Co-Combustion Characteristics and Kinetic Analyses of Biomass Briquette and Municipal Solid Waste in N₂/O₂ and CO₂/O₂ Atmospheres

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The thermal behavior of cotton straw briquette (CSB), municipal solid (MSW), and their blends was investigated using a waste thermogravimetric analyzer under N_2/O_2 and CO_2/O_2 atmospheres at 20 °C/min from an ambient temperature to 1000 °C. The kinetics and synergistic interaction between MSW and CSB in the co-combustion process were evaluated. The results indicated that MSW blended with CSB improved the ignition and burnout characteristics of the blends, while decreasing the comprehensive combustion characteristics index. The suitable proportions of CSB were less than 60% and 40% separately under 80N₂/20O₂ and 80CO₂/20O₂ atmospheres, respectively. The inhibitory effect of CO₂ induced burnout temperature and residual mass increased, and the high-temperature stage reaction varied. Kinetic analysis of the blends indicated that blending with CSB could promote MSW combustion in the first reaction stage, while the second and third decomposition stages were complicated because of the synergistic interaction between MSW and CSB in the co-combustion process. The nth order reaction model fit the mass loss of theca-combustion process for the blends very well.

Key words: Biomass briquette; Co-combustion; Kinetic analyses; CO₂/O₂ atmosphere; N₂/O₂ atmosphere

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INTRODUCTION

The "Junk Fortress Besieged" phenomenon and the burning of the municipal solid waste (MSW) has been an expanding environmental problem for Chinese urban development. Fossil fuels are required during the incineration of MSW because of its high moisture contents and relatively low heating values in most parts of China, especially in the summer. However, it not only increases the demand for energy load but also brings a series of environmental problems (Henry *et al.* 2006). The co-firing of MSW with biomass substituted for fossil fuel is a promising option because agricultural straw biomass is an abundant renewable energy and could reduce the problem of biomass open burning that threatens urban traffic safety in China. In addition, the combustion of MSW blended with straw biomass also reduces environmental pollution emitted from MSW incineration (Skodras *et al.* 2006; Ren *et al.* 2009).

Up to the present, most studies have mixed non-pretreated straw biomass with MSW for co-firing. The combustion efficiency of raw straw biomass in an incineration plant is only 10% to 15% because of the bulk volume, low energy density, and the seasonal,

high material transportation, and storage costs. Moreover, the high moisture contents of biomass suppress the combustion process and increase emissions of wet flue gas (Grover and Mishra 1996). An alternative way is to dry and pulverize raw straw biomass materials before co-firing. In this pre-treatment process, biomass is converted into hard-packed biomass briquettes or biomass pellets, which are an important renewable source of energy production (Larsson *et al.* 2008). Densification of these materials improves their behavior as a fuel by increasing their homogeneity and allowing a wider range of lignocellulosic materials to be used as fuel (Tabarés *et al.* 2000; Li *et al.* 2016). Pelletization may extend fuel devolatilization times compared with the original loose fuel constituents. Also, the amount of oxygen required for the combustion can be well matched with the amount of oxygen diffused from the outside, which positively affects the effectiveness of lateral fuel spreading and evenness of volatile matter release during combustion. This induces less combustion-wave and tends to be more stable during the burning process (Chirone *et al.* 2008; Roy *et al.* 2013; Liu *et al.* 2014).

Biomass pellets can be used in grate furnaces and fluidized bed combustion while offering advantages including easy storage and transport, lower pollution, lower dust levels, and higher heating values (Gil *et al.* 2010). Therefore, the co-combustion of MSW and biomass briquettes can solve the aforementioned problems, further improve the calorific value of the blend fuels, and enhance the burning efficiency and stability of MSW (Tian *et al.* 2013). The combustion performance and kinetic characteristics of briquetted biomass differs from non-pretreated biomass, leading to differences in device structure and combustion products (Houshfar *et al.* 2011; Liu *et al.* 2011; Roy *et al.* 2013). However, the combined firing of MSW and biomass briquettes, especially for those concerning the combustion kinetics, have not been studied systematically.

Oxygen combustion technology under a CO_2/O_2 atmosphere, instead of N_2/O_2 atmosphere, is a promising combustion technology associated with carbon capture and storage because of its low NOx emission and high sulfation efficiency (Liu and Okazaki 2003; Ge *et al.* 2015; Hees *et al.* 2016). However, comparison between the two models shows that there are distinctions in combustion characteristics such as burning stability, char burn-out, heat transfer, and gas temperature (Molina and Shaddix 2007; Lai *et al.* 2012). Therefore, there is a need to study combustion characteristics and reaction kinetics of MSW, biomass briquettes, and their blends in different blending ratios under N₂/O₂ and CO₂/O₂ atmospheres.

In this study, the kinetic parameters during combustion were obtained by the Coats-Redfern method under the nth order reaction model separately in the CO_2/O_2 and N_2/O_2 atmospheres. The synergistic interaction between MSW and CSB in the co-combustion process was also investigated. The obtained results elucidate the combustion process and offer reference and guidance for the design and operation of co-combustion of MSW and biomass briquettes.

EXPERIMENTAL

Materials

The MSW mixture was collected from Hefei University of Technology according to the typical component of MSW in Hefei, China. The samples were purified from raw MSW by the manual removal of metal, glass, dust, *etc*. Thus, the constituents were combustible, including food waste and fruit peels (FW&FP), plastic, rubber, textile, paper, and a mixture of bamboo and wood (BB&WD). The selected cotton straw biomass briquettes (CSB) provided by Anhui Haosheng Energy Technology Co., Ltd. (Hefei, Anhui, China) had a formation density of 1.36 g/cm^3 . The MSW and CSB were oven-dried at 105 °C for 12 h, smashed repeatedly by a FW100 crusher manufactured by Zhengzhou Kefeng Instrument and Equipment Co., Ltd. (Zhengzhou, Henan, China), and passed through a sieve with mesh size of 68 µm. The proximate analysis of MSW and CSB was carried out by a MAC-3000 fully auto-measuring industrial analyzer (Jiangyan Guochuang Analytical Instruments Co., Ltd., Taizhou, Jiangsu, China), of which the percentage of fixed carbon was determined by difference. The elemental compositions were carried out on a Vario El Cube elemental analyzer (Elementar, Hanau, Germany). The proximate and ultimate analyses of MSW and CSB are shown in Table 1, and the ash content of adjusted MSW was lower than that of CSB material.

