Combustion Characteristics of Cattle Manure and Pulverized Coal Co-firing under Oxy-Fuel Atmosphere in Non-Isothermal and Isothermal Conditions

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Combustion characteristics of cattle manure (CM) and pulverized coal blends under oxy-fuel atmosphere were considered. Factors such as the furnace temperature, O_2 concentration, and blending ratio were analyzed. The experiment under non-isothermal and isothermal conditions were used to study effects of the heating rate. Blended CM can improve the combustion characteristics of pulverized coal. However, a difference exists between the increase of the blending ratio of CM with Shanxi bituminous coal (SX) and Xiaolongtan lignite coal (XLT) under various O_2 concentration conditions. More attention should be paid to the blending ratio > 50%. CM and coal co-firing affected by the furnace temperature had a close association with its characteristics. Inhibition was found in most conditions, and the trend of interaction between CM and coal under the non-isothermal and isothermal condition was consistent. These experiments provided information for the utilization of livestock and poultry manure and pulverized coal blends in the oxy-fuel atmosphere.

Keywords: Cattle manure; Combustion characteristic; Coal/biomass co-firing; Isothermal condition; Oxy-fuel

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INTRODUCTION

With the recent flourish of the cattle industry and increasing numbers of large-scale cattle farms, the daily number of tons of cattle manure is far beyond the self-purification capacity of the environment. More importantly, the environmental problems caused by cattle manure have hindered the healthy development of the cattle industry.

A common consequence of livestock and poultry manure include composting and energy utilization (Cantrell *et al.* 2008; Santos Dalólio *et al.* 2017). The former is simple and low cost, but it needs a long time and a large occupation area (Fernandez-Lopez *et al.* 2015). Biological conversion, as a kind of energy utilization, needs a small occupation area and a low cost, but the process is long and unstable. However, the low purity of product gas makes it difficult to achieve high value utilization. The heat treatment is a short process, but high energy is needed (Santos Dalólio *et al.* 2017). In comparison, due to a small occupation area, the heat treatment is especially suitable for the treatment of livestock and poultry waste pollution in a large scale. In addition, with its little impact on surrounding environment, heat treatment is a promising development direction for large-scale farms in dealing with livestock and poultry manure.

Heat treatment technology includes pyrolyzation, gasification, and combustion (Cantrell *et al.* 2008; Santos Dalólio *et al.* 2017; Yi *et al.* 2018a,b). Combustion technology has the advantages of few flue gas products and easy management (Dávalos *et al.* 2002). Due to a high water content and ash content, and low heating value for livestock and poultry manure, direct combustion is prone to instability (Dávalos *et al.* 2002). Alkali and alkaline earth metal (AAEM) species in cattle manures exert both positive and negative effects on combustion (Yi *et al.* 2018a). Co-firing with pulverized coal can reduce the combustion instability, improve the combustion reactivity, and decrease the phenomenon of fouling and slag (Kim *et al.* 2015; Yurdakul 2016; Junga *et al.* 2017). Therefore, the blending ratio is an important parameter related to the combustion efficiency of the livestock and poultry manure. However, there are conflicting reports on the effects of the blending ratio in the biomass and coal co-firing (Kim *et al.* 2015; Yurdakul 2016; Junga *et al.* 2017; Zhu *et al.* 2017). Detecting the effective mechanism of the blending ratio on combustion is an important issue for optimizing the combustion process.

Santos Dalólio *et al.* (2017) suggested a broad prospect for the energy conversion from livestock and poultry manure, but the emission of harmful gases should be researched. Therefore, control of pollutants is an important part of energy utilization for the co-firing of poultry manure blends. Oxy-fuel combustion technology involves the use of pure O_2 blended with recycled flue gas instead of combustion air. Both the avoidance of N_2 through air separation system and the flue gas recycling contribute to a reduction in the volume of flue gas, which is beneficial for the enrichment and control of pollutants (Zheng *et al.* 2015). This is a new method to improve efficiency by adjustable O_2 concentration when applying oxy-fuel combustion technology to livestock and poultry manure blends. Therefore, to study appropriate blending ratio for livestock and poultry manure under various oxy-fuel condition was significant for the co-firing economy and competitiveness.

The oxy-fuel combustion of livestock and poultry manure has two steps, and it has a different effect on the combustion by the CO_2 in the atmosphere (López-González *et al.* 2017). During the release of volatile matter, CO_2 has no significant effect on this process. However, in the char combustion step, the low heat transfer coefficient of CO_2 leads to the delay of char oxidation. There are extensive studies on biomass and pulverized coal blends under oxy-fuel conditions (Pickard *et al.* 2014; Liu *et al.* 2015; Pu *et al.* 2015). Biomass blended with pulverized coal under oxy-fuel conditions generally has a catalytic effect (Bhuiyan and Naser 2016), but some studies have shown a negative effect on combustion efficiency (Pickard *et al.* 2014). There may be reduced pollutant discharge for co-firing (Pu *et al.* 2017) or enhanced corrosion in this system (Jurado *et al.* 2014). The contradictions in the experimental data may be due to the different blending of samples or the different reaction conditions. Therefore, co-firing of biomass and pulverized coal blends needs to be studied for specific fuels under specific conditions.

Thermogravimetry (TG) is the most common method for analyzing the combustion characteristics of fuel (Cheng *et al.* 2014; Yi *et al.* 2014; Yurdakul 2016; Yi *et al.* 2018a, b). A slight difference between isothermal and non-isothermal combustion has been observed in previous studies (Chen *et al.* 2015). An isothermal TG experiment with a high heating rate may be closer to the actual situation (Skreiberg *et al.* 2011; Wang *et al.* 2016; Yi *et al.* 2018b). Therefore, two methods including the non-isotherm and isotherm experiment were used in the study of combustion characteristics.

To promote sustainable development, livestock and poultry manure and pulverized coal co-firing have a good application prospects. Using oxy-fuel combustion technology in the co-firing system is beneficial to control the pollutant and adjust combustion characteristics. There are few studies on the co-firing characteristics of these materials. The factors such as furnace temperature, O_2 concentration, and blending ratio were studied in this paper. This data is expected to provide a reference for the utilization of livestock and poultry manure and pulverized coal blends in an oxy-fuel atmosphere.

