Combustion Characteristics of Densified Cattle Manure Briquette in an Isothermal Condition

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The densification process of cattle manure (CM) and its combustion characteristics in air were studied under isothermal conditions. To be better aligned with practical applications, cotton stalk (CS) and corn cob (CC) were chosen in this paper as the controls. The stability of densified biomass briquettes under compressive force of 20 kN, 30 kN, 40 kN, and 50 kN were studied. Factors affecting the densification of biomass, including moisture concentration, densification pressure, and briquette size were studied, in addition to combustion conditions including heating rate and O_2 concentration. The moisture concentration contained in the densified biomass briquettes were set at 5%, 10%, 15%, and 20%. The results showed a good stability of briquettes of CM (CM-B) under various densification pressures. The effects of moisture concentration on the combustion characteristics were small for CM-B. The influence of the densification pressure and O_2 concentration on the combustion characteristics was a monotonic change. In summary, considering the stability and economy, 30 kN and 30% O_2 concentration were judged to be favorable. The combustion characteristics of the CM-B did not monotonically increase with the size. The study's results showed that the CM-B could be used as a fuel under certain conditions.

Keywords: Cattle manure; Combustion characteristic; Densified biomass briquette; Isothermal condition

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INTRODUCTION

With increasing demand for energy and the continuous deterioration of the earth's environment, the need for clean energy use is growing more urgent. Being a type of traditional agricultural waste, the utilization of biomass is considered as a recycling of waste material. Biomass energy has clear advantages for the environment (Saidur *et al.* 2011), but its raw material properties, such as its high moisture content, low density, and unstable combustion process, limit its energy conversion and utilization (Vassilev *et al.* 2015). The densification of biomass can reduce the volume as well as the moisture content. It also can be used to alleviate combustion and transportation problems (Stelte *et al.* 2012).

There is a wide range of biomass sources, most of which can be made into biomass briquettes, such as sawdust, straw, rice husk, sludge, animal waste, *etc.*, and their combinations. Nolan's research shows that the cost per unit of energy for biomass particles is €7/GJ, which is economically competitive with kerosene and gas (Nolan *et al.* 2010). For agricultural waste, the consumed energy of densified briquettes is about 12~18% of the fuel value of the product (Sakkampang and Wongwuttanasatian 2014). However, the quality of the briquettes is affected by the composition, temperature, shape, pressure, and binder (Tumuluru *et al.* 2011). Some research shows that the cost of the raw material is the main cost of biomass briquettes (Stolarski *et al.* 2013); thus choosing suitable biomass is the key to improving the economy of biomass briquettes.

Though the cost of agricultural and forestry waste is generally low compared to other fuels, it may be more difficult to collect depending on the season. If continuous and stable biomass energy is required, the cost of collection and transportation will rapidly increase, which is not conducive to the healthy development of biomass briquettes. Meanwhile, large-scale livestock farms generate livestock waste in hundreds of tons per day. Due to the restriction of space and the surrounding environment, the low ability to dispose of livestock waste has seriously restricted the safety and stability of the farms. There are many methods of livestock waste disposal (Cantrell *et al.* 2008), including composting (Tang *et al.* 2006), anaerobic fermentation for methane (Maroušek *et al.* 2015a), and heat treatment (Font-Palma 2012). Because the composition of livestock waste is complex (Shen *et al.* 2015), the process time is long and the added value of products utilized is low (Maroušek *et al.* 2015b), which results in low enthusiasm for farms. According to the study of Mardoyan and Braun (2015), when only taking into account of energy, biomass has a low economic efficiency for fuel. In terms of waste disposal, however, it presents an obvious advantage. Combustion of livestock waste on-site to supply heat is a kind of technology used to achieve resource utilization, and is currently the fastest and most practical method for waste utilization at large-scale livestock farms.

In the early 1990s, research on livestock waste for energy utilization was reported, and pilot-scale tests showed the feasibility of such combustion (Sweeten *et al.* 1986). However, due to the small size of farms and the relative lack of farmland organic fertilizer, the economic benefits of thermal energy utilization was low. Known from the statistics of China's present livestock and poultry farms' scale, there are already quite a few large-scale farms and limited surrounding farmland to handle the organic fertilizer, which can be used as raw material for biomass energy utilization. A number of recent articles have studied the energy utilization of livestock and poultry waste (Lynch *et al.* 2013; Bidart *et al.* 2014; Vassilev *et al.* 2014; Monlau *et al.* 2015; Tsai and Liu 2016; Yurdakul 2016; Santos Dalólio *et al.* 2017), and some research results have been reviewed (Lynch *et al.* 2013; Monlau *et al.* 2015; Santos Dalólio *et al.* 2017).

