Investigation of co-combustion characteristics of pulverized coal with miscanthus floridulus biochar

Hsien-Tsung Lin[1], Guan-Bang Chen[2], Yueh-Heng Li[1] and Yei-Chin Chao[1]
[1]Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan
[2]Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan 701, Taiwan

1 Introduction

In the context of the current world energy crisis, global warming and increasing carbon dioxide emission, alternative fuels for replacing traditional fossil fuel such as coal and petroleum have been studied and developed worldwide [1]. Bioenergy production has been proposed as an alternative energy source and it is produced from organic material such as wood, grass, agricultural residues, animal waste and so on. From the perspective of the use for combustion, biomass can be considered as a carbon neutral fuel since it is able to fix carbon dioxide when it grows. The carbon cycle is much shorter when compared to fossil fuels so it may be treated as zero carbon emissions. Nowadays, two direct combustion techniques concerning biomass are noteworthy. The first one is to use only biomass as fuel for industrial furnaces, and the other is co-firing of biomass with fossil fuels. Unfortunately, raw material of biomass is relatively difficult to be handled and utilized because of its high moisture content, low grindability and low bulk and energy density [2]. In addition, direct combustion of biomass always brings the smoke problem, particulate matters and lower temperature as compared with coal. Various thermochemical conversion technologies such as thermal pyrolysis may be used to transform raw biomass into biofuels or biochar and improve combustion properties. Biochar is the main product of torrefection process, which is a mild pyrolysis process and carried out in the temperature range of 200-300 ºC in the oxygen-free condition [3]. After torrefaction, it makes the solid fuel easier to store and increases its heating value. Miscanthus floridulus is a kind of C4 perennial grass and possesses high lignin content when compared to woody biomass [4]. Originating from Asia and Africa, miscanthus is one of the hardly and drought-tolerant plants that is widely available and easy to grow around the world.

It is crucial to have complete database of the thermochemical characteristics of fuels when investigating its combustion behavior. In this study, we focus on the fuel properties of pulverized coal and miscanthus floridulus biochar mixtures and its combustion phenomenon at different blending ratios. Thermogravimetric analysis (TGA) was employed to observe the thermal behavior of the fuel. Furthermore, the fuel was pelletized in a cylindrical die under controlled conditions and its combustion process was examined by using a laboratory scale free-drop furnace.

2 Experimental methods

In this study, Australia pulverized coal and miscanthus floridulus biochar was used as the fuel material. Six different biomass blending ratios (BBRs) of biochar and coal are taken into consideration, and they are 0, 20, 40, 60, 80 and 100 wt. %. The biochar was made by an electric pyrolysis screw conveyor reactor at 200 ºC in the absence of oxygen and then crushed and sieved to make the particle with the size smaller than

Correspondence to: mikelin7747@hotmail.com

0.075 mm (200 mesh) were collected. The proximate, elemental and heating value analyses of the materials were performed to figure out their basic properties. The proximate analysis follows ASTM standard. The HHVs (higher heating value) of the sample were measured by a bomb calorimeter (Parr 6200).

In the analysis, Thermal analysis (PerkinElmer, STA 8000) was utilized to simultaneously carry out TGA and DSC (differential scanning calorimetry). The temperature range for the thermal analysis was set to 30-800 °C, with a corresponding heating rate of 20 °C/min. In each run, around 15 mg of sample was used. Air at a flow rate of 50 ml/min was employed as the carrying gas for the oxidation process. Ignition and burnout temperatures are important properties of solid fuels for their applications. The ignition temperature (T_i) is defined as the minimum temperature at which fuel ignites spontaneously in an environment without external source of ignition; burnout temperature (T_b) is identified at the temperature where the fuel conversion reaches 99%. In the study, T_i and T_b was calculated by intersection method [5] and conversion method, respectively. In addition, the results obtained were further used to determine the combustion characteristics index (S). A large value of S implies that the fuel have better reactivity and combustion performance, it is expressed as follows: [6]

$$S = \frac{(\frac{dW}{dt})_{max} \cdot (\frac{dW}{dt})_{mean}}{T_i^2 \cdot T_b}$$

Where $(dW/dt)_{max}$ and $(dW/dt)_{mean}$ represent the maximum and average mass loss rate, respectively. T_i and T_b stand for the ignition and burnout temperatures, respectively.