EXPERIMENTAL

Materials

Cattle manure (CM), as a typical livestock and poultry manure, was chosen for this study. Fresh CM was taken from Wuhan Jiangxia District Crusades Animal Husbandry Limited Liability Company (Wuhan, China). Shanxi bituminous coal (SX) and Xiaolongtan lignite coal (XLT) were chosen as the typical pulverized coal. All samples were dried at 105 °C for 24 h after primary crushing and fine crushing. They were placed in dry dishes after sieving through 60-mesh sieves. The proximate analysis, elemental analysis, and higher heating value (HHV) are shown in Table 1. Compared with coal, CM had a high ash, low fixed carbon, high O contents, and a low HHV.

Table 1. Proximate Analysis, Ultimate Analysis, and HHV of Samples

Sample	Proximate Analysis (wt.%.ad)				Ultimate Analysis (wt.%.daf)					HHV(MJ/kg)
	M	V	A	FC	C	H	O[1]	N	S	
XLT	8.25	42.23	6.20	43.32	66.11	5.15	25.95	1.88	0.91	23.801
SX	4.36	30.40	5.61	59.63	80.68	5.13	11.56	2.31	0.32	30.299
CM	9.49	45.80	32.19	12.52	41.13	5.89	49.92	2.69	0.37	13.426

Note: ad- air dry basis; daf- dry ash-free basis; M, moisture; V, volatile matter; A, ash; and FC, fixed carbon

[1]: Calculated by difference

Methods

The thermogravimetry equipment was described previously (Yi *et al.* 2018b). The non-isothermal experimental process was performed as follows. First, 200 mg ± 0.2 mg of the sample was placed in a quartz boat, which was placed in a furnace with a temperature program. The furnace was heated to 800 °C from room temperature at 20 °C/min under an O_2/CO_2 atmosphere, and the total gas flow rate was 1 L/min. In the isothermal experimental process, the furnace temperature was raised to the experimental temperature, and then the experimental gas was pumped into the furnace at a gas flow rate of 1 L/min. A quartz basket equipped with the sample was moved quickly to the center of the furnace.

Characteristic parameters

The ignition temperature (T_{ig}), the temperature of the maximum combustion rate (T_{max}), and the burnout temperature (T_b) were examined, as previously described (Li *et al.*2009; Yi *et al.* 2018b). To more completely reflect the combustion characteristics of biomass, the onset temperature of volatiles released were written by T_o, the peak of volatile matter released and its corresponding temperature were chosen, and those were written by $(dw/dt)_{vm}$ and (T_{vm}), respectively. The peak of char combustion process and its corresponding temperature was written as $(d_w/d_t)_{char}$ and (T_{char}). The comprehensive index of combustion characteristics (S) was defined to reflect the comprehensive characteristics of biomass ignition and burnout. A larger value of S indicates better combustion (Yi *et al.* 2014, 2018b). S was calculated using Eq. 1,

$$S=\frac{(d_w/d_t)_{\max}\times(d_w/d_t)_{\text{mean}}}{T_{\text{ig}}^2\times T_b} \quad (1)$$

where $(d_w/d_t)_{max}$ is the rate of maximum weight loss and $(d_w/d_t)_{mean}$ is the average weight loss rate between the ignition and burn point. Under the isothermal experiment, the data processing method was similar to previous reports (Yi *et al.* 2018b). T_{ig}, T_{max}, and T_b were replaced by t_{ig} , t_{max}, t_b, which represent the ignition time, the time of the maximum combustion rate, and the burnout time, respectively.

To determine the influence of various factors on the various stages of the combustion process, the stability factor (S_{sf}) was chosen for analysis of the non-isothermal experiment (Wang *et al.* 2014). The S_{sf} is the ratio of the burnout time to the peak value of the excessive combustion curve, as shown in Eq. 2.

$$S_{\text{sf}}=\frac{t_b}{(d_w/d_t)_{\max}} \quad (2)$$

A larger S_{sf} indicates a closer overall weight loss to the curve of average weight loss, suggesting a more stable state throughout the combustion process. Excessive combustion curve reflects the difference between the assumed average weight loss line and the actual weight loss line. Among those, the assumed average weight loss line is obtained through direct ligature from the start to the end.

Kinetic analysis methods

Fuel combustion involved a series of chemical and physical processes. Dynamic analysis was completed to compare the reaction of priority (Wang *et al.* 2012; Yi *et al.* 2014). The Arrhenius law is expressed in Eq. 3,

$$\frac{d\alpha}{dT} = k \cdot (1-\alpha)^n \quad (3)$$

where k is the constant of the combustion reaction rate and α is the sample conversion rate.

$$k = Ae^{-E/RT} \quad (4)$$

$$\beta = dT/dt \quad (5)$$

Using Eqs. 4 and 5, Eq. 3 can be transformed as follows:

$$\frac{d\alpha}{dT} = \frac{A}{\beta}e^{-E/RT}(1-\alpha)^n \quad (6)$$

Applying the Coats-Redfern integral method (Coats and Redfern 1964) yields the following approximation:

$$\text{If n}\neq 1,\ ln\left|\frac{1-(1-\alpha)^{1-n}}{T^2(1-n)}\right| = ln\left[\frac{AR}{\beta E}(1-\frac{2RT}{E})\right] - \frac{E}{RT} \quad (7)$$

$$\text{If n}=1,\ ln\left|\frac{\ln(1-\alpha)}{T^2}\right| = ln\left[\frac{AR}{\beta E}(1-\frac{2RT}{E})\right] - \frac{E}{RT} \quad (8)$$

For the coal and biomass combustion, $E/RT \geq 1$ and $1\text{-}2RT/E \approx 1$. Thus, $ln[AR/\beta E\ (1\text{-}2RT/E)]$ is almost constant, while the coal and biomass combustion process is generally considered a first-order reaction (Wang *et al.* 2012; Yi *et al.* 2014). The Coats-Redfern equation was used to calculate the apparent activation energy (E).

RESULTS AND DISCUSSION

Non-Isothermal Condition

As shown in Fig. 1, the combustion process of CM had three significant stages of dehydration, the release and oxidization of volatile matter, and the combustion of char and more thermally stable components. The corresponding temperatures were from room temperature to 120 °C, 200 °C to 300 °C, and 300 °C to 500 °C, respectively, which is similar to Wang *et al.* (2011). However, the second and third combustion phase did not have an apparent boundary, forming a single peak for the two-pulverized coal. The T_o and T_b of CM was lower than the T_o and T_b of SX, respectively. The rate of volatile matter release and char combustion of CM is higher than that of SX. In comparison, the combustion characteristic of CM is close to that of XLT.