A high moisture content in livestock and poultry manure can be dehydrated to 50% by a solid-liquid separator. After exposing in a dry air, the moisture content in the livestock and poultry manure can be dehydrated to 20%. Then, the process of densification can impede the biomass from absorbing moisture from the air, thus maintaining the moisture content at 20%. It can be used in both the grate and fluidized bed furnaces combustion (Abelha *et al.* 2003). Meanwhile, densification of cattle manure can improve the combustion characteristics for increasing its bulk density.

Thermogravimetry (TG) is the most common method for analyzing the combustion characteristics of fuel (Wang *et al.* 2011b; Yi *et al.* 2014; Chen *et al.* 2015; Hu *et al.* 2015; Ridha *et al.* 2015; Seo *et al.* 2016; Yi *et al.* 2016). However, most of the equipment can only be used for 5 mg to 10 mg samples, which is not suitable for the study of biomass briquettes. Some differences were found between isothermal and non-isothermal conditions (Wang and Zhao 2015). Meanwhile, an isothermal TG experiment with a high heating rate may be closer to the actual situation (Grotkjær *et al.* 2003). In addition, the advantages of biomass briquette combustion under isothermal conditions were shown

(Nakahara *et al.* 2015; Shan *et al.* 2017; Yan and Fujita 2017). Therefore, an isothermal TG method is suitable for the study of biomass briquette combustion.

In summary, biomass briquette production is an important method for biomass energy utilization, with livestock and poultry manure having an extensive application propensity for energy utilization. Meanwhile, the present biomass briquette combustion furnace is mainly aimed at the briquettes of forestry and agriculture residues rather than the briquettes of livestock and poultry. In this paper, the combustion characteristics of livestock and poultry manure biomass were studied. To be better combined with practical applications, cotton stalk (CS) and corn cob (CC) were chosen in this paper as the controls. The influence of moisture content, densification pressure, and O_2 concentration on the various combustion stages were also studied. These factors are expected to provide reference for the utilization of livestock and poultry manure in the combustion furnace.

EXPERIMENTAL

Materials

The CM was found to have higher fixed carbon (FC) contents (Shen *et al.* 2015), which was similar to the straw biomass. It was chosen as a typical livestock alongside poultry manure for this study. Fresh CM was taken from Wuhan Jiangxia District Crusades Animal Husbandry Limited Liability Company (Wuhan, China). The CS and CC were chosen from the experimental fields of Huazhong Agricultural University (Wuhan, China), and were sealed after drying. The CM was crushed directly, while the CS and CC were crushed after cutting them into small pieces. The crushed sample was kept in a drying oven at 105 °C for 48 h. Then the dried sample was kept in a sample bag after being sieved through 60-mesh sieves. The proximate analysis, chemical structure, and higher heating value (HHV) of the samples are shown in Table 1. Compared with the other samples, CM had high ash, low cellulose, and high other substance contents, as well as a low HHV.

Table 1. Proximate Analysis, Chemical Structure, and HHV of Samples

Sample	Proximate Analysis (wt%.ad)				Chemical Structure (wt%.daf)				HHV (MJ/kg)
	M	V	A	FC	Hemicellulose	Cellulose	Lignin	Other	
CM	9.49	45.80	32.19	12.52	29.73	23.06	4.91	42.30	13.426
CS	9.80	67.19	3.51	19.50	16.50	38.86	13.32	31.32	19.375
CC	7.62	66.74	10.31	15.34	39.99	37.74	1.55	20.72	17.239

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

Moisture content gradient was evaluated according to the method of Rudolfsson *et al.* 2015. The dry sample was taken in a spray environment with 5%, 10%, 15%, and 20% moisture contents, and was kept in a sealed configuration for 24 h. During the molding process, it was found that fully dry samples were not easily formed. Therefore, without specific indication, the moisture content of the densification sample was at 10%, according to the data of previous literature (Peng *et al.* 2013).

A total of 0.70 g ± 0.01g of the sample was taken in the cylinder, pressurized by the piston, and then placed in a compression mold on a worktable of a hydraulic universal testing machine (Kexin, Changchun, China). Binder has been used in much of the literature (Yank *et al.* 2016), but a binder should consider cost and environmental friendliness. Therefore, binderless preparation, in which briquettes were directly densified through a high pressure was chosen as the approach for the present work. At the same time, compared with hot densified briquettes, the cold densified briquettes present a low GHG emissions (Rahaman and Salam 2017). The diameter of the cylinder was 10 mm. The piston of force was set by a computer-controlled system (Kexin, Changchun, China) at 20 kN, 30 kN, 40 kN, and 50 kN. It was stabilized at the set pressure for 120 s, after which the biomass briquettes were removed. The briquettes of CM, CS, and CC were denoted as CM-B, CS-B, and CC-B, respectively. The raw samples and densified biomass briquettes are shown in Fig. 1.