Samples	Prox	ximate Ana	lysis (wt.%)	Ultimate Analysis (wt.%)							
	Ash	Volatile	Fixed carbon	С	Н	0	Ν	S			
MSW	6.32	76.95	16.73	40.26	5.19	37.64	1.21	0.24			
CSB	17.06	64.86	18.08	44.96	5.34	41.49	0.93	0.14			

Table 1. Ultimate and Proximate Analyses of MSW and CSB Samples

All treated components were mixed together one by one in a micro rotary mixer for one hour. In addition to the MSW and CSB individual samples, the mass percentages of CSB added to the MSW were 20%, 40%, 50%, 60%, and 80%, which were named 20C80M, 40C60M, 50C50M, 60C40M, and 80C20M, respectively. These samples were uniformly blended by the mechanical mixing method and stored in desiccators until they were used. Each test sample was taken separately by the coning quartering method before the experiment began. The initial weight of the samples for all runs was formulated as 10 \pm 0.5 mg.

Methods

The combustion characteristics of MSW, CSB, and their blends were studied using a Setsys Evo thermogravimetric analyzer (SETARAM, Lyon, France) with temperature precision and microbalance sensitivity of ± 0.3 °C and ± 0.023 µg, respectively. The balance was designed above the furnace to prevent pollution of residual products from volatile decomposition. A counterweight and crucible were suspended by filaments at both ends of the TG to minimize the buoyancy effect. The crucible with the sample was always at the center of the chamber to avoid thermogravimetric error caused by changes of the sample gravity position, and the sample could be contacted fully with the atmosphere purged from top to bottom, which was important during the combustion test.

All the non-isothermal combustion experiments in $80N_2/20O_2$ and $80CO_2/20O_2$ atmospheres were carried out from an ambient temperature to 1000 °C at a heating rate of 20 °C/min. The flow rate of mixed gas was maintained at 60 mL/min. To eliminate the systematic errors caused by the weight of the crucible, temperature, and effect of buoyancy, a blank test without samples was conducted to obtain baseline data before each experiment. All the experiments in each case were performed repeatedly at least twice to ensure the accuracy, and the results of reproducibility were quite good.

Characteristics of Combustion Phenomenon

To evaluate the comprehensive combustion characteristics of MSW, CSB, and their blends, the comprehensive combustion characteristic index S was introduced in Eq. 1 (Hu *et al.* 2015),

$$S = \frac{\left(\frac{\mathrm{d}W}{\mathrm{d}t}\right)_{\mathrm{max}} \left(\frac{\mathrm{d}W}{\mathrm{d}t}\right)_{\mathrm{mean}}}{T_i^2 T_f} \tag{1}$$

where $(dW/dt)_{max}$ and $(dW/dt)_{mean}$ were the maximum and average mass loss rate, respectively. T_i was the ignition temperature determined based on a comprehensive consideration of thermogravimetric and differential thermogravimetric method (TG-DTG), in which a tangent line was drawn that corresponded to the cross-point between the TG curve and the vertical line to the maximum weight loss rate of DTG curve, and the ignition temperature was defined as the intersection between the above tangent line and the tangent line to the point of the mass loss started. The burnout temperature T_f was obtained when the mass loss of sample reached 98% of the weight loss (Fang *et al.* 2015). The larger value of the index *S*, which was representative of the characteristics of MSW, CSB, and their blends, the better vigorous combustibility was (Hu *et al.* 2015).

Kinetic Theory

The combustion reaction process of MSW or CSB can be simplified as typical solid heterogeneous reaction, which may take place through a series of parallel and competitive reactions. The fundamental rate equation of heterogeneous solid phase reactions could be described with the Arrhenius equation (Eq. 2) (Liu *et al.* 2009; Lin *et al.* 2014),

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = k(T)f(\alpha) = A\exp(-\frac{E}{RT})(1-\alpha)^n \tag{2}$$

where *t* is the time, *E* is the apparent activation energy, *A* is the pre-exponential Arrhenius

factor, *R* is the universal gas constant, *T* is the reaction temperature, $f(\alpha) = (1-\alpha)^n$ is a function depended on the assumed reaction mechanism in the combustion process of biomass and MSW (Liu *et al.* 2009; El-Sayed and Mostafa 2014), and *n* is the order of the reaction.

The degree of conversion of the weight loss is expressed according to Eq. 3,

$$\alpha = (m_0 - m_t) / (m_0 - m_\infty) \tag{3}$$

where m_0 and m_∞ are the initial and final masses, respectively, of the samples, and m_t is the mass of the samples at time *t*.

For the non-isothermal thermogravimetric experiments with linear heating rate program of $\beta = dT/dt$, Eq. 2 is transformed, as shown in Eq. 4,

$$\frac{\mathrm{d}\alpha}{\mathrm{d}T} = \frac{A}{\beta} \exp(-\frac{E}{RT})(1-\alpha)^n \tag{4}$$

The Coats-Redfern method is widely used to evaluate the kinetic parameters from TG-DTG curves (El-Sayed and Mostafa 2014; Oyedun *et al.* 2014). Starting with Eq. 4 and after certain algebra, the kinetic equation leads to the following integral forms, shown in Eqs. 5 and 6,

For n =1,
$$\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] = \ln\left[\frac{AR}{\beta E}\left(1-\frac{2RT}{E}\right)\right] - \frac{E}{RT}$$
(5)

For
$$n \neq 1$$
, $\ln \left[\frac{1 - (1 - \alpha)^{1 - n}}{T^2 (1 - n)} \right] = \ln \left[\frac{AR}{\beta E} \left(1 - \frac{2RT}{E} \right) \right] - \frac{E}{RT}$ (6)

Because the temperature range and activation energy in this work, 2RT/E << 1 (Lin *et al.* 2014; Oyedun *et al.* 2014), then $\ln[AR/\beta E(1-2RT/E)]$ could be almost regarded as a constant *c*. Assuming that the left side of the above Eqs. 5 and 6 both were *Y*, b = -E/R, and X = 1/T, thus the Eq. 5 and Eq. 6 can be presented in the forms of Y=c + bX. The plot of *Y* vs. *X* will obtain various straight lines, while the appropriate reaction order *n* is determined by the highest value of the correlation coefficient (El-Sayed and Mostafa 2014). The *E* and *A* can be obtained from the slope and intercept of the fitted straight line.