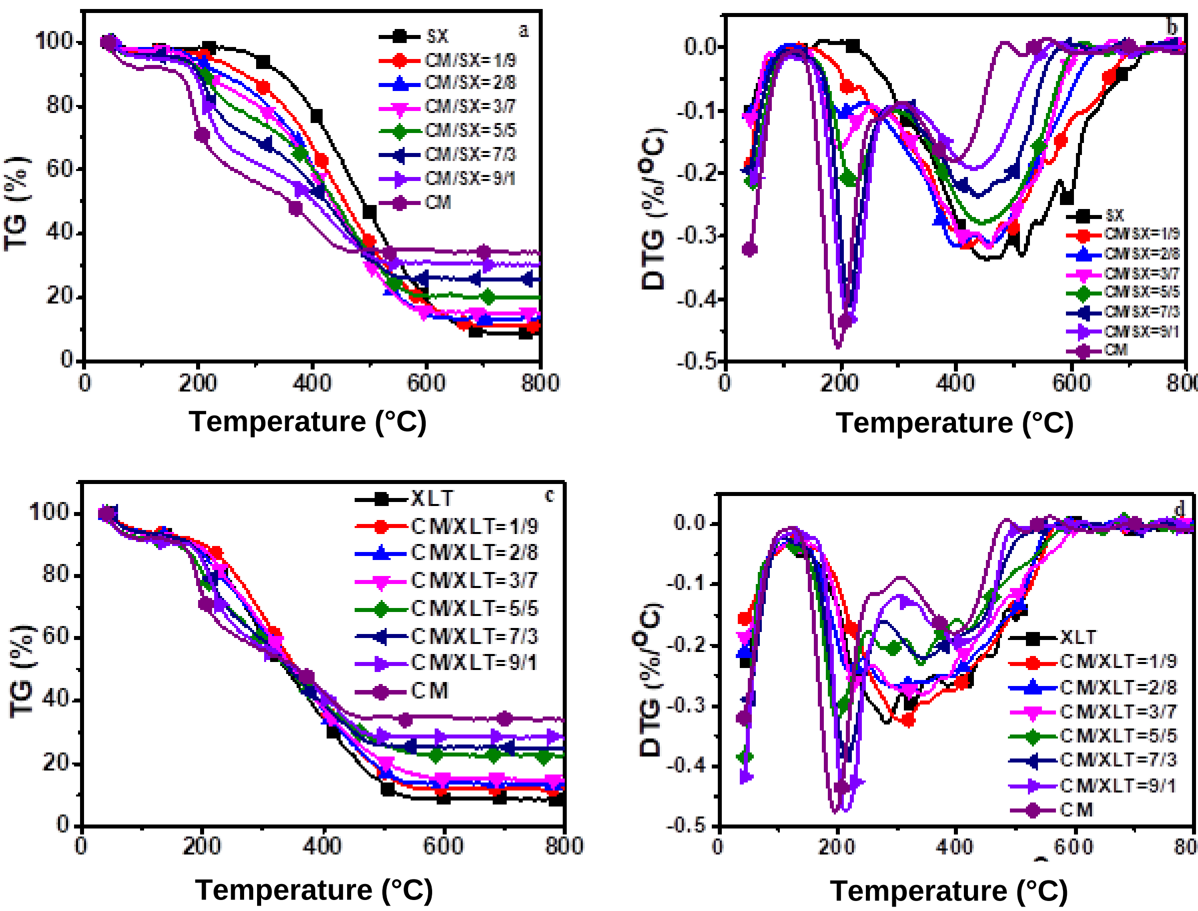

Fig. 1. Combustion behavior of different blending ratios of CM and coal in a non-isothermal conditions under 21% O_2 / 79% CO_2 atmosphere: (a) CM/SX, TG, (b) CM/SX, DTG, (c) CM/XLT, TG, and (d) CM/XLT, DTG

According to the results of the different ratio of CM blended with pulverized coal, the combustion curve was close to the low temperature, and the rate of weight loss decreased as the blended amount of CM in SX coal increased. The $(d_w/d_t)_{vm}$ release gradually increased, but the $(d_w/d_t)_{char}$ decreased. The T_{vm} gradually decreased at the blending ratio less than 30% but increased at the blending ratio of approximately 50% to 90%. The results suggest that the release of volatile matter from CM/SX blends are mainly influenced by high blending ratio of approximately 50% to 90%, which is related to the overlap of pulverized coal and CM. The trend of CM/XLT blends under high blending ratio is similar to the trend of CM/SX blends. However, due to the similar combustion characteristics of CM to the XLT lignite, the influence of the blending ratio on XLT was smaller than that of SX. No significant effect on the combustion characteristic was achieved until the CM blending ratio reached approximately 70% to 90%.

The characteristic parameters from the combustion curve are listed in Table 2. The T_{ig} and T_b values were reduced as the blending ratio of CM increased. The difference of T_{vm} among various blending ratio was less than 20 °C, and the change of weight loss rates ranged from 0.06%/°C to 0.48%/°C. The change of T_{max} of CM/SX blends was less than 30 °C, and the $(d_w/d_t)_{max}$ was in the range from 0.19%/°C to 0.34 %/°C. However, the change of T_{max} of CM/XLT blends was up to 90 °C, and the change of $(d_w/d_t)_{max}$ was in the range from 0.17%/°C to 0.33%/°C. The *S* increased with the increase of CM blending ratio for both of the pulverized coal, and the affect trend is more obvious for SX. The *S* of CM is 3 to 4 times to the *S* of pulverized coal, so the CM had significant improvement of pyrolysis and char combustion characteristic. As the blending ratio increase from 0 to 10% and 30% to 50%, the changes in combustion characteristic are both great. Thus, the blending ratio should be controlled within 30% to minimize the impact on combustion.