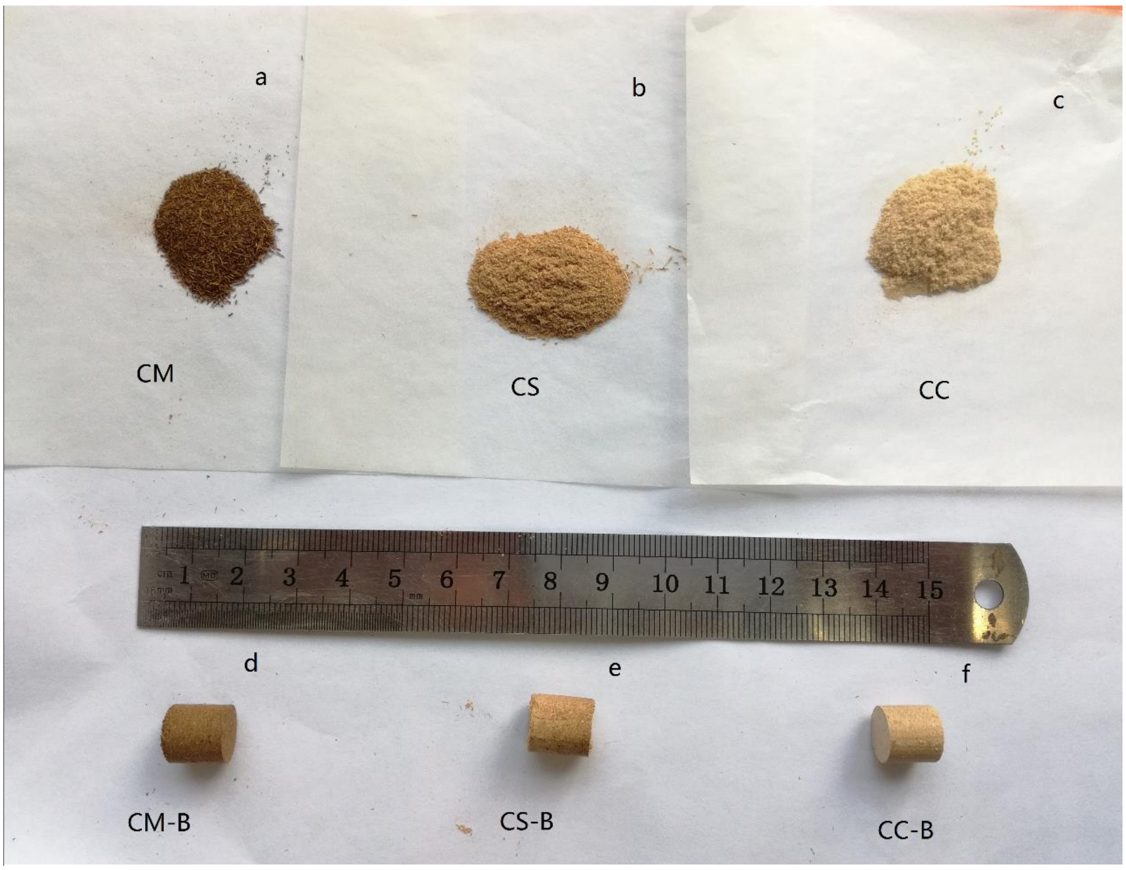

Fig. 1. Experimental sample: (a) raw CM, (b) raw CS, (c) raw CC, (d) CM-B, (e) CS-B, and (f) CC-B

Methods

The experiment was conducted using a thermogravimetry (TG) analyzer that was designed by the authors (Huazhong Agricultural University, Wuhan, China). It consisted of a gas cylinder, mass flow controller, heating furnace, quartz reactor, balance and auxiliary air cooling, water cooling pipe, lifting equipment, and computer. The furnace was heated by a double temperature control system, with the length of a constant temperature at 300 mm. The inner diameter of the reactor in the furnace was 50 mm, and the diameter of quartz hanging basket was 35 mm. The gas purity of O_2 and N_2 was 99.999%. The accuracy of balance was 0.1 mg. Data of the balance and thermocouples were collected per second, and was sent to the computer and stored in real-time.