RESULTS AND DISCUSSION

Thermogravimetric Analysis of MSW and CSB

MSW

The profiles of DTG curves of MSW in Fig. 1b showed that there were three noteworthy peaks in the combustion process under both N_2/O_2 and CO_2/O_2 atmospheres, and correspondingly TG curves characterized by three weight loss stages in Fig. 1a were easily distinguished. To further analyze the combustion characteristics of MSW, thermogravimetric experiments for all single components of MSW were also carried out under an N_2/O_2 atmosphere.



Fig. 1. Combustion of MSW and CSB under N_2/O_2 and CO_2/O_2 atmospheres: (a) TG curves; (b) DTG curves

Figure 2a displays the first and second mass loss peaks of paper and BB&WD presented similar temperature zone of mass loss because they had similar components of lignocellulose. The first peak occurred at 339.5 °C and 334.6 °C, respectively, and accounted for devolatilization of lignocellulosic fractions, in which the hemicelluloses and cellulose had high reactivity and burned completely around 340 °C, while lignin burned

within a broader temperature range (Lai *et al.* 2012; Zhou *et al.* 2015). The second mass loss stage occurred from about 390 to 560 °C and was mainly due to the further decomposition and burning of lignin and afterwards, the combustion of chars (Tang *et al.* 2011; Fan *et al.* 2016). Above 600 °C, the DTG curve of paper had the third mass loss stage until 800 °C, which was attributed to the degradation of calcium carbonate and other minerals (Liao and Ma 2010). The combustion of textiles showed that the maximum rate of mass loss at 345.4 °C was attributable to the devolatilization and burning of cotton (mainly composed of cellulose, the main component of textiles). The second peak at 423.7 °C resulted from the decomposition and combustion of polyester, another usual ingredient of textiles (Alongi *et al.* 2011). The combustion of residues of aforementioned components resulted in the third mass loss stage.



Fig. 2. DTG curves for single component of MSW in N_2/O_2 atmosphere: (a) DTG curves of paper, textiles, and BB&WD; (b) DTG curves of FW&FP, plastic, and rubber.

As shown in Fig. 2b, the DTG curve of FW&FP, which is composed of rice and banana peel in a mass ratio of 4:1, presented three peaks. The first tiny peak of banana peel devolatilization occurred at a lower temperature of 205.7 °C, revealing the degradation of pectin, hemicelluloses, and sugars (Branca and Blasi 2015; Zhou et al. 2015). Based on the previous studies, the second peak at 317.8 °C was the primary peak caused by the cellulose and starch decomposition and part of lignin combustion (Tang et al. 2011; Branca and Blasi 2015; Fang et al. 2015). The third peak had a broader temperature zone between 400 and 570 °C, which was attributed to the further combustion of lignin and char burning. The first peak of plastic was at 439.8 °C and resulted from the thermal decomposition of polyethylene terephthalate, which was the main component of the plastic, and the second one was most likely due to the combustion of carbonaceous residue and other additives (Brems et al. 2011). The peaks at 276.9 °C and 444.2 °C revealed the decomposition and burning of rubbers, of which natural rubber degraded at lower temperature and synthetic rubber (polybutadiene rubber or styrene-butadiene rubber) decomposed at higher temperature (Cui et al. 1999; Tang et al. 2015). The third one was at 545.2 °C because of the combustion of carbon black and minerals (Cui et al. 1999).

Therefore, three mass loss stages of MSW were obtained: the first decomposition stages centered on 316 °C under both of the two atmospheres with weight loss of about 43%. This stage represented the devolatilization and combustion of lignocellulosic materials, pectin, starch, sugars, and part of rubber components. The second peaks at around 431 °C with mass loss of about 24% were due to the decomposition and combustion

of lignin, polyethylene terephthalate, polyester and synthetic rubber. The third ones were caused by the combustion of remaining char, carbon black, and some inorganic compounds with weight loss of about 27%. The main decomposition process resulted from the release and combustion of volatile component, which accounted for the major proportion of MSW in proximate analysis. Similar conclusions were also obtained by Hu *et al.* (2015). The third mass loss stage of paper from 600 to 800 °C reflected in the decomposition process of MSW as an inconspicuously tiny change might be because of the influence of interactions among the single components (Zhou *et al.* 2015), which can be hypothesized that was not a mass loss peak in the thermogravimetric analysis.

CSB

As shown in Fig. 1a, the remnant of CSB was higher than MSW, which was in accordance with the higher fixed carbon and ash content in Table 2. Obernberger and Thek (2004) stated that a higher ash content of pellets in comparison with unprocessed raw materials could be acceptable, which were destined for industrial use due to the greater robustness and sophistication of industrial combustion systems. Wang *et al.* (2007) reported that the fixed carbon of briquetted biomass burned more evenly; the terminated temperature and persistence of combustion were increased compared to uncompressed biomass. The ignition temperature of MSW was 284.3 °C, while CSB was 245.7 °C, which was about 40 °C lower than MSW under the N₂/O₂ atmosphere. The burnout temperature of CSB (557.0 °C) was almost around 20 °C lower than that of MSW (575.5 °C) under the N₂/O₂ atmosphere. In the CO₂/O₂ atmosphere, the ignition and burnout temperatures of the CSB were also about 40 °C and 30 °C below the MSW, respectively. Therefore, the ignition and burnout characteristics of MSW could be improved by the addition of CSB.

The CSB, which is mainly composed of lignocelluloses, was different from MSW composed of lignocelluloses, plastics, and rubber, etc. Two prominent mass loss peaks of CSB were shown in Fig. 1b under two atmospheres, and the primary mass loss stages centered on 327.4 C °C in the N₂/O₂ atmosphere and 328.6 °C in the CO₂/O₂ atmosphere were attributed to the devolatilization and combustion of cellulose, hemicelluloses, and partial lignin. The second peaks occurred at higher temperatures of 445.0 °C in the N_2/O_2 atmosphere and 448.1 °C in the CO₂/O₂ atmosphere were due to the combustion of residual lignin and char. As shown in Fig. 1, the TG and DTG curves below 300 °C of CSB in two atmospheres represented the similar tendency, which indicated that the influence of carbon dioxide on the initial phase of combustion was weak. Also, the replacement of N₂ by CO₂ caused a small shift of curve to higher temperature without significant change in the shape of TG and DTG cures for MSW. The remnant of MSW in the CO₂/O₂ atmosphere was higher, and the mass loss rate under the CO₂/O₂ atmosphere was lower. The results of CSB revealed the same characteristics except that a small hump centered on 500 °C formed under N₂/O₂ atmosphere, while the rate of mass loss declined continuously until about 580 °C in CO_2/O_2 atmosphere. This result might be due to the reactivity in the CO_2/O_2 atmosphere being reduced at higher temperature.

