x - 3.6268$	$R^2 = 0.8906$	87.31	1.12E + 04
20% torrefied bamboo/80% coal	10	511-836	$y = -9{,}919.2x - 2.8066$	$R^2 = 0.9643$	82.47	5.99E + 03
	20	540-866	$y = -9{,}951.3x - 3.3446$	$R^2 = 0.9721$	82.74	7.02E + 03
	30	559-894	$y = -9{,}416.3x - 4.0152$	$R^2 = 0.9796$	78.29	5.10E + 03
	40	580-915	$y = -7{,}360.9x - 6.2057$	$R^2 = 0.9920$	61.20	5.94E + 02
30% torrefied bamboo/70% coal	10	520-840	$y = -11{,}033x - 1.5733$	$R^2 = 0.9916$	91.73	2.29E + 04
	20	555-875	$y = -7{,}986.3x - 5.0306$	$R^2 = 0.9870$	66.40	1.04E + 03
	30	570-896	$y = -7{,}377.8x - 5.9850$	$R^2 = 0.9932$	61.34	5.57E + 02
	40	575-912	$y = -8{,}666.1x - 5.1454$	$R^2 = 0.9807$	72.05	2.02E + 03
40% torrefied bamboo/60% coal	10	525-821	$y = -8{,}783.4x - 3.7756$	$R^2 = 0.9728$	73.03	2.01E + 03
	20	532-884	$y = -8{,}142.4x - 4.9953$	$R^2 = 0.9857$	67.70	1.10E + 03
	30	589-891	$y = -6{,}372x - 6.8479$	$R^2 = 0.9981$	52.98	2.03E + 02
	40	590-906	$y = -6{,}431.5x - 6.9070$	$R^2 = 0.9968$	53.47	2.57E + 02

of temperature and stopping from 821°C to 919°C for different heating rates and mixing ratios. In conclusion, cocombustion of torrefied bamboo/coal was more feasible with a stabler combustion process in this research.

Tables 3 and 4 showed the kinetic parameters from cocombustion of bamboo and torrefied bamboo with coal. For cocombustion of bamboo and coal shown in Table 3, it was obvious that activation energy in lower temperature zone was lower than that in higher temperature zone. For example, the activation energy was 25.32 kJ/mol within 235-361°C of temperature range and 87.10 kJ/mol within 486-806°C of temperature range for blends of 10% bamboo and 90% coal with 10°C/min of heating rate. For other samples, the change of activation energy was similar, that is, the higher combustion temperature zone corresponded to a higher activation energy. This indicated coal would require higher temperature and longer reaction time to oxidize compared with bamboo. It was found that activation energy of high temperature zone decreased with increase in heating rates.

For cocombustion of torrefied bamboo and coal in Table 4, the activation energy also gradually decreased as increase in heating rates and mixing ratios. The activation energy of blends from 10% torrefied bamboo and 90% coal was 140.49 kJ/mol for 10°C/min of heating rate, 95.91 kJ/mol for 20°C/min of heating rate, 90.66 kJ/mol for 30°C/min of heating rate, and 87.31 kJ/mol for 40°C/min of heating rate. For 20°C/min of heating rate, the activation energy was 95.91 kJ/mol for blends from 10% torrefied bamboo and 90% coal, 82.74 kJ/mol for blends from 20% torrefied bamboo and 80% coal, 66.40 kJ/mol of blends from 30% torrefied bamboo and 70% coal, and 67.70 kJ/mol of blends from 40% torrefied bamboo and 60% coal. These indicated that the reactivity of blends

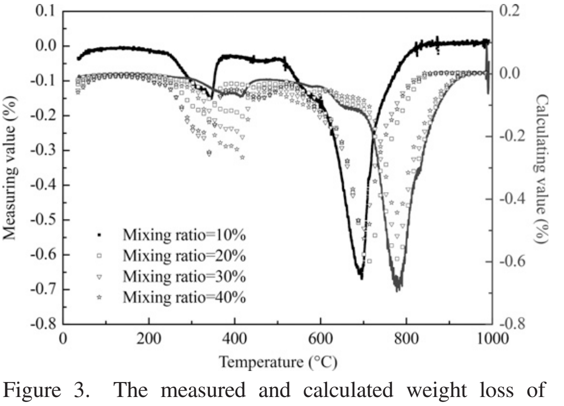

Figure 3. The measured and calculated weight loss of blends with bamboo and coal during cocombustion at 20°C/min of heating rate.