For the isothermal experimental process, the furnace temperature was raised to 800 °C, and then the experimental gas was pumped into the furnace at a gas flow rate of 1 L/min. When the temperature and atmosphere were stable, a quartz hanging basket equipped with the briquettes was quickly taken to the center of the furnace. The temperature and weight acquisition system were clicked at the same time. The related data were recorded and saved after finishing the experiment. The combustion characteristics of the sample were also adopted in a non-isothermal experiment. The furnace was heated from room temperature to 900 °C at 20 °C/min, and then experimental gas was taken into the quartz reactor. The briquettes were taken to the quartz hanging basket and put in the center of the furnace *via* a lifting system. After these, the data of temperature and weight were collected and recorded in the computer.

Characteristic parameters

In this paper, the relaxation factor was selected to reflect the stability characteristics of briquettes, denoted by k. It was defined as the volume change ratio of briquettes between just after densification and after 24 h. A larger value of k resulted in poorer stability of densification,

$$k = \frac{V_t}{V_0} \tag{1}$$

where V_0 and V_t represent the initial volume (mm^3) and instantaneous volume (mm^3) of the sample, respectively.

The ignition time (T_{ig}; s), the time of the maximum combustion rate (T_{max}; s), and the burnout time (T_b; s) were used for comparison among different non-isothermal conditions. The 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 under an isothermal condition. All of these were obtained through thermal gravimetric curves using the methods in previous literature (Wang *et al.* 2012).

The combustion reactivity R is defined as (Wang *et al.* 2012),

$$R = -\frac{1}{m_t}\frac{dm_t}{dt} = \frac{1}{1 - X_t}\frac{dX_t}{dt} \tag{2}$$

where $X_t = (m_0 - m_t) / (m_0 - m_{ash})$ is the fuel conversion rate obtained from TG/differential thermogravimetry (DTG) curves, in which m_0, m_{ash}, and m_t represent the initial, ultimate, and instantaneous masses of the sample, respectively. A carbon conversion rate of 50% was selected in this study, denoted by R_{50}.

To evaluate the combustion performance of fuel under various conditions, comprehensive combustibility index S was defined as follows (Wang *et al.* 2011a, 2012; Yi *et al.* 2014),

$$S = \frac{(dw/dt)_{max} \times (dw/dt)_{av}}{T_{ig}^2 \times T_b} \tag{3}$$

where $(dw/dt)_{max}$ is the maximum combustion rate (%/s) and $(dw/dt)_{av}$ is the average weight loss rate (%/s). Generally, a higher S value indicates a higher reactivity of the fuel combustion process.

RESULTS AND DISCUSSION

The Stability of Biomass Briquettes

The densification pressure was related to the stability of biomass briquettes, and it determined the densification efficiency and cost. The *k* of briquettes under various pressure conditions was studied and is shown in Table 2. By comparison, there was no obvious effect of increasing pressure on the *k* of CM-B. The main reason was a high ash content of CM-B, while the ash was less affected by pressure. For the CS-B, *k* increased with the forming pressure increase. This was related to the lignin content, which had a strong hardness at low temperatures. A greater pressure resulted in more expansion in the latter. However, the *k* of CC-B decreased with the forming pressure increase. The trend correlated with the high hemicellulose content, which increased the compressive stability. It can be seen from Table 2, the *k* of several samples subjected to pressures of 20 kN to 50 kN was in the range of 1.0 to 1.2 and the *k* of CM-B was smaller than the other briquettes. In summary, the stability of CM-B after densification was better than that of the straw briquettes.

Table 2. The Relaxation Factor of Briquette at Various Forming Pressures

Sample	20 kN	30 kN	40 kN	50 kN
CM-B	1.075	1.075	1.068	1.072
CS-B	1.090	1.142	1.156	1.146
CC-B	1.120	1.098	1.063	1.038

Combustion Characteristics of Densified Biomass Briquettes

Figure 2 shows the TG/DTG curves of three densified biomass briquettes at 30 kN under an air atmosphere. Figure 2a exhibits a low heating rate under non-isothermal conditions.