In order to investigate the combustion behavior of fuel pellets made from the mixture of coal and biochar, around 800 mg of fuel powder was placed in the cylindrical die and compressed to 2 Ton and hold for 1 minute. After pressed out, the pellet size is nearly ϕ 12mm x 6mm. A free drop furnace was used to determine the combustion characteristics of single pellet and the schematic diagram of the system was shown in Fig. 1. The furnace was made by two heating plate with the PID controlled electrical wall heaters and it can reach to 900 °C with a 220V/ 2 kW power supply. Pre-heated air was continuously delivered into the furnace from the bottom with a fixed flow rates of 3.5 L/min. The sample was dropped through the transmission tube to the stainless mesh platform which connected to the quartz holder. The furnace had an observation window in front to record the combustion process with a video camera and the weight change of the sample can be measured by the electronic scale in real time (once per second). Combustion experiments were carried out at the furnace temperature of 500-700 °C. The fuel can be ignited if the environmental temperature is high enough, so that ignition delay time, total combustion time and flame patterns can further be measured.

3 Results and discussion

The basic properties of coal and biomass are presented in Table1. It can be found that Australia coal possesses higher fixed carbon content (50.5%) but lower volatile matter (29.6%) when compared to raw miscanthus. After undergoing torrefaction at 200 °C, the moisture, volatile content, H and O atoms are decreased, and the fixed carbon, ash content and higher heat value (HHV) of biochar are higher than those of raw biomass. The HHV is also increased by 27.4%. The proximate analysis show that the volatile matter in biochar is 51.5%, which is still more than that in Australia coal. This implies that using biochar with coal in co-firing will result in lower ignition temperature than for pure coal [7].

The TG, DTG and Heat flow curves of coal and biochar at various BBRs are shown in Fig. 2. The oxidation processes of pure coal exhibit a two-stage thermal degradation, which occurs in 360-720 °C and 720-820 °C, respectively. The major weight loss takes place in the first stage and the peak intensity is about 5.414 (wt.%/min) at 601 °C. In contrast to coal, the weight loss in pure biochar occurs in 220-340 °C and 360-580 °C, and the peak intensity is about 11.39 (wt.%/min) at 300 °C as shown in Fig. 2(b). This implies that the higher volatile matter content is easier to release from biochar during low temperature zone. Therefore, with the increase of BBRs, the DTG curve will significantly shift from higher temperature zone to lower temperature zone. The first stage of thermal degradation is enhanced and the second stage is declined. This is due to the differences fuel structure between coal and biochar. Besides, the maximum weight loss will shift from the second stage to the first stage when BBR=40-60 wt.% and it means the fuel properties is primarily dominated by biochar. According to the aforementioned, the thermal degradation behavior of the mixture seems like linear superposition in terms of every single material.

The ignition temperatur (T_i), burnout temperature (T_b) and combustibilty index (S) of mixtures are calculated and shown in Fig. 3. An increase in BBR leads to decrease T_i and T_b but it will increase S index of the fuel. It also reveals that S index are nearly the same in the cases of BBRs less than 50 wt.%. When BBR is higher than 50%, the S index will suddenly increase due to the larger mass loss rate and smaller T_i and T_b in biochar when compared to pure coal.

