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Full Length Article

Carbonization and combustion characteristics of palm fiber

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ABSTRACT

The carbonization of palm fiber with a muffle furnace was investigated by thermogravimetric analysis. The experimental results showed that palm fiber char has better combustion properties than those of palm fiber. The palm fiber char yield decreases with the increase in carbonization temperature. From 200 °C to 300 °C, the mass loss rate of palm fiber char is 45.97%. As the carbonization temperature increases, the high heat value of palm fiber char increased by 41.39%. The palm fiber char exhibited lower moisture and volatile, higher energy density and heating value. With the rise in temperature, the H/C and O/C decreased from 14.31 and 76.01 to 0.15 and 5.80, respectively. As the carbonization temperature increases, the ignition temperature and the average combustion rate increase, accordingly. The maximum combustion rate of the palm fiber char at 400 °C is 2.87 mg/min. The comprehensive combustion index increases by approximately 12 times from 200 °C to 400 °C.

1. Introduction

Today, fossil fuels are being exhausted, and the degradation of the ecological environment, as well as increasing energy and environmental problems have restricted the development of the world economy, and therefore, it is imperative to develop new clean alternative energy [1,2]. Biomass includes wood and wood waste, crop and byproduct waste, livestock waste, city solid waste, and aquatic plant waste [3], which has lower ash and almost no sulfur. The utilization of biomass for energy should be vigorously developed because the discharge of pollutants can be efficiently reduced during the process [4,5].

As one of the biomass thermochemical conversion technologies [6], carbonization technology refers to the process whereby biomass is heated and forms biochar after thermal decomposition under anoxic conditions [7]. The disadvantages of biomass such as difficulty in transportation, low melting temperature, and caloric value can be efficiently improved, the energy density and storage characteristics of biomass can be efficiently advanced, and the heat and energy of carbonized products can replace non-renewable fossil fuel [8]. By this technology, biomass material has the advantages of being readily combustible and having low bulk density and high caloric value after carbonization, and it also can be used as a fertilizer, to decrease water pollution, and for soil remediation [9].

Combustion characteristics are very important for the direct utilization of biomass, which is why combustion characteristics of biomass are widely studied around the world [10]. Liu, Z. et al. [11] studied the combustion characteristics of bamboo char, and concluded that this char had higher energy density and higher heating value (HHV), lower hydrogen to carbon (H/C) and oxygen to carbon (O/C) ratios, and more stable combustion with higher thermal efficiency compared with bamboo. Lu K. M. et al. [12] investigated the properties of oil palm fiber and eucalyptus pretreated with nitrogen and air atmospheres at temperatures of 250–350 °C for 1 h. Based on energy and solid yield and introducing an energy-mass co-benefit index (EMCI), oil palm fiber pretreatment under nitrogen at 300 °C provided the solid fuel with higher energy density and less volume compared to other temperatures. Idris J. et al. [13] proposed a self-sustained carbonization system based on oil palm biomass and tested it at the pilot scale. The obtained HHV was between 23 and 25 MJ/kg with low gaseous emissions. Qi J. et al. [14] investigated carbonization of biomass at different temperatures (300–800 °C). Based on ultimate analysis, they provided an estimation method for higher heating value for torrefied/carbonized biomass. Cao J. et al. [15] investigated the kinetics of lignin carbonization by a Thermo-Gravimetric Analyzer coupled with a Fourier Transform Infrared Spectrometry (TG-FTIR). The amorphous carbon basically formed in the temperature of 500–900 °C with an activation energy of 70 kJ/mol. Álvarez, A. et al. [16] used thermal analysis and analysis with the Coats-Redfern method to determine the kinetic parameters of 28 typical biomass samples and proposed a two-stage reaction model. The model was not suitable for use with the Flynn-Wall-Ozawa (FWO) method or the Kissinger-Akahira-Sunose (KAS) method to solve the dynamic parameters of biomass combustion. Determination of most of

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the biomass combustion properties is concentrated in parameter optimization and system process control, especially in the combustion process and dynamics parameters [17,18]. Therefore, to study combustion characteristics, the thermochemical behavior of biomass should be studied first.

Oil palm is a typical biomass commonly found in western Africa, southeast Asia, Latin America, and India [19,20]. Palm fiber is a byproduct obtained after oil extraction of oil palm, and the reserve of palm fiber is very rich and it is potentially a low-cost material for production of energy densified carbonaceous products [21,22]. Palm shells and palm fiber, which are byproducts of the oil extraction process, are also being increasingly accepted by new energy companies as environmentally friendly material. Palm fiber can be used for fuel [23], but it is difficult to control the combustion process as a result of the presence of water and a high degree of moisture. In the process of carbonization, the volatile compounds of biomass are reduced, and the carbon content increases [24]. Therefore, carbonization is an efficient way to improve its combustion. Because of a lack of research, it is necessary to study the combustion characteristics of palm fiber char. The range of temperature for carbonization is 200–800 °C, which is of significance to the design and operation of palm fiber combustion and the design and operation of the combustion system.