Table 2. Combustion Characteristic Parameters of CM/Coal Blends In a Non-Isothermal Condition

Sample	T_{ig} (°C)	T_{vm} (°C)	$(d_w/d_t)_{vm}$ (%/°C)	T_{char} (°C)	$(d_w/d_t)_{char}$ (%/°C)	T_b (°C)	S×10^{-9} [%^{2}/(s^2·°C^3)]
SX	351	-	-	442	0.335	695	0.91
CM/SX 1/9	320	218	0.069	458	0.317	660	1.01
CM/SX 2/8	310	202	0.105	461	0.310	608	1.64
CM/SX 3/7	276	198	0.161	456	0.318	582	1.58
CM/SX 5/5	194	224	0.220	444	0.278	577	2.38
CM/SX 7/3	190	213	0.409	437	0.237	552	3.77
CM/SX 9/1	190	213	0.431	434	0.192	529	3.88
XLT	244	-	-	329	0.298	569	2.03
CM/XLT 1/9	212	-	-	313	0.328	546	3.05
CM/XLT 2/8	212	-	-	287	0.268	534	2.43
CM/XLT 3/7	228	-	-	344	0.280	574	1.8
CM/XLT 5/5	182	199	0.321	341	0.231	564	3.05
CM/XLT 7/3	189	215	0.381	343	0.221	527	3.74
CM/XLT 9/1	194	215	0.474	397	0.198	475	5.16
CM	172	195	0.476	390	0.180	453	6.56

Isothermal Experiment

During actual combustion, the furnace is at a high temperature before the fuel enters. In the next set of experiments, the combustion characteristics were investigated under the constant high temperature conditions.

Influence of temperature

Temperature affects the occurrence of reaction and reactivity. The CM and XLT were combusted at 500, 600, 700, 800, and 900 °C, and the results are shown in Fig. 2. The combustion curve is divided into two distinct sections. The first segment is the rapid reaction area which is mainly the release and combustion of volatile matter. The second segment is the burnt out of char. A rise of temperature made the TG curve of CM move to the low temperature. The change is larger for the temperature from 500 °C to 600 °C. However, the range of curve movements was relatively small as the temperature increased from 700 °C, meaning that the combustion characteristic was achieved well for temperatures above 700 °C.

The T_o of XLT were similar under various temperatures, but it was relatively slow at 500 °C. At 500 °C the weight loss curve of XLT was flat, and there was no obvious turning point on the curve. At the stage of burnout, the combustion rate increased as the furnace temperature increased. The effect of furnace temperature on the combustion rate of pulverized coal lay mainly in the burnout stage. Compared with CM, the combustion of XLT lignite was more significantly affected by furnace temperature in the range of 500 °C to 900 °C. It was related to the fixed carbon content, so the smaller content of low reactive carbon in CM resulted a shorter ignition time. Both the burnout rate of pulverized coal and CM increased as the furnace temperature increased, but the change was smaller because of the decomposition of some minerals (Huang *et al.* 2015).

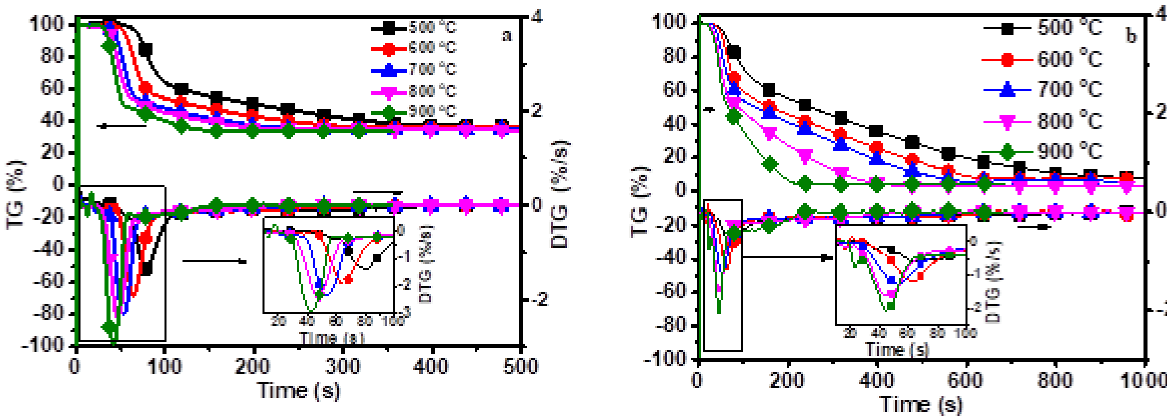

Fig. 2. The combustion behaviour of sample at various temperature in 21% O_2 / 79% CO_2 atmosphere: (a) CM and (b) XLT

The T_{ig}, T_b, S_{sf}, and S of CM and XLT are shown in Table 3. Both T_{ig} and T_b decreased as the furnace temperature increased, so raising the furnace temperature can help increase the combustion rate of fuel.

Table 3. Combustion Characteristic Parameters of CM and XLT at Different Temperature in 21% O_2 / 79% CO_2 Atmosphere

Sample	Temperature (°C)	t_{ig} (s)	t_b (s)	S_{sf} (s/%)	S×10^{-7} (%^{2}/s^5)
CM	500	67	384	14.12	1.51
	600	54	310	9.82	5.02
	700	43	230	7.21	17.55
	800	38	188	4.68	17.62
	900	34	136	4.05	111.39
XLT	500	48	922	33.22	0.28
	600	46	618	20.21	1.37
	700	38	564	16.89	2.66
	800	33	450	13.22	7.74
	900	32	212	7.63	46.62

The S_{sf} decrease indicated the increase of reaction intensity with the increase of furnace temperature. The S increase indicated the reaction rate increases with the increase of furnace temperature. To sum up, the combustion stability of CM is worse than pulverized coal, but its comprehensive reaction is superior to pulverized coal.

Influence of blending ratio

The blending ratio of CM directly affected the physical and chemical characteristics of CM and coal blends, and the influence degree of the combustion characteristics in the later stage also determined the efficiency and economy of the actual application. This blending ratio of CM is 10, 20, 30, 50, 70, and 90%, respectively. The experimental condition was 800 °C and 21% O_2/79% CO_2 atmosphere.

There was no apparent stage for the combustion process of blends under the isothermal condition from Fig. 3. The CM blend to the XLT had less effect on the combustion characteristic than that of blending to SX within 100 s. The inflection point of the combustion curve was moved to the low temperature, which indicated an increase in volatile matter for the blended sample as the addition of CM increased. At the same time, all the combustion curves of weight loss were moved to the low temperature indicating an advance combustion.