The above results suggested that carbon dioxide had negative effects on the combustion reaction, which indicated that the materials burned more fully under the $80N_2/20O_2$ atmosphere than the $80CO_2/20O_2$ atmosphere. Lai *et al.* (2012) reported that the combustion performances of higher oxygen concentration in CO_2/O_2 atmosphere could be well matched with that in N_2/O_2 atmosphere.

Co-combustion Behavior of the Blends

Effect of blending of MSW with CSB under N₂/O₂

Figure 3a represents the DTG curves of MSW, CSB, as well as their blends at different quality ratios under N_2/O_2 atmospheres. It can be seen that the DTG curves of the blends under N_2/O_2 atmosphere lay between that of the individual components. A similar phenomenon was observed in a study of combustion of MSW and oil shale (Fan *et al.* 2016). As the mass proportion of CSB increased in the blends, the DTG curves changed slightly below 390 °C, while the maximum weight loss rate gradually decreased. Hence, the diversities in combustion profiles of DTG curves were extended. The characteristic parameters of all samples under N_2/O_2 atmosphere are displayed in Table 2. The mass loss rate of second peaks was higher than the third peaks when the CSB ratios were 20% and 80% in blends as well as the individual compounds, while weight loss rate of third peaks were greater than the second ones at the CSB ratio of 40%, 50%, and 60%. The reason for this result might be the alkali components of CSB were oxygen carriers to the residue char of MSW, which catalyzed char combustion in the third mass loss stage of MSW.



Fig. 3. DTG curves for all samples: (a) under N₂/O₂ atmosphere; (b) under CO₂/O₂ atmosphere

As shown in Table 2, the initial temperature decreased from 284 to 246 °C with the increase of CSB proportion. This was mainly due to the fact that CSB was mainly composed of lignocelluloses, while the plastic fractions in MSW were decomposed at a higher temperature compared with lignocelluloses. The burnout temperature of blends was also lower than that of pure MSW. This result indicated that the ignition and burnout characteristics of blends could be improved by adding CSB into MSW. The total mass loss declined, and remnants of blends increased with the increased quality ratio of CSB. The value of index *S* of MSW was higher than that of CSB, and the *S* decreased from 20.12 to $11.39 (\times 10^{-07} \text{min}^{-20} \text{C}^{-3})$ with CSB ratio increased in the blends, which indicated that the comprehensive combustion characteristics of MSW was more vigorous than that of CSB on the basis of noncombustibles removed from MSW under realistic industrial processing conditions. Therefore, the combustion characteristics of the blends were improved compared with individual compounds. In addition, when the ratio of CSB was less than 60%, the index *S* value of blends was still relatively large, which provided a suitable mixing ratio of MSW and CSB under the $80N_2/20O_2$ atmosphere.

Samples	T₁ª (°C)	T ^b _f (°C)	<i>T</i> ₁ ^c (°C)	<i>DTG</i> ₁ ^d (%/min)	<i>T</i> ₂ ^c (°C)	<i>DTG</i> 2 ^d (%/min)	<i>T</i> ₃ °(°C)	DTG₃ ^d (%/min)	<i>DTG</i> _{mean} e (%/min)	<i>M</i> ^f (%)	S ^g (10 ⁻⁰⁷ min ⁻² °C ⁻³)
MSW	284	576	317	-16.07	432	-8.55	483	-7.69	-5.82	6.63	20.12
20C80M	283	572	316	-15.46	431	-7.64	481	-7.57	-5.72	8.62	19.34
40C60M	279	572	317	-14.72	433	-7.02	480	-7.47	-5.50	10.72	18.20
50C50M	271	575	316	-13.46	433	-6.20	472	-7.03	-5.15	13.36	16.45
60C40M	264	561	318	-12.46	435	-5.62	471	-6.72	-5.15	16.10	16.39
80C20M	262	557	316	-11.12	468	-6.11	512	-3.63	-4.86	20.95	14.13
CSB	246	557	327	-8.95	445	-4.17	500	-3.46	-4.28	27.27	11.39

 Table 2. Combustion Characteristic Parameters of Samples in N₂/O₂ Atmosphere

^a T_i , the ignition temperature; ^b T_f , the burnout temperature; ^c T_1 , T_2 , T_3 , the temperature according to the first peak, the second peak and the third peak; ^d DTG_1 , DTG_2 , DTG_3 , the rate of mass loss according to the first peak, the second peak and the third peak; ^e DTG_{mean} , the average rate of mass loss from the ignition temperature to burnout temperature; ^f M_f , the combustion residue mass; ^gS, the comprehensive combustion characteristic index; * the symbols are shared for Table 3.

Samples	T₁²(°C)	T₁♭(°C)	T₁º(°C)	<i>DTG</i> ₁ ^d (%/min)	T₂ ^c (°C)	DTG₂ ^d (%/min)	T₃º(°C)	DTG₃ ^d (%/min)	DTG _{mean} e (%/min)	$M_t^{f}(\%)$	S ^g (10 ⁻⁰⁷ min ⁻² °C ⁻³)
MSW	286	588	317	-15.84	431	-8.41	485	-6.80	-5.55	8.56	18.23
20C80M	280	586	316	-14.44	431	-7.17	482	-6.66	-5.28	9.22	16.59
40C60M	280	590	316	-13.47	432	-7.02	471	-6.95	-5.10	11.38	14.86
50C50M	273	616	315	-12.20	433	-6.08	470	-6.66	-4.48	13.65	11.95
60C40M	271	605	315	-11.85	432	-5.50	473	-6.04	-4.40	17.74	11.76
80C20M	262	578	316	-10.34	470	-5.46	522	-2.93	-4.40	22.41	11.46
CSB	250	560	329	-8.30	448	-3.78	-	-	-4.16	28.34	9.84

Table 3. Combustion Characteristic Parameters of Samples in CO₂/O₂ Atmosphere

Effect of blending of MSW with CSB under CO₂/O₂

As shown in Fig. 3b, the DTG curves of blends and individual MSW and CSB under the CO_2/O_2 atmosphere were similar to those under the N_2/O_2 atmosphere. Table 3 also shows the characteristic parameters of all samples under the CO_2/O_2 atmosphere. The total mass loss of the blends in the CO_2/O_2 atmosphere were lower than that in the N_2/O_2 environment at the same ratio of CSB, and the burnout temperature of the blends were all higher than that in the N_2/O_2 environment. Notably, when the ratio of CSB was 50%, the burnout temperature was the highest. This may be due to the ash content of the burning CSB hindering the combustion of the blend, and CO_2 has a higher density and specific heat capacity than N_2 . All the blends revealed three mass loss peaks that were close to MSW, but the CSB combustion only had two mass loss stages in the CO_2/O_2 atmosphere.

