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Development of an ultra-small biomass gasification and power generation system: Part 1. A novel carbonization process and optimization of pelletization of carbonized wood char

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ABSTRACT

Small-scale, distributed and low cost biomass power generation technologies are highly required in the modern society. The biomass pretreatment process, that is, a combination of carbonization and pelletization processes of cedar wood were explored in this study. For the carbonization process, a novel carbonizer composed of one carbonization chamber and one combustion chamber was tested, and the mass and energy balances during cedar wood carbonization at 400–500 °C were analyzed, respectively. During the initial heating stage, about 22 kg of wood with dry basis should be supplied into the combustion chamber through several batches. When the temperature in the carbonization chamber reached to the range of 200–220 °C, the combustion chamber could be self-heated by burning the pyrolysis gas (tar vapor, CH_4, H_2, CO) sent from the carbonization chamber. The specific wood consumption for producing 1 kg of wood char was within 3.6–4.4 kg, which presented an increase trend with increasing the carbonization temperature. Moreover, this carbonization system can deal with different kinds of biomass with various water contents and shapes. For the pelletization process, effects of adding amount of the binder (poval solution), water and the carbonization temperature on the pellet quality were studied so as to explore the optimal condition for making high quality pellets from the crushed wood char. The results indicated that there was an optimal ratio among char, added water, and the binder for making high quality pellets. Considering the energy transfer efficiency and pellet quality, the mass ratio of 0.93:0.32:0.10 for 450 °C-char in the dry basis: added water plus water in char: poval solution was the optimal condition for making high quality pellets.

1. Introduction

Biomass resources have been getting more and more attentions for the heat and energy utilization processes [1–4]. In the rural area of Japan, many houses are always built by the high-density synthetic wood which is mainly composed of cedar wood. A number of buildings collapsed after the natural disasters such as big earthquakes and floods. How to rationally make full use of these waste wood materials is still a challenge in Japan as the high transport cost and low energy density of wood, especially in the rural places. Also, ticklish problems on how to deal with the frozen food appear when the power is cut off for a long time in the disaster area. Development of portable ultra-small biomass gasification and power generation system may be a feasible technology for the on-spot utilization of these waste biomass resources to supply electricity in the disaster area.

So far, the downdraft and updraft gasifiers are extensively applied in the small scale power generation system as these two kinds of gasifiers present simple structure and are easily operated and transferred to realize portable and distributed characters [5–9]. It is well known that the capacity and stability of power generation depends a great extent on the quality of the syngas from the gasifier. Compared to the downdraft gasifier, the updraft gasifier can produce higher quality gas with higher calorific value due to more complete char burnout and better internal heat exchange [10–12]. However, the big problem associated with the updraft gasifier is a series of issues caused by the tar content. If the wood is directly gasified, the excessive tar released will easily damage the engine [13–15]. In addition, wood wastes found in disaster areas may have high moisture content as well as various shapes and size, which are not appropriate for direct usage as a gasification fuel. Therefore, wood and other biomass wastes available in disaster areas need some pretreatment. In this research, such biomass wastes were firstly carbonized to remove water and tar components, then pelletized to be used as fuels for the gasification and power generation system.

In most of the reported literatures, electrical heating was required

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Table 1
The characteristic data of cedar wood.

Sample	Proximate analysis/d, wt%			Ultimate analysis/d, wt%				LHV/MJ·kg^{-1}
	VM	FC	Ash	C	H	N	O*	
Cedar wood	72.95	26.83	0.21	36.08	4.43	0.11	59.38	18.8

Note: VM – volatile matter; FC-fixed carbon; d-dry basis; O* was calculated by difference. LHV denotes the low heating value of wo.

for the carbonization process.[16–20] In our research, a novel carbonization system, composed of one combustion chamber and one carbonization chamber, was adopted for carbonizing wood (4 h/batch, 80–100 kg raw wood/batch). Initially, the wood supplied in the carbonization chamber is heated by the combustion heat of wood supplied in the combustion chamber. When the pyrolysis gas (including tar vapor, CH_4, H_2, and CO et.al) is produced, this gas will be transferred to the combustion chamber, and then, the carbonization chamber will be self-heated by burning the pyrolysis gas in the combustion chamber. Therefore, this system requires no electricity supply and is also user-friendly and portable, which is very suitable for the pretreatment of biomass wastes in disaster areas including food wastes. In addition, most of tar components can be removed through the carbonization process which will significantly alleviate the tar problem associated with the gasification process.