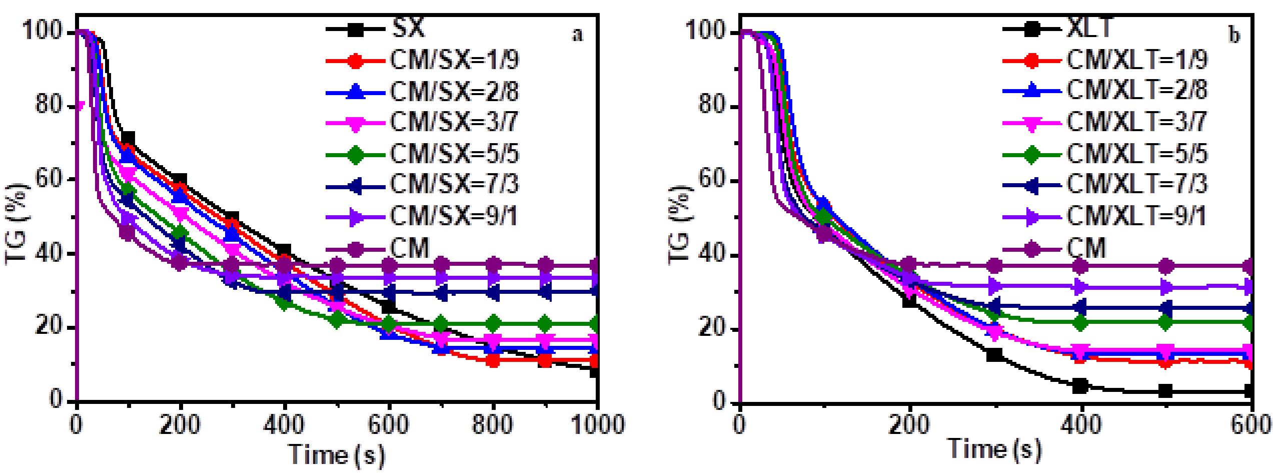

Fig. 3. The combustion behaviour of different blending ratios of CM and coal at 800 °C in 21% O_2 / 79% CO_2 atmosphere: (a) CM/SX and (b) CM/XLT

As shown in Table 4, the T_b became shorter as the CM amount increased. The CM exhibited a higher reactivity than SX for ignition and combustion. At the same time, the heat released from the combustion process of CM promoted its combustion. Secondly, the S_{sf} gradually decreased with the increase of the ratio of CM, indicating that the larger the CM blend, the more violent the combustion reaction. Along with the addition of CM, the effect trend on the XLT was similar with SX. The combustion time was shortened, and the S_{sf} decreased. Moreover, a significant change of S_{sf} and S was shown at approximately 50% to 70% as the increase of the blending ratio of CM with SX and XLT. More attention should occur on the influence of CM on the blended sample when the blending ratio is more than 50%.

Table 4. Combustion Characteristic Parameters of Different Blending Ratios of CM At 800 °C in 21% O_2 / 79% CO_2 Atmosphere

Sample	t_{ig} (s)	t_b (s)	S_{sf} (s)	S×10⁻⁸ (%²/s⁵)
SX	51	986	38.43	3.61
CM/SX 1/9	37	760	31.49	12.82
CM/SX 2/8	36	674	27.40	17.12
CM/SX 3/7	24	690	24.24	40.68
CM/SX 5/5	30	576	18.72	45.12
CM/SX 7/3	28	340	11.35	140.17
CM/SX 9/1	30	290	8.55	200.12
XLT	33	450	13.22	0.77
CM/XLT 1/9	42	450	13.47	29.06
CM/XLT 2/8	46	398	12.52	45.88
CM/XLT 3/7	38	376	10.62	77.65
CM/XLT 5/5	42	364	10.39	69.61
CM/XLT 7/3	33	328	8.74	210.24
CM/XLT 9/1	33	280	7.49	208.24
CM	38	188	4.68	204.95

Influence of O_2 concentration

Table 5 shows that the T_b of CM/XLT blends decreased with increasing O_2 concentration. At the O_2 concentration equal to or greater than 30%, the S_{sf} was around 9 s/%. An increased O_2 concentration, only in a specific scope, facilitated the combustion. The same phenomena occurred in the S and S_{sf}. Comprehensively, 30% O_2 concentration was the most appropriate choice for the combustion of CM blended sample. With increasing O_2 concentration, the T_b of SX shortened, the S_{sf} decreased, and the S and S_{sf} were both elevated, which is consistent with the general trend of CM/SX blends.

Table 5. Combustion Characteristic Parameters of CM/Coal 3/7 under Different O_2 Concentration in an Isothermal Conditions

Sample	O_2/CO_2	t_{ig} (s)	t_b (s)	S_{sf} (s/%)	S×10⁻⁷ (%²/s⁵)
CM/SX 3/7	21/79	24	690	24.297	4.068
	30/70	33	460	18.971	4.813
	40/60	30	338	15.116	11.747
CM/XLT 3/7	21/79	38	376	10.624	7.765
	30/70	33	280	8.689	20.942
	40/60	28	230	8.459	40.655

According to S of various CM/coal blends under approximately 21% to 40% O_2 condition in Fig. 4, the combustion characteristics index of coal/CM blends increased for the two types of pulverized coal as the blending ratio of CM increased. Under the various O_2 concentration conditions, blending of less than 50% of CM did not affect the overall combustion situation of pulverized coal. At the same time, the combustion characteristic of CM/SX blends with less than 50% CM had no apparent gap in the three types of O_2 concentration conditions. However, CM/XLT blends were greatly influenced by the O_2 concentration. When the O_2 concentration increased from 21% to 30% or 30% to 40%, S showed an apparent improvement for the both conditions. When the blend ratio of CM was more than 50%, the effect of the two types of pulverized coal was similar, which was influenced by the O_2 concentration and blending ratio significantly. In conclusion, if the control has no significant change for the combustion characteristics of a blended sample, the blending amount of CM should be controlled within 50%. At the same time, the O_2 concentration should be increased to 30% to maintain a favorable combustion reactivity of XLT.