The mass loss rate of the first two mass loss peaks all decreased with the CSB mass percentage increases. The temperatures according to the second and third peaks at the CSB mass ratio of 80% both were more than 30 °C higher than the other blends because of the contribution of CSB to the blend. This phenomenon was similar to that of 80C20M under N₂/O₂ atmosphere. As shown in Table 3, the index *S* of blends declined from 18.23 to 9.84 (×10⁻⁰⁷min⁻² °C⁻³) with the increase of CSB ratio. Considering the ignition characteristic, burnout characteristic, and index *S*, the blending of MSW with CSB could improve the comprehensive combustion characteristics to some extent under CO₂/O₂ atmosphere when the CSB mass percentage was less than 40% in the blend.

Interaction of MSW with CSB under N₂/O₂ and CO₂/O₂ Atmosphere

In order to evaluate the possible synergistic interaction between MSW and CSB, the theoretical TG (TG_{CAL}) and DTG curves (DTG_{CAL}) of the blends were calculated by the arithmetic weighted average of the individuals, which could be stated as follows (Hu *et al.* 2015; *Peng et al.* 2015),

$$W_{\text{total}} = \lambda_{MSW} W_{MSW} + \lambda_{CSB} W_{CSB} \tag{9}$$

where λ_{MSW} and λ_{CSB} were the mass ratio of MSW and CSB in the blends, and W_{MSW} and W_{CSB} were the mass loss or mass loss rate of MSW and CSB, respectively.

The parameter ΔTG ($\Delta TG = TG_{EXP} - TG_{CAL}$) was introduced to compare and evaluate the degree of deviation between the calculated and experimental results, where TG_{EXP} was the experimental TG curves. Figures 4a and 4b display the ΔTG curves of blends under the N₂/O₂ and CO₂/O₂ atmospheres, respectively. All the ΔTG curves of blends presented the similar variation tendency, and the deviations at high-temperature stage were substantially larger than that of low-temperature stage. The experimental TG curves at different CSB mass ratios were all under the calculated TG curves at above 465.3 °C in N_2/O_2 atmosphere and 311.2 °C in N_2/O_2 atmosphere, and the mass loss of calculated TG curves were lower than those of experimental ones. This phenomenon could be explained as the synergistic interaction during the co-combustion of MSW and CSB. Two maximum peaks and two minimum peaks were observed in all ΔTG curves of blends, and the corresponding temperature were about 297 °C, 445 °C, 366 °C, and 493 °C under the N₂/O₂ atmosphere and around 429 °C, 560 °C, 368 °C, and 514 °C under the CO₂/O₂ atmosphere. The lag of peak temperature was attributed to the negative effect on the combustion reaction in the CO₂/O₂ atmosphere. In conclusion, the above analysis indicated that the interaction effects of MSW and CSB co-combustion at high temperature were relatively intense, and the greater influence of interaction occurred at the proportions of CSB of 40% and 50% under both atmospheres.

Figures 4c and 4d show that the calculated and experimental DTG curves when the mass ratio of CSB were 40% and 50% under both atmospheres, respectively. The profiles of each two DTG curves were consistent throughout the combustion process except for a large gap around the peaks of DTG curves, where the experimental mass loss rates were higher than that of calculated ones and the peaks of experimental DTG curve appeared in advance compared to the calculated DTG curve. As shown in Figs. 4c and 4d, the deviations between the calculated and experimental DTG curves mainly occurred in the range 300 to 600 °C, which corresponded with the temperature range of two maximum peaks and two minimum peaks of ΔTG curves under the two atmospheres. This further demonstrated that there was a synergistic effect between the MSW and CSB co-combustion rather than the weighted average of the two individual compounds. Similar interactions in the study of co-combustion of MSW and paper mill sludge, or MSW and oil shale were also obtained by Hu *et al.* (2015) and Fan *et al.* (2016), respectively.



Fig. 4. Δ TG curves of blends at different mass ratios in N₂/O₂ atmosphere (a) and CO₂/O₂ atmosphere (b); the comparison of calculated and experimental DTG curves at mass ratio of CSB were 40% and 50% in N₂/O₂ atmosphere (c) and CO₂/O₂ atmosphere (d)

The mechanism of synergistic interactions between MSW and CSB during cocombustion process needed to be investigated. The content of volatile matter in MSW was higher than that of CSB, as shown in Table 1. The combustion of volatile matter generated enormous heat, which promoted char burning of CSB, whose thermal decomposition occurred at higher temperature. Therefore, the mass loss rate of blends and temperature corresponding to the mass loss peak was most advanced with the increased mass ratio of MSW. In contrast, Huang et al. (2014) found that large quantities of catalytic components (such as KCl, KSO, etc.) were contained in the ash of cotton straw. The addition of CSB to MSW had the similar role of catalysts in the combustion process of MSW, and the catalysts induced the weakening of intermolecular interaction in polymeric chains. Thus, the concentrations of volatile gases around MSW increased, and the ignition temperature of blends was decreased as the proportion of CSB increased. In addition, when oxygen was absorbed in the surface of catalysts, activated oxygen spills would be released to react with MSW char at a lower temperature (Shen and Lei 2006). Therefore, the burnout temperature of blends was lower than that of individual MSW under N_2/O_2 atmosphere, but this phenomenon was not the same as in CO_2/O_2 atmosphere. A possible cause for this might be that the interaction was influenced by the atmosphere, and further studies on the mechanism of this synergistic interaction were needed by experimental design. As a result, the synergistic interactions in the co-combustion process of MSW and CSB were thought to result from the combined action of individual components, and the co-combustion of MSW and CSB could implement the co-processing of two solid wastes.