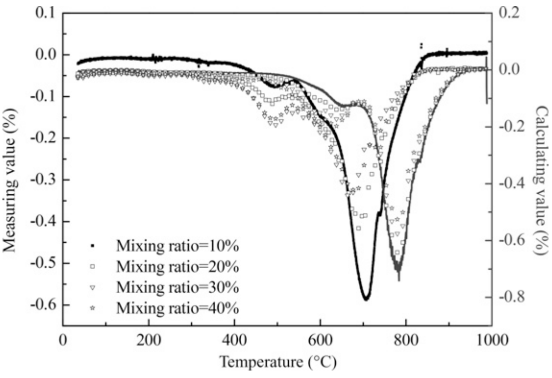

Figure 4. The measured and calculated weight loss of blends with torrefied bamboo and coal during cocombustion at 20°C/min of heating rate.

was improved during combustion process when adding bamboo or torrefied bamboo to coal.

Synergistic Analysis

Co-firing biomass residues with coal in traditional coal-fired boilers for electricity production generally represents one of the most cost-effective and efficient renewable energy and climate change technology, with investment costs commonly ranging around 100-600 USD/kWe depending on the fuel and technical option chosen (Peduzzi et al 2014). Gil et al (2010) investigated thermal behaviors of coal and biomass blends during cocombustion and did not find interactions between the components of the blends occurred, reflecting the additive behavior of the coal/biomass blends. Fitzpatrick et al (2009) found synergy in organic emissions from the coal/pine blends during cocombustion with lower emissions than would be expected on an additive basis. To investigate whether synergy occurred between bamboo, torrefied bamboo, and coal during cocombustion, the theoretical value of weight loss was calculated based on measured value of bamboo, torrefied bamboo, and coal.

Figures 3 and 4 showed the measured and calculated differential thermal gravimetric curve of bamboo and torrefied bamboo with coal during cocombustion at a heating rate 20°C/min. It was very obvious that calculated value (theoretical value) of combustion characteristics located at higher temperature zone. This indicated the presence of synergistic interactions between bamboo/torrefied bamboo and coal during cocombustion.

As shown in Table 5, T_i^a is measured ignition temperature, T_i^b is calculated ignition temperature, T_b^a is measured burnout temperature, T_b^b is calculated burnout temperature, T_{peak}^a is measured peak temperature, and T_{peak}^b is calculated peak temperature. T_i^a was 239°C, lower than T_i^b 297°C for blends of 10% bamboo and 90% coal, T_i^a was 237°C, lower than T_i^b 300°C for blends of 20% bamboo and 80% coal, decreased from 291°C of calculated value to 232°C of measured value for blends of 30%

Table 5. Measured and calculated cocombustion characteristics of bamboo and coal during cocombustion with 20°C of heating rate.

		First combustion zone			Second combustion zone			
Mixing rates (%)	T_i (°C)	Temperature range (°C)	T_{peak} (°C)	R_{max} (mg/min)	Temperature range (°C)	T_{peak} (°C)	R_{max} (mg/min)	T_b (°C)
10	239[a]	239–381[a]	345[a]	0.15[a]	509-868[a]	696[a]	0.68[a]	868[a]
	297[b]	297–454[b]	413[b]	0.07[b]	693-953[b]	779[b]	0.67[b]	953[b]
20	237[a]	237–387[a]	344[a]	0.26[a]	532-874[a]	700[a]	0.48[a]	874[a]
	300[b]	300–465[b]	416[b]	0.13[b]	692-969[b]	779[b]	0.59[b]	969[b]
30	232[a]	232–387[a]	344[a]	0.26[a]	529-868[a]	699[a]	0.49[a]	868[a]
	291[b]	291–474[b]	413[b]	0.20[b]	688-975[b]	781[b]	0.53[b]	975[b]
40	188[a]	188–391[a]	346[a]	0.26[a]	528-876[a]	702[a]	0.53[a]	876[a]
	282[b]	282–465[b]	414[b]	0.25[b]	694-987[b]	780[b]	0.45[b]	987[b]

T_i, ignition temperature; T_b, burnout temperature; R_{max}, the maximum of weight loss.
[a] Measured combustion characteristics of blends.
[b] Calculated combustion characteristics of blends.

Table 6. Measured and calculated cocombustion characteristics of torrefied bamboo and coal with 20°C of heating rate.