The carbonized wood then will be crushed and pelletized so as to increase the volumetric energy density of char and assure stable operation of the gasifier. The ideal reaction form of pellets in the downdraft or updraft gasifier is the unreacted shrinking core model. The time of the stable operation of the gasifier will be relatively extended if the pellets can maintain a certain particle shape for a longer time so as to avoid the adverse reaction conditions such as the channeling and the hot-spot. As pellets will receive a certain static pressure in the bed of the gasifier, it is especially important to make pellets with high strength. Moreover, a high bulk density of pellets will be favorable for improving the production rate of the syngas.

The pelletization process that use uncarbonized wood as the feedstock has been reported by many researchers [21–29]. However, pelletization combined with a foregoing carbonization step was rarely reported [30–35]. In 2005, a combination of torrefaction and pelletization process (TOP) was proposed by Energy Research Centre of Netherlands (ECN) [36]. Binders were always added for making pellets of raw biomass and the corresponding char, which included representative organic binders, such as lignin and starch [30–32], as well as the inorganic binders, such as calcium chloride ($CaCl_2$), calcium oxide (CaO), $Ca(OH)_2$ and NaOH [31,32]. As the carbonized pellets will be gasified in our research, thus the binder should not only assure the strength of pellets with low cost, but also not bring issues of device erosion and environmental pollution. The alkali metal or chlorine contained binders should be avoided as the cations are prone to cause slagging inside gasifiers and the anion can lead to device corrosion. Based on this consideration, an environment friendly binder should be properly adopted to produce high quality carbonized pellet. It is well known that poval can be used for polyvinyl acetate emulsions, specifically in wood and paper adhesives, and it is also an environment friendly agent with relatively low cost and high stability at room temperature. This paper is the first to explore using poval for binding carbonized wood char. Among the factors, the adding amount of poval solution, water, and carbonization temperatures present key effects on the quality of pellets. Therefore, the pelletization process of woody char was studied so as to explore the optimal condition for making high-quality pellets for the future gasification experiments.

2. Materials and methods

2.1. Char preparation

The cut cedar wood block was obtained from the disaster area of Japan. Table 1 shows the characteristic data of this wood. The woody char preparations were carried out in an almost energy-free carbonizer with a moving sample carrier. Initially, the wood in the carbonization chamber was heated from the combustion heat of wood in the combustion chamber. When the pyrolysis gas (including tar vapor, CH_4, H_2, and CO et.al) was significantly produced, the whole carbonization system could realize self-heating through the heat from the combustion of the pyrolysis gas as shown in Fig. 1. The exhaust smokestack was always opened for discharging of flue gas. However, the emergency smokestack was initially closed, and would be switched on or off for several times according to the target carbonization temperature. The carbonized wood char was prepared in the temperature range from 400 °C to 500 °C with an interval of 25 °C so as to explore the effect of the carbonized temperature on the pellet quality. Our heat exchange system is based on the design of a divided wall type heat exchanger, and the temperature distribution of the wood layer inside the carbonization chamber is uneven. The carbonization temperature denotes the gas temperature inside the carbonization chamber measured by the thermal couple in this study.

2.2. Pelletization process

After carbonizing, the char experienced grinding in a roll crushing mill (DG-230 × 300, China) with the screen size of 3 mm. As the thermocouple of carbonizer can only measure the gas temperature, it is necessary to measure the temperature distribution of wood layer. We stuck the thermal label to the inside wall of several small sealed containers to check the temperature changes at different woody layers during carbonization. Fig. 2 shows the variations of real temperatures measured by thermal labels at the center position of the upper, middle, and lower parts of woody layer, respectively. As the upper part of woody bed directly contacted with the hot gas, the temperature of this position was close to the gas temperature. The temperatures of the middle and bottom layers were lower than the gas temperature. Moreover, the bottom layer presented the lowest temperature in the woody bed during the carbonization. Therefore, the temperature decreased with the decrease of the height of the woody bed. The chars produced in different layers were uniformly mixed before each batch crush. Then the crushed char samples were mixed together with water and the binder solution in a roller mixer. After fully mixing, the moist powder was pressed in a pelletizer fixed with a pair of revolving rollers (F-5/11–175, Japan) for making pellets as shown in Fig. 3. The production rate of pellets was about 10 kg·h^{-1} in this study.