The following summarizes effects of environmental temperature and coal/biochar mixture at different BBRs on single pellet combustion process. The combustion of a solid fuel follows different steps [8], including heating up, drying, pyrolysis/devolatilization, volatiles burning, char burning and ash formation. The duration of each step is largely influenced by the particle shape, weight, volatile content and fuel nature. As shown in Fig. 4, when the pure coal pellet was suddenly dropped into the furnace at T=600 ^oC, the water evaporation and volatile gas release occur from the pellet surface to its interior due to the heat transfer. When the released volatile gas reaches to a critical condition, the gas phase reactions take place (ignition) and the pellet was wrapped around by the diffusion flame. In this case, the ignition occurs at t=27.6 s. When the diffusion flame was disappeared (t=97.5 s), the oxygen molecular will diffuse into the pellet surface and react with the char, which results in the phenomena called "char burning". On the other hand, it shows that ignition occurs earlier (t=11.4 s) and the flame length is longer in BBR=60% when compared to pure coal. The reason is due to the high pyrolysis reaction rate and volatile gas concentration in biochar.

Fig. 5(a) shows a typical mass loss history of single pellet at each regime. It reveals that the maximum weight loss takes place in the volatile burning regime. The char oxidation process usually takes a long time with a fixed mass loss rate. The mass loss history of pellet combustion at different BBRs are presented in Fig. 5(b). According to the results, the rate of weight loss will increase with increasing BBR and the environmental temperature. The primary reason is that biochar has more volatile substance but less fixed carbon content when compared to pure coal. Besides, it is worth noting that the rates of weight loss in the char burning regime for different BBRs are almost unaffected at the temperature of 600 and 700 ^oC. It is suspected that the raction rate of char oxidation process (heterogeneous combustion) is primarily dominated by oxygen molecular diffusion [9].

Fig. 6 shows the ignition delay time (t_i), volatiles burning time (t_{flame}) and total combustion time (t_{total}) for different BBRs and environmental temperature. Ash content is measured when the char burning process is finished. The results show that the volatile flame can not be observed for all the BBR cases at T=500 ^oC. When the furnace temperature increases to T=550 ^oC, gas phase ignition can be found when BBR>60 wt.% and it occurs in all the cases when the furnace temperature reaches to 600 or 700 ^oC. As the results shown in Fig. 6, t_i and t_{total} are reduced with increasing BBR and furnace temperature. t_{flame} is slightly increased when BBR>20 wt.% and it seems that t_{flame} is larger at T=600 ^oC when compared to the case at 700 ^oC. The reason may be believed that the release rate of volatile matter is smaller in lower environmental temperature. However, the ash content in pure coal and biochar is about 18.9 and 12.9 wt.%, respectively. This implies that using biochar to replace partial coal may not only reduce carbon emission but also reduce the cost associated with ash disposal in the coal-firing system.

4 Conclusions

To investigate the combustion characteristics of coal and miscanthus floridulus biochar mixtures with different blending ratios, thermogravimetric analysis was employed to observe the thermal behavior of the fuel. The single pellet combustion was also carried out by using a laboratory scale free-drop furnace at different temperatures.

According to the results, biochar possesses higher volatile substance but less fixed carbon and ash content when compared to pure coal. An increase in BBR leads to decrease ignition temperature and burnout temperature but it will increase combustion characteristic index (S) of the fuel. The maximum weight loss will shift from high temperature regime to low temperature regime when BBR=60 wt.%. In the real combustion, the ignition delay time and char combustion time will reduced, flame length and the rate of weight loss will increase with increasing BBR and in higher environmental temperature. On the whole, the co-firing of miscanthus floridulus biochar with coal obviously improves flame stability and combustion characteristics.

Table 1: Properties of coal and raw/torrefied miscanthus floridulus.

Fuel type	Proximate analysis (wt. %)				Elemental analysis (wt. %)					HHV (kcal/kg)
	M	VM	FC	Ash	C	H	O	N	S	
Australia coal	1.42	29.63	50.51	18.44	73.3	4.17	5.25	1.14	0.52	6122
Raw miscanthus	7.11	69.11	16.53	7.25	44.85	6.55	48.06	0.04	-	3758
Biochar (200 °C torrefied)	2.92	51.51	31.54	14.03	48.92	5.74	33.95	0.64	-	4788

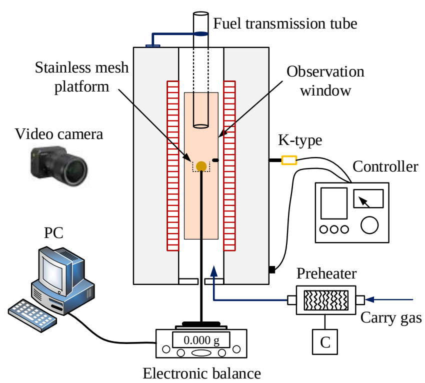

Figure 1. Schematic diagram of single pellet combustion system.