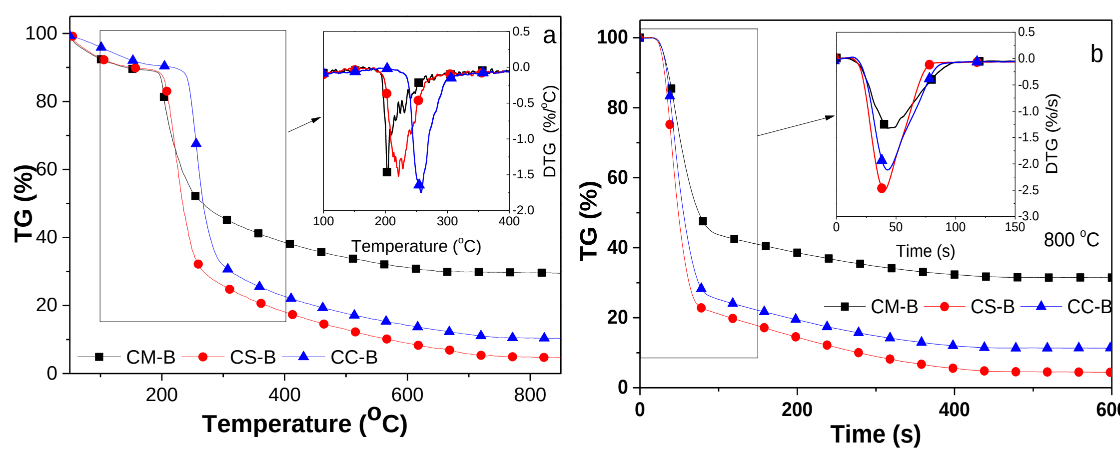

Fig. 2. The TG and DTG curves of three densified biomass briquettes: (a) non-isothermal condition and (b) isothermal condition

Three kinds of samples had slow reactivity at the dehydration stage before 200 °C. These produced a violent reaction during the release of volatile matter or char combustion at 200 °C to 350 °C. It was a slow reactivity at the stage of char burnout or mineral transformation at 350 °C to 700 °C. The T_o of CM-B was low, but the most violent reaction during the onset reaction stage was near 200 °C. The reaction rate was gradually reduced as the reaction progressed. The DTG presented a "V" type of curve with a steep side on the left. A similar DTG with "V" type was found in the combustion of CS-B and CC-B, but the "V" was symmetrical for the two sides. The difference between the combustion curves of CS-B and CC-B was a lower reaction temperature for CS-B. The isothermal experiments with a high heating rate are shown in Fig. 2b. The T_o and t_b were the same for the three samples, and the difference among them was the reaction intensity that was associated with the content of combustible substance. The reaction rate followed the order: CS-B > CC-B > CM-B. In summary, the T_o of CM-B was lower, but due to the lower combustible material content, the reaction intensity was lower than that of CS-B and CC-B at a high heating rate condition.

Influence of moisture content

The moisture content in the biomass is known to have an influence on the quality of densified biomass briquettes (Kaliyan and Vance Morey 2009; Tumuluru *et al.* 2011). The densified biomass briquettes with various moisture content were studied as shown in Fig. 3. Moisture content did not noticeably affect the combustion characteristics, especially for the CS-B. Compared with the other samples, CC-B was clearly affected by the moisture concentration. The t_{max} increased as the moisture concentration increased. The $(dw/dt)_{max}$ decreased as the moisture content changed from 5% to 10%, but it increased as the moisture content changed from 10% to 20%.

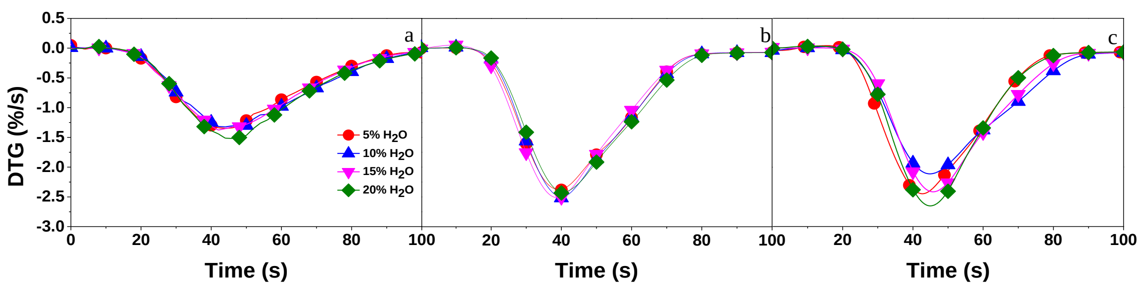

Fig. 3. DTG curves of various moisture content: (a) CM-B, (b) CS-B, and (c) CC-B

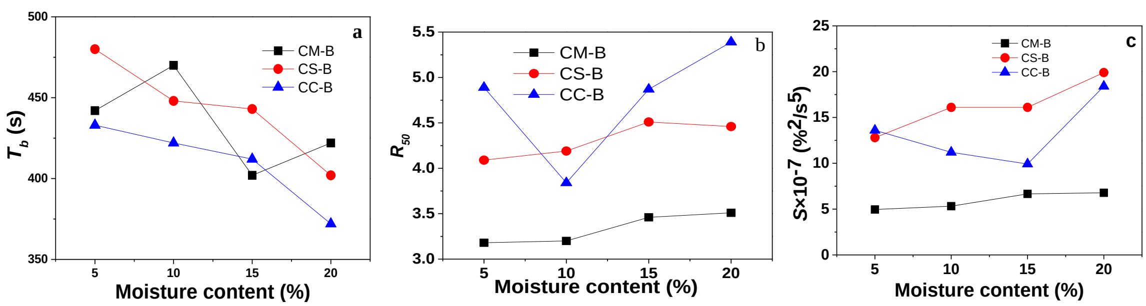

Fig. 4. Characteristic parameters of various moisture contents: (a) t_b, (b) R_{50}, and (c) S