Kinetic Analysis

Using only one simple dynamic reaction model is not adequate for interpreting complicated co-combustion process of MSW and CSB, and thus the Coats-Redfern method was adopted to obtain the kinetic parameters and correlation coefficients under nth order reaction model under two atmospheres (Table 4). The coefficients of determination values of R^2 were all between 0.9406 and 0.9972, reflecting that the nth order reaction model was appropriate, and the calculated parameters were credible. The combustion of pure MSW and pure CSB both exhibited three steps under N₂/O₂ atmosphere, for which the activation energies values of *E* were 82.88, 26.68, and 90.26 kJ/mol and 42.58, 5.17, and 84.25 kJ/mol, respectively. The *E* values of CSB in three stages were all lower than that of MSW, explaining the reason why the ignition and burnout temperature of CSB were lower than that of MSW. A similar phenomenon was also found under CO₂/O₂ atmosphere.

The values of *E* for MSW were in agreement with those obtained by Liu *et al.* (2009) and Lai *et al.* (2011) of MSW ranged from 65.6to137.87 kJ/mol for the first stage, 55to80.18 kJ/mol for the second step, and 7.4to155.17 kJ/mol for the last reaction, respectively. The reaction orders of MSW were also close to that reported in the abovementioned studies. However, the activation energies and reaction orders of CSB were all lower than that obtained by El-Sayed and Mostafa (2014). The variability of kinetic parameters was affected by the differences in materials, operating facility, method, sample size, and others in experiments.

		The	age			The se	econd s	stage		The third stage					
Samples	TR ^a (°C)	<i>E</i> ⁵ (kJ/mol)	nc	<i>A</i> ^d (min⁻¹)	R^{2e}	TRª (°C)	<i>E</i> ⁵ (kJ/mol)	nc	A ^d (min⁻¹)	R^{2e}	<i>TR</i> ª (°C)	<i>E</i> ⁵ (kJ/mol)	nc	A ^d (min⁻¹)	R^{2e}
Under N ₂ /O ₂ atmosphere															
MSW	243-378	82.88	3.94	4.5×10 ⁷	0.9665	378-455	26.68	1.21	109.8	0.9406	455-575	90.26	1.56	1.6×10 ⁷	0.9873
20C80M	241-379	82.53	3.77	4.2×10 ⁷	0.9733	379-448	29.39	1.53	235.5	0.9466	450-571	79.62	1.50	2.5×10 ⁶	0.9931
40C60M	236-381	73.22	3.11	5.2×10 ⁶	0.9751	381-449	30.11	1.64	303.4	0.9509	449-572	88.10	1.55	1.2×10 ⁷	0.9925
50C50M	228-381	64.15	2.52	7.0×10⁵	0.9752	381-446	35.26	2.10	1.2×10 ³	0.9569	446-575	114.15	1.93	1.6×10 ⁹	0.9907
60C40M	223-385	57.44	2.11	1.6×10⁵	0.9753	384-444	42.79	2.58	7.5×10 ³	0.9652	444-560	67.61	1.35	3.1×10⁵	0.9922
80C20M	219-386	56.52	2.09	1.3×10⁵	0.9781	386-505	7.60	0.90	0.8	0.9654	505-557	101.44	1.65	1.4×10 ⁸	0.9543
CSB	203-390	42.58	1.16	5.6×10 ³	0.9690	390-486	5.17	0.16	0.4	0.9943	486-557	84.25	1.52	7.7×10 ⁶	0.9502
Under CO	2/O2 atmos	phere	-												
MSW	244-379	91.20	4.72	3.0×10 ⁸	0.9625	379-456	19.24	0.64	17.0	0.9602	456-588	67.59	1.44	2.7×10⁵	0.9958
20C80M	238-381	74.64	3.71	8.4×10 ⁶	0.9698	381-452	22.94	1.17	51.2	0.9614	452-585	68.79	1.49	3.6×10⁵	0.9972
40C60M	237-379	74.30	3.48	7.3×10 ⁶	0.9759	379-449	33.83	1.97	747.9	0.9478	449-590	94.38	1.82	4.2×10 ⁷	0.9960
50C50M	230-384	67.07	3.28	1.7×10 ⁶	0.9765	384-446	32.66	1.95	626.8	0.9630	446-615	106.14	2.14	5.1×10 ⁸	0.9820
60C40M	228-383	64.18	2.91	8.2×10⁵	0.9726	383-444	28.41	1.82	246.8	0.9693	444-604	154.69	2.60	2.9×10 ¹²	0.9906
80C20M	220-387	55.32	2.31	1.1×10⁵	0.9715	387-514	8.02	0.17	0.9	0.9768	514-578	125.57	2.03	1.1×10 ¹⁰	0.9650
CSB	208-395	42.32	1.49	5.8×10 ³	0.9675	395-560	8.87	0.45	1.5	0.9966	-	-	-	-	-

Table 4. Kinetic Parameters and Correlation Coefficients for All the Samples

^a*TR*, temperature range; ^b*E*, apparent activation energy; ^c*n*, reaction order; ^d*A*, Arrhenius pre-exponential factor; ^e*R*², coefficients of determination.

For the blends under two atmospheres, all runs were similar to MSW with three reaction stages. The value of activation energy, pre-exponential factor, and reaction order in the first stage all showed a trend of monotonous reduction as the mass ratio of CSB increased in blends. The activation energy in the second stage had an increasing tendency at first, and then decreased gradually as the proportion of CSB increased. The activation energy of blends were up to the maximum of 42.79 kJ/mol at CSB mass ratio of 60% under theN₂/O₂ atmosphere and 33.83 kJ/mol at the 40C60M blend under theCO₂/O₂ atmosphere, while the activation energy of 80C20M under the two atmospheres were all close to that of CSB. The variation trends of pre-exponential factor and reaction order of blends in the second stage were close to that of activation energy. Unlike the aforesaid two stages, the activation energy, pre-exponential factor, and reaction order in the third stage all changed complexly under the N_2/O_2 atmosphere but raised to peaks at 60C40M blend firstly and decreased afterwards under the CO₂/O₂ atmosphere. These phenomena might be attributed to the complicated synergistic interaction during the co-combustion process of MSW and CSB (Lin et al. 2015). As a whole, the blending of MSW with CSB could decrease the kinetic parameters of blends on some level, and the good correlation coefficients indicated that the nth order reaction model could excellently fit the experimental results by the three stages reaction.