2. Materials and methods

2.1. Materials

Palm fiber was used in the experiment for the current study that was conducted in Jiangsu Province of China. The proximate and ultimate analysis (Proximate Analyzer: 5E-MAG6700, Changsha Kaiyuan Instruments, PRC; Ultimate Analyzer: vario MACRO cube, Elementar, Germany) is shown in Table 1. The particle size distribution of the biomass feedstock used in carbonization and combustion experiments is less than 0.074 mm.

2.2. Experimental setup

There are three types of carbonization devices (external heat, internal heat, and self-ignition). For the external heat and internal heat ones, the heat source heats the biomass directly or indirectly. Self-igniting devices have the lowest energy consumption. Its heat comes from the combustion of gases generated by the thermal decomposition of biomass during the carbonization process. To avoid the phenomenon of incomplete carbonization in self-ignition carbonization devices, this experiment adopted sub-stage carbonization according to the three stages of distillation (drying stage, distillation stage, and insulation stage).

An electric furnace was used, and the suitable heating temperature range used was from room temperature to 800 °C. The temperature accuracy of ± 5 °C. Firstly, the sample was ground and then screened

Table 1
Proximate and ultimate analysis of palm fiber.

Contents	value	Unit
A_{ad} [a]	4.13	%
V_{ad}	73.5	%
FC_{ad}	20.11	%
M_{ad}	3.11	%
C_{ad}	48.44	%
H_{ad}	6.93	%
O_{ad}	36.82	%
N_{ad}	2.05	%
S_{ad}	0.11	%
$Q_{net,d}$	19.86	MJ/kg

$Q_{net,d}$: net calorific value, dry basis.
[a] ad: air-dry basis.

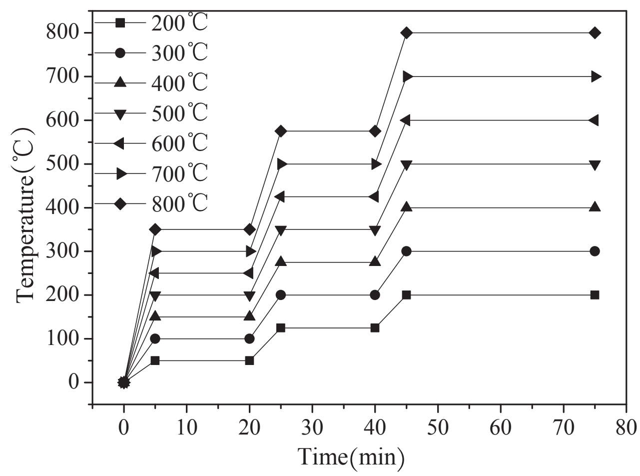

Fig. 1. Temperature variation in the furnace.

with a 200-mesh sieve. The carbonization temperature was determined by the final temperature in the furnace. There were three stages of heating during the total carbonization time of 75 min, consisting of first and second stages of 15 min, while the third stage was 30 min. The temperature variation in the furnace is shown in Fig. 1.

The experimental procedure was as follows. Palm fiber was filled and sealed in a weighed crucible. The crucible was put in the center of a furnace and heated according to the temperature variation set. After the heating was finished, the sample was taken out of the furnace at 150 °C and placed in a dryer to cool to room temperature. The sample was weighed again. The yield of biochar (φ_m) refers to the ratio of the mass of the sample after carbonization (m_2) and before carbonization (m_1), which is shown in Eq. (1).

$$\varphi_m = \frac{m_2}{m_1} \times 100\% \tag{1}$$

In this study, a thermogravimetric analyzer (Mettler-Toledo DGA, USA) was adapted to conduct tests. The test conditions of thermogravimetric analysis are as follows:

(1) Temperature range: 25–800 °C
(2) Heating rate: 15 °C/min;
(3) Test atmosphere: O_2;
(4) Gas flow: 50 ml/min;
(5) Quantity of the micro-sample: 10 mg
(6) Balance accuracy: 0.1 μg
(7) Crucible capacity: 900 μL

Through TG-DTA, the ignition temperature (T_i), maximum combustion rate (V_m) and the temperature corresponding to that rate (T_m), average combustion rate (V_{mean}), burnout temperature (T_h), and comprehensive combustion characteristic index (S) could be obtained.

The graphed ignition temperature T_i formed a vertical line down the peak of the DTG curve, and the vertical line intersected with TG curve at a point and made a tangent line at the point. The horizontal ordinate of the tangent line and the focus of the smooth curve after dehydration is the ignition temperature T_i. The maximum combustion rate is the point with the most significant change in the TG curve, and the corresponding temperature is the maximum combustion rate T_m:

Average combustion rate V_{mean}

The formula is shown in Eq. (2):

$$V_{mean} = (w_1 - w_2)/t \tag{2}$$

where w_1 is the weight of the sample when the ignition point was reached, w_2 is the weight of the sample when burnout temperature was reached, and t is the interval between two temperatures.

Burnout temperature T_h refers to the temperature when the DTG