Attributed to the forming characteristics of CC-B, as the moisture increased, *k* of CC-B decreased in the densification process of various moisture content. In comparison to CC-B with 5% moisture, CC-B with 10% moisture had a smaller contact area and a weaker reaction intensity. With the content of moisture increasing from 10% to 20%, more steam was released from the densified biomass, leading to particle breakage. There was a larger contact area generated, and the reaction intensity became enhanced. Thus, the moisture in CC-B was required to be within a limited range for a positive effect on the combustion reaction. The change only existed at 20% moisture content in the CM-B, which showed a long t_{max} and a high $(dw/dt)_{max}$.

As shown in Fig. 4, the t_b decreased as the moisture content in densified biomass briquettes increased. Due to it being a complex material with more than one ingredient, there was not a monotonous change for CM-B. With the increase of moisture content, R_{50} and S exhibited an increasing trend for both CM-B and CS-B, but for CC-B it first decreased and then increased. This was related to a low formed strength and density for CC-B at low moisture contents. A high reaction rate was observed for the CC-B, but due to bad stability, it was not easy to transport. In summary, the effect of moisture content on CM-B and CS-B was similar, which was lower than that of CC-B. Therefore, around 20 % moisture content of CM-B after compression can be used for combustion directly.

Influence of forming compression force

The forming compression force is an important parameter for the preparation of densified biomass, and it could affect the combustion characteristics. Therefore, the influence of forming compression force was studied, as shown in Fig. 5. In reference to some studies on the compression force factors, 20 kN to 50 kN was selected in this paper. Densified biomass briquette combustion was considerably different from powder particle combustion. The $(dw/dt)_{max}$ of densified biomass briquettes was remarkably lower than that of powder particles, and the t_{max} of densified biomass briquettes was longer than that of the powder particles. Insufficient contact with air for densified biomass may be the reason. When the compression force increased from 20 kN to 30 kN, the $(dw/dt)_{max}$ decreased and the t_b increased. Due to the increase of density, the contact of densified biomass briquettes and air further weakened. Continuing to increase the forming pressure to 40 kN or 50 kN, the $(dw/dt)_{max}$ showed no obvious difference. The reason was that the high pressure densified biomass briquette combustion and was easily cracked due to the uneven heating in the interiors of the particles. As a consequence, there was an increased contact area between the densified biomass briquettes and air, and this made the reaction rate increase. Continuing to increase the forming compression force to 50 kN showed no obvious cracking effect.

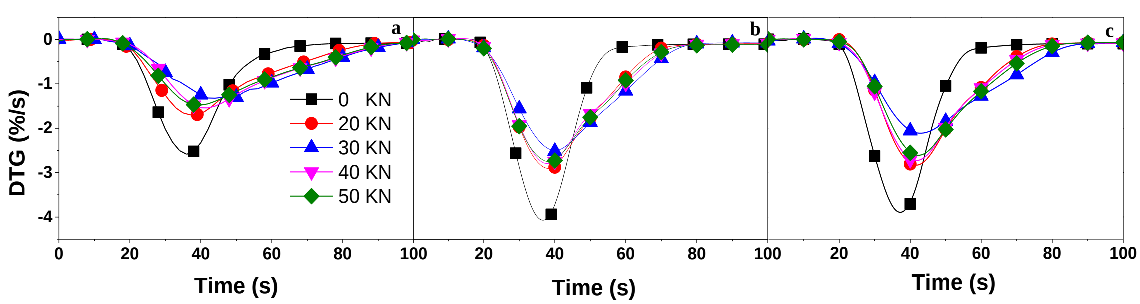

Fig. 5. DTG curves of different compression forces: (a) CM-B, (b) CS-B, and (c) CC-B

R_{50} and S values of three densified biomass briquettes increased after initially decreasing as the densification pressure was increased in the range 0 to 40 kN (Fig. 6). When the densification pressure was above 40 kN, there was a slight increase for CS-B and CC-B, whereas CM-B decreased. This further illustrated a two-sided effect of densification pressure for the combustion of densified biomass briquettes. Therefore, the chosen densification pressure should be as small as possible. In conclusion, the influence of densification pressure on the CM-B was similar to that of CS-B and CC-B, which increased with increased densification pressure. Thus, the chosen densification pressure was almost 30 kN.