CONCLUSIONS

- 1. The ignition and burnout characteristics of blends were improved by adding CSB into MSW, while the comprehensive combustibility index *S* decreased as the CSB ratio increased in the blends. The suitable mass ratios of CSB were less than 60% under the $80N_2/20 O_2$ atmosphere and less than 40% under the $80CO_2/20O_2$ atmosphere.
- 2. The mass loss percentages of blends in the CO_2/O_2 atmosphere were lower than that in the N_2/O_2 environment at the same ratio of CSB, and the burnout temperature was higher than in the N_2/O_2 environment. The replacement of N_2 by CO_2 had negative effect on burnout temperature, residual mass and high-temperature region combustion.
- 3. The synergistic interactions between MSW and CSB co-combustion were relatively intense at high temperature, and the greater influence of interaction occurred when the proportion of CSB was 40% and 50% under both atmospheres.
- 4. The combustion process of blends was divided into three stages. The synergistic interaction between MSW and CSB promoted activation energy of blends reduced in the first reaction stage, and it complicated the activation energy in the subsequent two reaction stages. The high correlation coefficients values reflected that nth order reaction model was appropriate for describing the weight loss process of blends.

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REFERENCES CITED

- Alongi, J., Ciobanu, M., Tata, J., Carosio, F., and Malucelli, G. (2011). "Thermal stability and flame retardancy of polyester, cotton, and relative blend textile fabrics subjected to sol–gel treatments," *Journal of Applied Polymer Science* 119(4), 1961-1969. DOI 10.1002/app.32954
- Branca, C., and Blasi, C. D. (2015). "A lumped kinetic model for banana peel combustion," *Thermochimica Acta* 614, 68-75. DOI: 10.1016/j.tca.2015.06.022
- Brems, A., Baeyens, J., Vandecasteele, C., and Dewil, R. (2011). "Polymeric cracking of waste polyethylene terephthalate to chemicals and energy," *Journal of the Air and Waste Management Association* 61(7), 721-31. DOI: 10.3155/1047-3289.61.7.721
- Chirone, R., Salatino, P., Scala, F., Solimene, R., and Urciuolo, M. (2008). "Fluidized bed combustion of pelletized biomass and waste-derived fuels," *Combustion and Flame* 155(1), 21-36. DOI: 10.1016/j.combustflame.2008.05.013
- Cui, H., Yang, J., and Liu, Z. (1999). "Thermogravimetric analysis of two Chinese used tires," *Thermochimica Acta* 333(2), 173-175. DOI: 10.1016/S0040-6031(99)00119-7
- El-Sayed, S. A., and Mostafa, M. E. (2014). "Pyrolysis characteristics and kinetic parameters determination of biomass fuel powders by differential thermal gravimetric analysis (TGA/DTG)," *Energy Conversion and Management* 85(9), 165-172. DOI: 10.1016/j.enconman.2014.05.068
- Fang, S., Yu, Z., Lin, Y., Hu, S., Liao, Y., and Ma, X. (2015). "Thermogravimetric analysis of the co-pyrolysis of paper sludge and municipal solid waste," *Energy Conversion and Management* 101, 626-631.DOI: 10.1016/j.enconman.2015.04.026
- Fan, Y. L., Yu, Z. S., Fang, S. W., Lin, Y., Liao, Y., and Ma, X. (2016). "Investigation on the co-combustion of oil shale and municipal solid waste by using thermogravimetric analysis," *Energy Conversion and Management*117, 367-374. DOI: 10.1016/j.enconman.2016.03.045
- Ge, P., Zhu, W. L., Zhou, H. P., Lei, Q., Zhang, Z. R., and Liu, J. J. (2015). "Cocombustion characteristics of inferior coal and biomass blends in an oxygen-enriched atmosphere," *BioResources* 10(1), 1452-1461.DOI: 10.15376/biores.10.1.1452-1461
- Gil, M. V., Oulego, P., Casal, M.D., Pevida, C., Pis, J. J., and Rubiera, F. (2010).
 "Mechanical durability and combustion characteristics of pellets from biomass blends," *Bioresource Technology* 101(22), 8859-8867. DOI: 10.1016/j.biortech.2010.06.062
- Grover, P. D., and Mishra, S. K. (1996). *Biomass Briquetting: Technology and Practices* (Field Document No. 46), Food and Agriculture Organization of the United Nations, Bangkok, Thailand.
- Hees, J., Zabrodiec, D., Massmeyer, A., Habermehl, M., and Kneer, R. (2016).
 "Experimental investigation and comparison of pulverized coal combustion in CO₂/O₂ and N₂/O₂atmospheres," *Flow, Turbulence and Combustion* 96(2), 417-431. DOI: 10.1007/s10494-015-9662-9
- Henry, R. K., Zhao, Y., and Jun, D. (2006). "Municipal solid waste management challenges in developing countries – Kenyan case study," *Waste Management* 26(1), 92-100. DOI: 10.1016/j.wasman.2005.03.007
- Houshfar, E., Skreiberg, Ø., Løvås, T., Todorović, D., and Sørum, L. (2011). "Effect of excess air ratio and temperature on NOx emission from grate combustion of biomass in the staged air combustion scenario," *Energy & Fuels* 25(10), 4643-4654. DOI: 10.1021/ef200714d