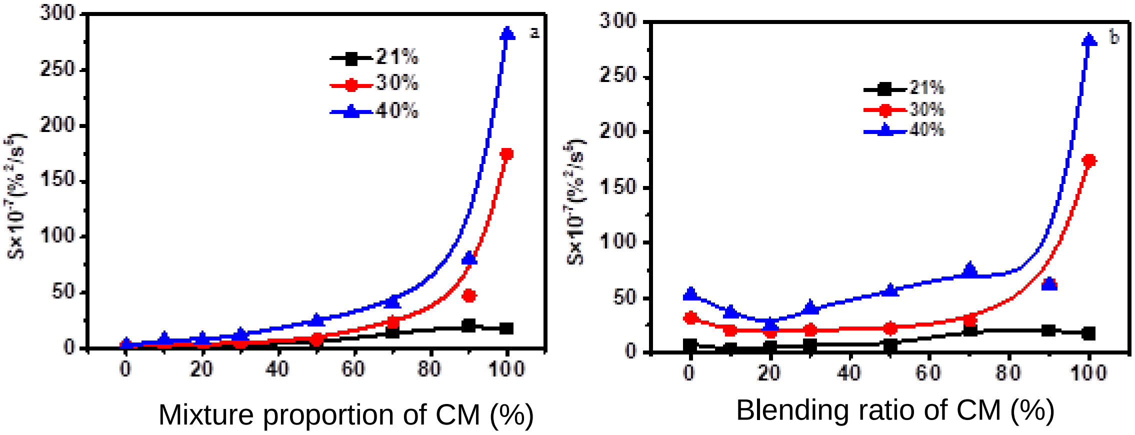

Fig. 4. Combustion behaviour of various blending ratio of CM/coal blends under different O_2 concentration at 800 °C: (a) CM/SX and (b) CM/XLT

Interactions between the Components of the Blends

The interaction between the components of the blends is an important aspect of the combustion reaction mechanism. The interaction was calculated from the difference between the weight value according to the single sample and the experimental value. There is a synergistic effect when the experimental value of weight loss rate is higher than its theory value. Otherwise, it has an inhibiting effect (Liu *et al.* 2015). Figure 5 shows a comparison of combustion reaction between the theoretical value and experimental value in the non-isothermal and isothermal conditions. Under the non-isothermal condition, less than 30% CM had a promoting effect on the CM/SX blends, and approximately 50% to 90% CM had an inhibitory effect on the volatile release and is a promoting role in the char burnout for the CM/SX blends. The burnout was reduced gradually as the blending amount increased in the range. The experimental value was similar to the theoretical value. However, there was an inhibition for the all blending amount excepted for the approximately 70% to 90% blending on the char burnout. Under the isothermal condition, the CM blending generally showed a positive effect on the SX, and the extent of this effect increased first and then decreased. In the release of volatile matter, there was an inhibiting effect. Similarly, the inhibition increased first and then decreased. According to the results of the two conditions, the trend of interaction between CM and coal under the non-isothermal and isothermal condition was consistent. The only difference was in the change rate. The CM blending generally exerted the promotion effect on the char combustion of CM/SX blends and an inhibition effect for the release of volatile matter. The CM blending generally exerts the inhibiting effect for the combustion of CM/XLT blends. The synergistic effect may be related with the different release rate of volatile matter between coal and biomass. Meanwhile, the heterogeneity, nature and distribution of reacting species in the blend also present interactive effects (Liu *et al.* 2015).

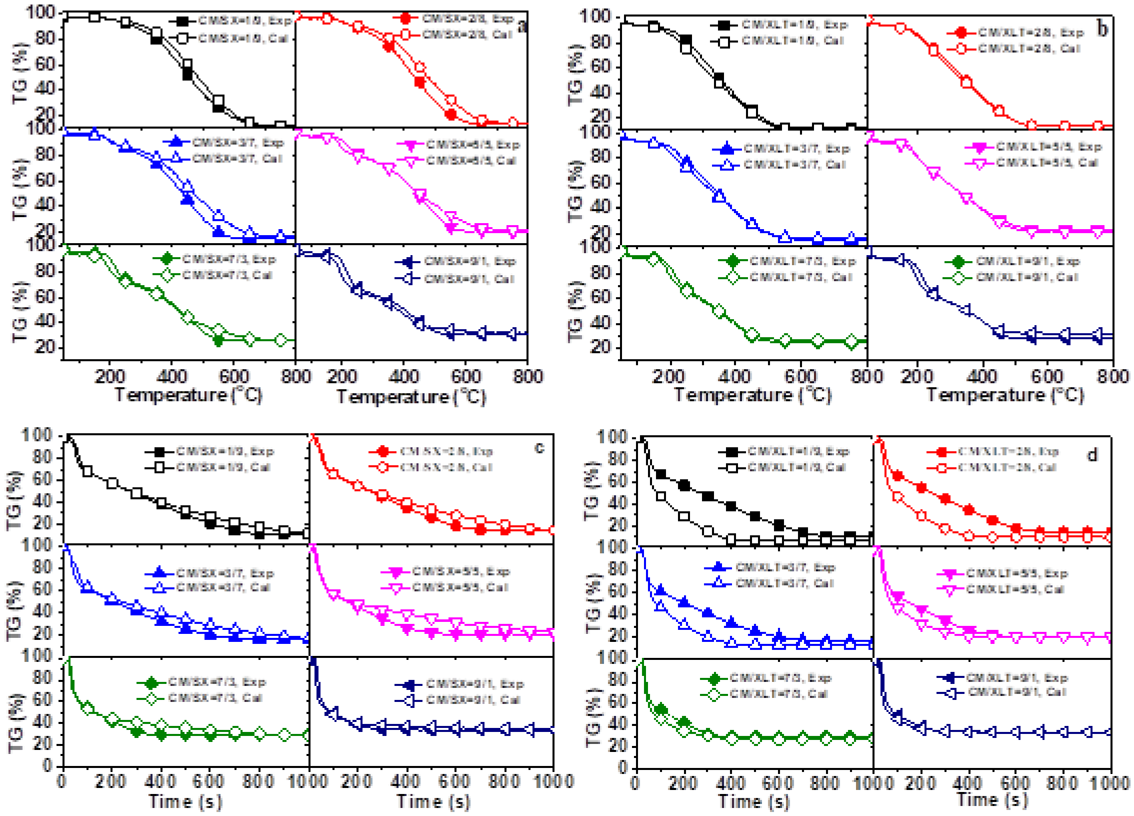

Fig. 5. Interactions behavior of various blend ratio of CM/coal blends: (a) CM/SX, non-isothermal conditions, (b) CM/XLT, non-isothermal conditions, (c) CM/SX, isothermal conditions and (d) CM/XLT, isothermal conditions

Kinetic Analysis

Through the above analysis, the reaction characteristics gradually improved as the blending ratio increased, especially when the CM blending rate was more than 50%. To determine if there was any association with the *E*, a kinetic analysis was performed. From Fig. 6a, the *E* of two types of pulverized coal was higher than that of CM. At the same time, *E* of SX was higher than that of XLT. In general, a low apparent activation energy indicates a high reactivity, and the same result of a low *E* was found in the heat treatment of livestock and poultry manure (Kirubakaran *et al.* 2007; Toptas *et al.* 2015). Under different blending ratios in the CM condition, the *E* value was reduced significantly when the blending ratio was more than 50% for the two types of pulverized coal, and the *E* of blending sample was similar to that of CM combustion. At a low or high CM blending ratio, the CM blending ratio had little influence on the *E*. The *E* and *lnA* showed good linearity due to the compensation effect of the kinetic analysis of *E* and *A* (Brown and Galwey 2002). The relation was $lnA = aE + b$ (Yi *et al.* 2014), as shown in Fig. 6b. All of the linear correlation coefficients in the above equations were greater than 0.98.