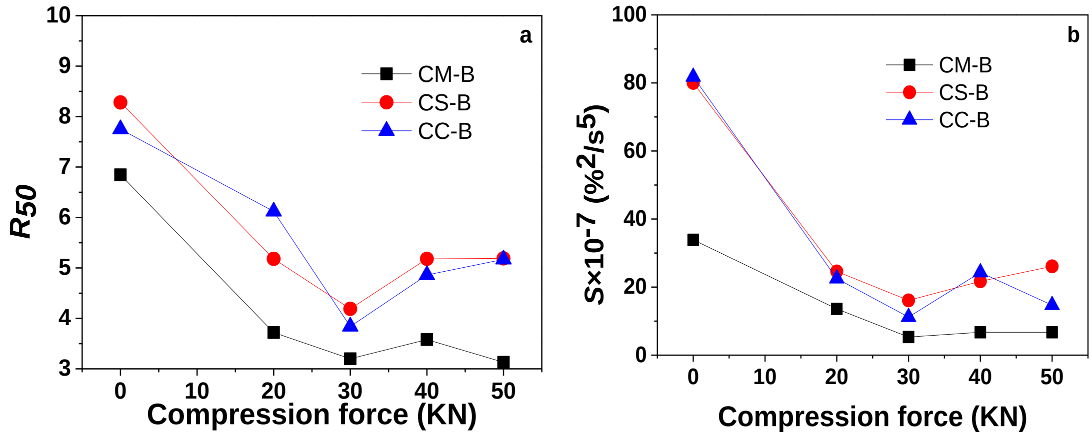

Fig. 6. Combustion characteristics of different compression force: (a) R_{50} and (b) S

Influence of briquette sizes

The briquette size affected the combustion characteristics of densified biomass briquettes, because of the densification model with fixed diameter in this article. Therefore, the sample amount determined the size of the densified biomass briquettes. Amounts of 0.5 g, 0.7 g, and 0.9 g were chosen in this paper, and their combustion curve is shown in Fig. 7. The t_o and t_b values of the densified biomass briquettes with 0.5 g and 0.9 g were both shorter than that of 0.7 g densified biomass briquette. Combustion curves of 0.5 g CM-B were the same as that of 0.9 g CM-B. Moreover, 0.5 g CC-B had a shorter reaction time and more intension reaction than 0.9 g CC-B. Therefore, the effect of size on the combustion characteristics of CM-B was not a monotonous relationship, which was similar for CC-B. So actual conditions of particle size should consider the efficiency of densification.

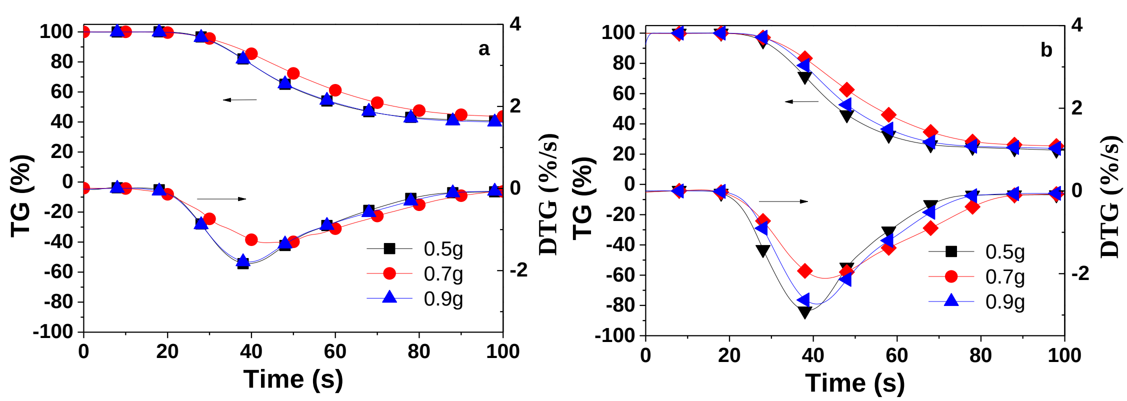

Fig. 7. DTG curve of densified biomass briquette with various sample weight: (a) CM-B and (b) CC-B