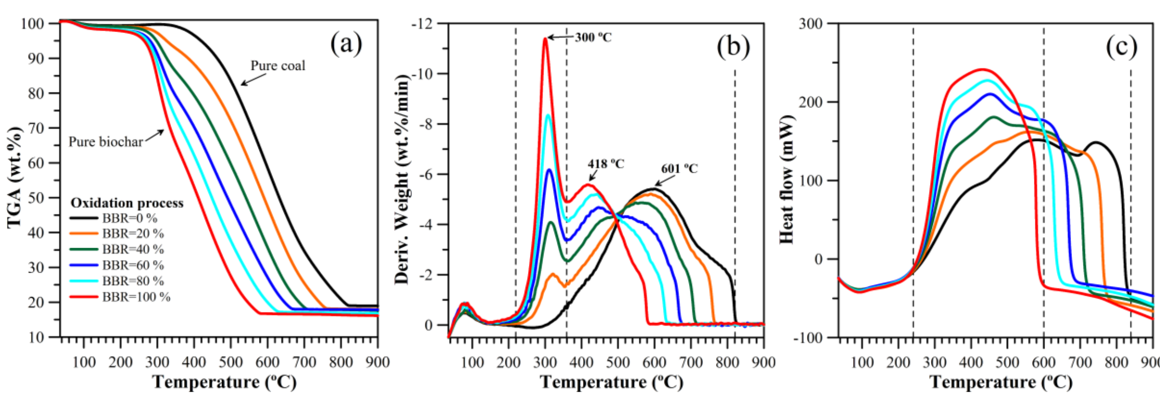

Figure 2. TGA burning profile of coal and miscanthus biochar at different BBRs. (a)TG curve, (b)DTG curve and (c)Heat flow curve.

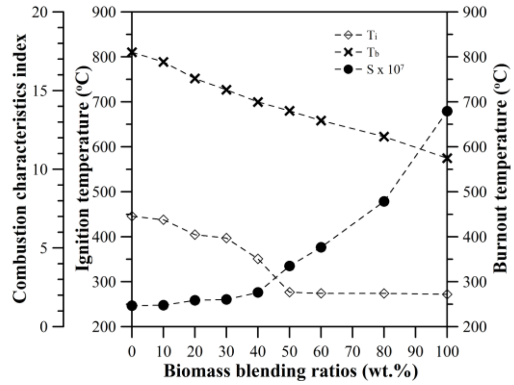

Figure 3. Ignition temperature, burnout temperature and combustion characteristics index (S) of coal and biochar at different BBRs.