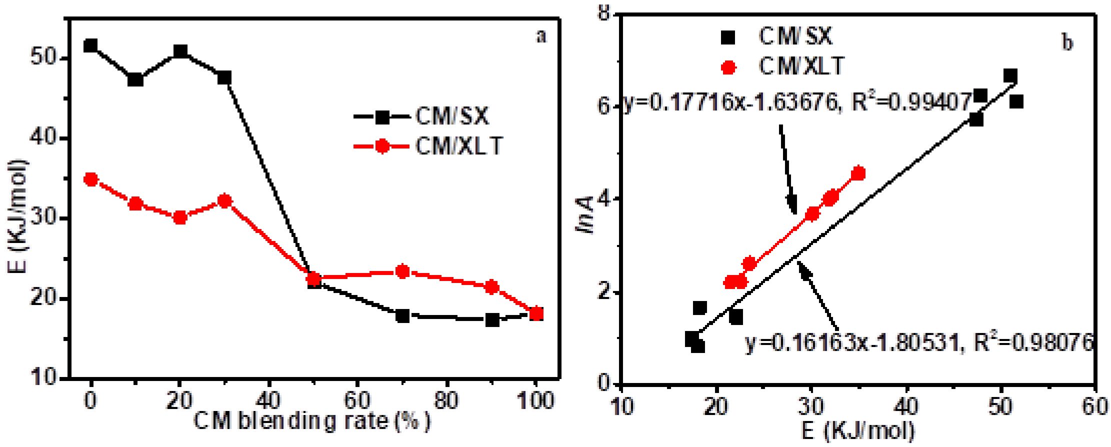

Fig. 6. Apparent activation energy and compensation effect analysis of various blend ratio of CM/coal blends in non-isothermal conditions: (a) CM/SX and (b) CM/XLT

CONCLUSIONS

1. With the increase of the blending ratio of CM in coal, the comprehensive combustion characteristics, combustibility, and burnout for the co-firing improved.
2. Combustion of CM and coal blends affected by furnace temperature had close association with the content of fixed carbon.
3. When the blend ratio of CM was more than 50%, two types of pulverized coal were significantly affected by O_2 concentration and blending ratio.
4. The trend of interaction between CM and coal under the non-isothermal and isothermal condition was consistent. However, the effects on the combustion process were different for the different types of coal.

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REFERENCES CITED

Bhuiyan, A. A., and Naser, J. (2016). "Thermal characterization of coal/straw combustion under air/oxy-fuel conditions in a swirl-stabilized furnace: A CFD modelling," *Applied Thermal Engineering* 93, 639-651. DOI: 10.1016/j.applthermaleng.2015.10.024

Brown, M. E., and Galwey, A. K. (2002). "The significance of "compensation effects" appearing in data published in “computational aspects of kinetic analysis”: ICTAC project, 2000,” *Thermochimica Acta* 387(2), 173-183. DOI: 10.1016/S0040-6031(01)00841-3

Cantrell, K. B., Ducey, T., Ro, K. S., and Hunt, P. G. (2008). “Livestock waste-to-bioenergy generation opportunities,” *Bioresource Technology* 99(17), 7941-7953. DOI: 10.1016/j.biortech.2008.02.061

Chen, W. H., Peng, J., and Bi, X. T. (2015). “A state-of-the-art review of biomass torrefaction, densification and applications,” *Renewable and Sustainable Energy Reviews* 44, 847-866. DOI: 10.1016/j.rser.2014.12.039

Cheng, Q., Via, B., Wang, J., and Zondlo, J. (2014). “Primary study of woody biomass and coal for energy production investigated by TGA-FTIR analysis,” *BioResources* 9(2), 2899-2906. DOI: 10.15376/biores.9.2.2899-2906

Coats, A., and Redfern, J. (1964). “Kinetic parameters from thermogravimetric data,” *Nature* 201, 68-69. DOI: 10.1038/201068a0

Dávalos, J. Z., Roux, M. V., and Jiménez, P. (2002). “Evaluation of poultry litter as a feasible fuel,” *Thermochimica Acta* 394(1), 261-266. DOI: 10.1016/S0040-6031(02)00256-3

Fernandez-Lopez, M., Puig-Gamero, M., Lopez-Gonzalez, D., Avalos-Ramirez, A., Valverde, J., and Sanchez-Silva, L. (2015). “Life cycle assessment of swine and dairy manure: Pyrolysis and combustion processes,” *Bioresource Technology* 182, 184-192. DOI: 10.1016/j.biortech.2015.01.140

Huang, F., Zhang, L. Q., Yi, B. J., Xia, Z. J., and Zheng, C. G. (2015). “Transformation pathway of excluded mineral pyrite decomposition in CO_2 atmosphere,” *Fuel Processing Technology* 138, 814-824. DOI: 10.1016/j.fuproc.2015.07.028

Junga, R., Knauer, W., Niemiec, P., and Tańczuk, M. (2017). “Experimental tests of co-combustion of laying hens manure with coal by using thermogravimetric analysis,” *Renewable Energy* 111, 245-255. DOI: 10.1016/j.renene.2017.03.099

Jurado, N., Darabkhani, H. G., Anthony, E. J., and Oakey, J. E. (2014). “Oxy-combustion studies Into the Co-firing of coal and biomass blends: Effects on heat transfer, gas and ash compositions,” *Energy Procedia* 63, 440-452. DOI: 10.1016/j.egypro.2014.11.047