- Huang, S., Wu, S., Wu, Y., and Gao, J. (2014). "The physicochemical properties and catalytic characteristics of different biomass ashes," *Energy Sources Part A Recovery Utilization and Environmental Effects* 36(36), 402-410(9). DOI: 10.1080/15567036.2012.722746
- Hu, S., Ma, X., Lin, Y., Yu, Z., and Fang, S. (2015). "Thermogravimetric analysis of the co-combustion of paper mill sludge and municipal solid waste," *Energy Conversion* and Management 99, 112-118. DOI: 10.1016/j.enconman.2015.04.026
- Lai, Z. Y., Ma, X. Q., Tang, Y. T., and Lin, H. (2011). "A study on municipal solid waste (MSW) combustion in N₂/O₂ and CO₂/O₂ atmosphere from the perspective of TGA," *Energy* 36(2), 819-824. DOI: 10.1016/j.energy.2010.12.033
- Lai, Z., Ma, X., Tang, Y., Lin, H., and Chen, Y. (2012). "Thermogravimetric analyses of combustion of lignocellulosic materials in N₂/O₂ and CO₂/O₂ atmospheres," *Bioresource Technology* 107, 444-450. DOI: 10.1016/j.biortech.2011.12.039
- Larsson, S. H., Thyrel, M., Geladi, P., and Lestander, T. A. (2008). "High quality biofuel pellet production from pre-compacted low density raw materials," *Bioresource Technology* 99, 7176-7182. DOI: 10.1016/j.biortech.2007.12.065
- Li, A., Liu, H. L., Wang, H., Xu, H. B., Jin, L. F., Liu, J. L., and Hu, J. H. (2016).
 "Effects of temperature and heating rate on the characteristics of molded bio-char," *BioResources* 11(2), 3259-3274. DOI: 10.15376/biores.11.2.3259-3274
- Liao, Y., and Ma, X. (2010). "Thermogravimetric analysis of the co-combustion of coal and paper mill sludge," *Applied Energy* 87(11), 3526-3532. DOI: 10.1016/j.apenergy.2010.05.008
- Lin, Y., Ma, X., Yu, Z., and Cao, Y. (2014). "Investigation on thermochemical behavior of co-pyrolysis between oil-palm solid wastes and paper sludge," *Bioresource Technology* 166(8), 444-450. DOI: 10.1016/j.biortech.2014.05.101
- Lin, Y., Ma, X., Ning, X., and Yu, Z. (2015). "TGA-FTIR analysis of co-combustion characteristics of paper sludge and oil-palm solid wastes," *Energy Conversion and Management* 89, 727-734. DOI: 10.1016/j.enconman.2014.10.042
- Liu, G., Ma, X., and Yu, Z. (2009). "Experimental and kinetic modeling of oxygenenriched air combustion of municipal solid waste," *Waste Management* 29(2), 792-6. DOI: 10.1016/j.wasman.2008.06.010
- Liu, H., and Okazaki, K. (2003). "Simultaneous easy CO₂ recovery and drastic reduction of SOx and NOx in O₂/CO₂ coal combustion with heat recirculation," *Fuel* 82(11), 1427-1436. DOI: 10.1016/S0016-2361(03)00067-X
- Liu, S., Wang, Y., Bai, B., Su, C., Yang, G., and Zhang, F. (2011). "Analysis on combustion kinetics of corn stalk briquetting densification fuel," *Transactions of the Chinese Society of Agricultural Engineering* 27(9), 287-292. DOI: 10.3969/j.issn.1002-6819.2011.09.050
- Liu, Y., Wang, X., Xiong, Y., Tan, H., and Niu, Y. (2014). "Study of briquetted biomass co-firing mode in power plants," *Applied Thermal Engineering* 63(1), 266-271. DOI: 10.1016/j.applthermaleng.2013.10.041
- Molina, A., and Shaddix, C. R. (2007). "Ignition and devolatilization of pulverized bituminous coal particles during oxygen/carbon dioxide coal combustion," *Proceedings of the Combustion Institute* 31(2), 1905-1912. DOI: 10.1016/j.proci.2006.08.102
- Obernberger, I., and Thek, G. (2004). "Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behavior," *Biomass and Bioenergy* 27(6), 653-669. DOI: 10.1016/j.biombioe.2003.07.006

- Oyedun, A. O., Tee, C. Z., Hanson, S., and Chi, W. (2014). "Thermogravimetric analysis of the pyrolysis characteristics and kinetics of plastics and biomass blends," *Fuel Processing Technology* 128, 471-481. DOI: 10.1016/j.fuproc.2014.08.010
- Peng, X., Ma, X., and Xu, Z. (2015). "Thermogravimetric analysis of co-combustion between microalgae and textile dyeing sludge," *Bioresource Technology* 180, 288-95. DOI: 10.1016/j.biortech.2015.01.023
- Ren, Q., Zhao, C., Wu, X., Liang, C., Chen, X., Shen, J., and Wang, Z. (2009). "TG-FTIR study on co-pyrolysis of municipal solid waste with biomass," *Bioresource Technology* 100(17), 4054-4057. DOI: 10.1016/j.biortech.2009.03.038
- Roy, M. M., Dutta, A., and Corscadden, K. (2013). "An experimental study of combustion and emissions of biomass pellets in a prototype pellet furnace," *Applied Energy*108, 298-307. DOI: 10.1016/j.apenergy.2013.03.044
- Shen, B., and Lei, Q. (2006). "Study on MSW catalytic combustion by TGA," *Energy Conversion and Management* 47(11–12), 1429-1437. DOI: 10.1016/j.enconman.2005.08.016
- Skodras, G., Grammelis, P., Basinas, P., Kakaras, E., and Sakellaropoulos, G. (2006). "Pyrolysis and combustion characteristics of biomass and waste-derived feedstock," *Industrial and Engineering Chemistry Research* 45(11), 3791-3799. DOI: 10.1021/ie060107g
- Tabarés, J. L. M., Ortiz, L., Granada, E., and Viar, F. P. (2000). "Feasibility study of energy use for densificated lignocellulosic material (briquettes)," *Fuel* 79(10), 1229-1237. DOI: 10.1016/S0016-2361(99)00256-2
- Tang, Y. T., Ma, X. Q., and Lai, Z. Y. (2011). "Thermogravimetric analysis of the combustion of microalgae and microalgae blended with waste in N₂/O₂ and CO₂/O₂ atmospheres," *Bioresource Technology* 102(2), 1879-85.DOI: 10.1016/j.biortech.2010.07.088
- Tang, Y. T., Ma, X. Q., Lai, Z. Y., and Fan, Y. (2015). "Thermogravimetric analyses of co-combustion of plastic, rubber, leather in N₂/O₂ and CO₂/O₂ atmospheres," *Energy* 90, 1066-1074.DOI: 10.1016/j.energy.2015.08.015
- Tian, Y., Ma, Z., Xu, Q., and Min, Z. (2013). "Features of biomass-waste co-combustion and environmental analysis," *Chinese Agricultural Science Bulletin* 29(35), 193-198. DOI: 10.11924/j.issn.1000-6850.2013-0143
- Wang, X., Li, D. K., Ni, W. D., Li, Z., and Zhang, H. D. (2007). "Combustion properties of pelletized biomass," *Journal of Combustion Science and Technology* 13(1), 86-90. DOI: 10.3321/j.issn:1006-8740.2007.01.018
- Zhou, H., Long, Y., Meng, A., Li, Q., and Zhang, Y. (2015). "Thermogravimetric characteristics of typical municipal solid waste fractions during co-pyrolysis," *Waste Management* 38(1), 194-200. DOI: 10.1016/j.wasman.2014.09.027

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