		First combustion zone			
Mixing ratios (%)	T_i (°C)	Temperature range (°C)	T_{peak} (°C)	R_{max} (mg/min)	T_b (°C)
10	540[a]	540-873[a]	705[a]	0.59[a]	873[a]
	694[b]	694-959[b]	786[b]	0.69[b]	959[b]
20	540[a]	540-866[a]	694[a]	0.54[a]	866[a]
	692[b]	692-972[b]	779[b]	0.64[b]	972[b]
30	555[a]	555-875[a]	668[a]	0.45[a]	875[a]
	696[b]	696-977[b]	786[b]	0.59[b]	977[b]
40	532[a]	532-884[a]	680[a]	0.42[a]	884[a]
	697[b]	697-981[b]	783[b]	0.55[b]	981[b]

T_i, ignition temperature; T_b, burnout temperature; R_{max}, the maximum of weight loss.
[a] Measured combustion characteristics of blends.
[b] Calculated combustion characteristics of blends.

bamboo and 70% coal, decreased from 282°C of calculated value to 188°C of measured value for blends of 40% bamboo and 60% coal. Similarly, measured values of peak temperature (T_{peak}) in both combustion zones and burnout temperature also shifted to lower temperatures for all blends.

According to results from Table 6, the same trend was observed for all combustion characteristics of blends of torrefied bamboo and coal. For blends of 10% torrefied bamboo and 90% coal, ignition temperature decreased from 694°C to 540°C, peak temperature decreased from 786°C to 705°C, and burnout temperature decreased from 959°C to 873°C. This also confirmed that the reactivity and combustion efficiency of blends were improved during cocombustion when adding bamboo or torrefied bamboo to coal. Farrow et al (2013) also found that biomass addition enhanced the devolatilization of coal during biomass/coal coprocessing.

Figures 5 and 6 showed the deviation between measured and calculated weight loss of bamboo and torrefied bamboo with coal. There were also two stages on the deviation for blends of bamboo and coal with different mixing ratios. Only one stage was observed for blends of torrefied bamboo and coal. This was similar

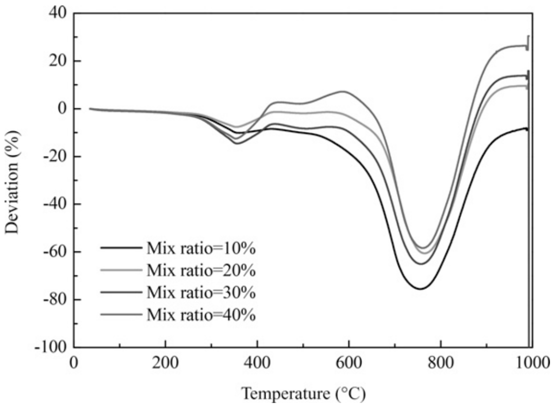

Figure 5. The deviation between measured and calculated weight loss of blends with bamboo and coal at different temperatures.

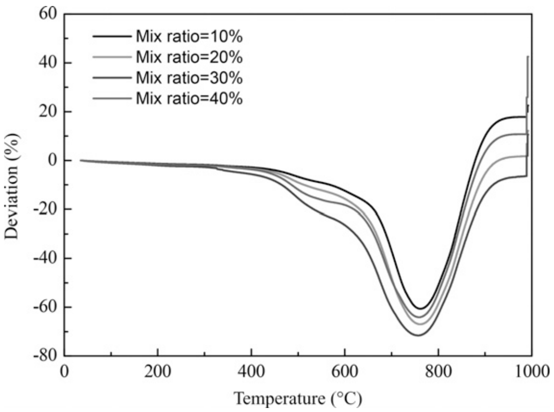

Figure 6. The deviation between measured and calculated weight loss of torrefied bamboo and coal at different temperatures.

with TGA curves of their cocombustion processes. In each stage, deviation gradually decreased to reach a maximum value at certain temperature and then gradually increased. It was clear that blends of bamboo and coal with a higher mixing ratio had a less deviation. For blends of torrefied bamboo and coal, the most deviation was found to blends of 30% torrefied bamboo and 70% coal, followed by blends of 20% torrefied bamboo and 80% coal and the lest deviation corresponded to blends of 10% torrefied bamboo and 90% coal. The earlier results confirm the presence of synergy and the interactions between bamboo and torrefied bamboo with coal during cocombustion. The addition of bamboo or torrefied bamboo to blends decreased combustion characteristics and improved fuel qualities.

CONCLUSIONS

Cocombustion of bamboo and coal included two main combustion zones. The combustion processes of lower and higher temperature zones were bamboo and coal combustion, respectively. The higher temperature zone corresponded to a higher activation energy. Cocombustion of torrefied bamboo and coal only had a combustion zone at higher temperature. Combustion characteristics gradually increased with increase in heating rates and decreased in bamboo or torrefied bamboo contents of blends. Calculated value (theoretical value) of combustion characteristics shifted to higher temperatures during cocombustion, indicating the presence of synergistic interactions between bamboo/torrefied bamboo and coal. Cocombustion of torrefied bamboo/coal was more feasible with a stabler combustion process.

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