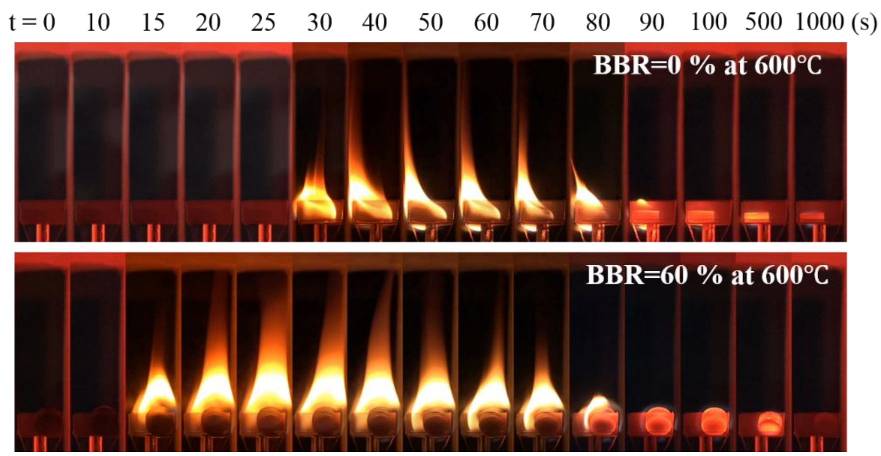

Figure 4. Combustion steps of pellets when BBRs= 0 and 60 wt. % at 600 °C.

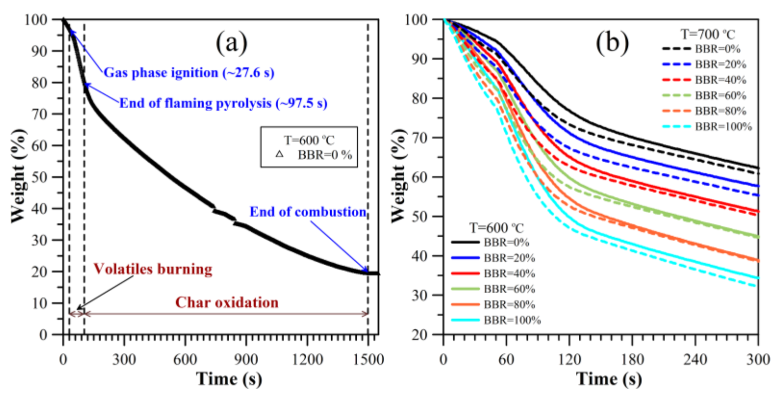

Figure 5. The variation of weight for (a)coal pellet and (b)pellets at different BBRs with time.

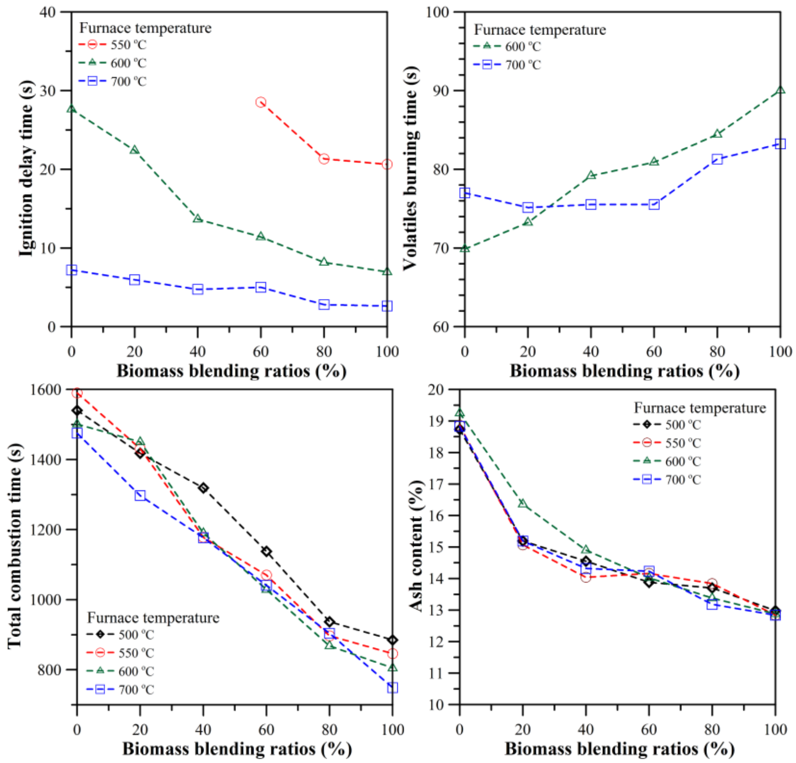

Figure 6. Ignition delay time, volatiles burning time, total combustion time and ash content of coal/biochar pellet at different BBRs and temperature.

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