Kim, J. K., Kim, H. S., Park, S. U., Lee, H. D., and Kim, S. C. (2015). “Combustion possibility of cattle manure as a blended fuel of pulverized coal fired power plant using TGA and 100 kg/h test furnace,” *Journal of Chemical Engineering of Japan* 48(4), 307-319. DOI: 10.1252/jcej.14we034

Kirubakaran, V., Sivaramakrishnan, V., Premalatha, M., and Subramanian, P. (2007). “Kinetics of auto-gasification of poultry litter,” *Journal of the Energy Institute* 4(5), 519-534. DOI: 10.1080/15435070701583102

Li, Q., Zhao, C., Chen, X., Wu, W., and Li, Y. (2009). "Comparison of pulverized coal combustion in air and in O_2/CO_2 mixtures by thermo-gravimetric analysis," *Journal of Analytical and Applied Pyrolysis* 85(1-2), 521-528. DOI: 10.1016/j.jaap.2008.10.018

Liu, X., Chen, M., and Wei, Y. (2015). “Combustion behavior of corncob/bituminous coal and hardwood/bituminous coal,” *Renewable Energy* 81, 355-365. DOI: 10.1016/j.renene.2015.03.021

López-González, D., Parascanu, M. M., Fernandez-Lopez, M., Puig-Gamero, M., Soreanu, G., Avalos-Ramírez, A., Valverde, J. L., and Sanchez-Silva, L. (2017). “Effect of different concentrations of O_2 under inert and CO_2 atmospheres on the swine manure combustion process," *Fuel* 195, 23-32. DOI: 10.1016/j.fuel.2017.01.041

Pickard, S. C., Daood, S. S., Pourkashanian, M., and Nimmo, W. (2014). "Co-firing coal with biomass in oxygen- and carbon dioxide-enriched atmospheres for CCS applications," *Fuel* 137, 185-192. DOI: 10.1016/j.fuel.2014.07.078

Pu, G., Zan, H., Du, J., and Zhang, X. (2017). "Study on NO Emission in the oxy-fuel combustion of co-firing coal and biomass in a bubbling fluidized bed combustor," *BioResources* 12(1), 1890-1902. DOI: 10.15376/biores.12.1.1890-1902

Pu, G., Zhu, W., Zhou, H., Lei, Q., Zhang, Z., and Liu, J. (2015). "Co-combustion 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

Santos Dalólio, F., da Silva, J. N., Carneiro de Oliveira, A. C., Ferreira Tinôco, I. d. F., Christiam Barbosa, R., Resende, M. d. O., Teixeira Albino, L. F., and Teixeira Coelho, S. (2017). "Poultry litter as biomass energy: A review and future perspectives," *Renewable and Sustainable Energy Reviews* 76, 941-949. DOI: 10.1016/j.rser.2017.03.104

Skreiberg, A., Skreiberg, Ø., Sandquist, J., and Sørum, L. (2011). "TGA and macro-TGA characterisation of biomass fuels and fuel mixtures," *Fuel* 90(6), 2182-2197. DOI: 10.1016/j.fuel.2011.02.012

Toptas, A., Yildirim, Y., Duman, G., and Yanik, J. (2015). "Combustion behavior of different kinds of torrefied biomass and their blends with lignite," *Bioresource Technology* 177, 328-336. DOI: 10.1016/j.biortech.2014.11.072

Wang, C., Shao, H., Lei, M., Wu, Y., and Jia, L. (2016). "Effect of the coupling action between volatiles, char, and steam on isothermal combustion of coal char," *Applied Thermal Engineering* 93, 438-445. DOI: 10.1016/j.applthermaleng.2015.09.103

Wang, C., Zhang, X., Liu, Y., and Che, D. (2012). "Pyrolysis and combustion characteristics of coals in oxyfuel combustion," *Applied Energy* 97(0), 264-273. DOI: 10.1016/j.apenergy.2012.02.011

Wang, C., Wang, J., and Lei, M. (2014). "Study on the determination method of combustion characteristics of coal and biomass blends under non-isothermal condition," *Acta Energiae Solaris Sinica* 35(10), 0254-0096. DOI: 10.3969/j.issn.0254-0096.2014.10.003

Wang, L., Shahbazi, A., and Hanna, M. A. (2011). "Characterization of corn stover, distiller grains and cattle manure for thermochemical conversion," *Biomass and Bioenergy* 35(1), 171-178. DOI: 10.1016/j.biombioe.2010.08.018

Yi, B., Yuan, Q., Cao, H., Niu, W., Wang, M., Yao, Z., and Yan, S. (2018a). "Effect of alkali and alkaline earth metal species on the combustion characteristics of cattle manures," *RSC Advances* 8, 11705-11713. DOI: 10.1039/c8ra00965a.

Yi, B., Yuan, Q., Cao, H., Wang, M., Niu, W., and Yan, S. (2018b). "Combustion characteristics of densified cattle manure briquette in an isothermal condition," *BioResources* 13(2), 3571-3584. DOI: 10.15376/biores.13.2.3571-3584

Yi, B., Zhang, L., Huang, F., Mao, Z., and Zheng, C. (2014). "Effect of H_2O on the combustion characteristics of pulverized coal in O_2/CO_2 atmosphere," *Applied Energy* 132(0), 349-357. DOI: 10.1016/j.apenergy.2014.07.031

Yi, B., Zhang, L., Yuan, Q., Yan, S., and Zheng, C. (2016). "The evolution of coal char structure under the oxy-fuel combustion containing high H_2O," *Fuel Processing Technology* 152, 294-302. DOI: 10.1016/j.fuproc.2016.06.017

Yurdakul, S. (2016). "Determination of co-combustion properties and thermal kinetics of poultry litter/coal blends using thermogravimetry," *Renewable Energy* 89, 215-223. DOI: 10.1016/j.renene.2015.12.034

Zheng, C., Liu, Z., Xiang, J., Zhang, L., Zhang, S., Luo, C., and Zhao, Y. (2015). "Fundamental and technical challenges for a compatible design scheme of oxyfuel combustion technology," *Engineering* 1(1), 139-149. DOI: 10.15302/j-eng-2015008

Zhu, D., Yang, H., Chen, Y., Li, Z., Wang, X., and Chen, H. (2017). "Fouling and slagging characteristics during co-combustion of coal and biomass," *BioResources* 12(3), 6322-6341. DOI: 10.15376/biores.12.3.6322-6341

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