Influence of O_2 concentration

For the densified biomass briquette combustion, O_2 concentration was one of the important affecting factors for the reaction rate. The combustion characteristics of O_2 concentration that changed from 21% to 50% were studied to investigate whether the densified biomass briquette was necessary in the O_2-rich atmosphere. The experimental results are shown in Fig 8. The combustion rate of densified biomass briquettes increased with the increase of O_2 content. The $(dw/dt)_{max}$ increased and t_{max} decreased with the O_2 concentration increase for the three densified biomass briquettes. An increased O_2 concentration resulted in good contact between the densified biomass briquettes and O_2. A high reaction rate with enough O_2 resulted in a shorter burning time. At the same time, it is worth emphasizing that the most obvious change of $(dw/dt)_{max}$ was O_2 concentration increase from 21% to 30%, but it was not obvious for > 30% O_2 concentration. This indicated that an appropriate O_2 concentration increase could increase the reaction rate of densified biomass. Other combustion characteristics are shown in Table 3. Considering the economy of O_2 production cost, the O_2 concentration for the densified biomass briquette combustion needed to be 30%. Compared with CS-B and CC-B, the comprehensive combustion reaction rate of CM-B was slightly slow.

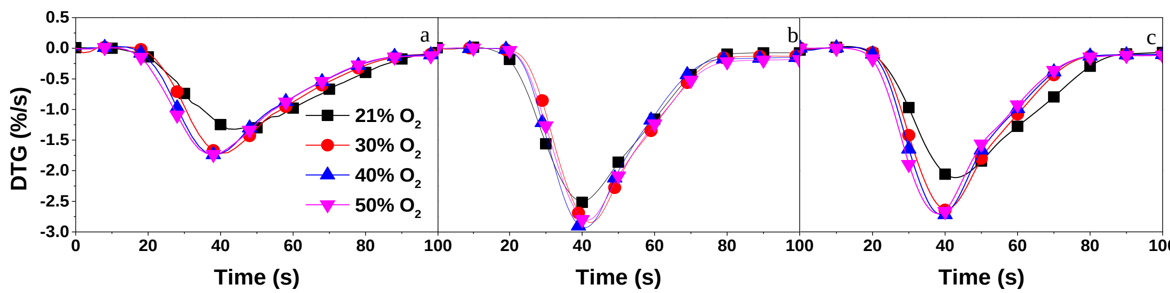

Fig. 8. DTG curve of densified biomass briquette with various O_2 concentrations: (a) CM-B, (b) CS-B, and (c) CC-B

Table 3. Characteristic Parameters of Densified Biomass Briquette with Various O_2 Concentrations

Sample	O_2 Concentration (%)	t_o (s)	t_{max} (s)	t_b (s)	$(dw/dt)_{max}$ (%/s)	$(dw/dt)_{av}$ (%/s)	R_{50}(%/s)	$S*10^{-7}$(%^{2}/s^5)
CM-B	21	28	44	470	1.32	0.15	3.2	5.32
	30	29	40	300	1.71	0.25	3.76	16.8
	40	27	38	300	1.74	0.24	2.6	22.7
	50	26	38	204	1.73	0.37	4.23	43.5
CS-B	21	28	40	430	2.51	0.23	4.19	16.1
	30	32	43	267	2.86	0.38	4.71	39.2
	40	30	41	219	2.95	0.47	4.94	70.4
	50	30	42	208	2.82	0.51	4.81	76.6
CC-B	21	32	44	400	2.12	0.23	3.84	11.2
	30	30	40	274	2.64	0.34	5.26	36.5
	40	28	38	252	2.72	0.38	4.55	52.0
	50	27	38	224	2.72	0.43	5.07	71.0

CONCLUSIONS

1. The stability of briquettes formed from cattle manure (CM-B) was better than those formed from corn stalk (CS-B) and corn cob (CC-B) in the range of 20 kN to 50 kN of applied pressure during briquette preparation. Although reaction temperatures of CM-B were lower, due to the low combustible material content, the reaction intensity was lower than CS-B and CC-B at a higher heating rate condition.
2. The influence of moisture concentration on the CM-B was similar to that of CS-B, which was smaller than that of CC-B. The influence of the densification pressure on the combustion characteristics of three densified biomass briquettes was the same, which were reduced as the densification pressure increased. Considering the stability and economy of the densified biomass briquettes, it is recommended that the densification pressure should not exceed 30 kN.
3. The combustion characteristics of the densified biomass briquettes did not monotonically increase as the size did, so the densified biomass briquette size should be considered with the densification efficiency during practical application. The CM-B was similar to other densified biomass briquettes, which should be combusted under 30% O_2 concentration. The study's results showed that the CM-B can be used as a fuel under some conditions.

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