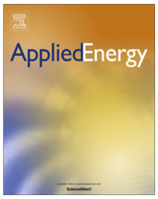
Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Characterization of solid and liquid products from bamboo torrefaction ☆

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HIGHLIGHTS

- Torrefaction temperature of 300 °C is recommended for upgrading bamboo.
- Acids, alcohols, ketones, phenols, aldehydes, esters, etc. are detected in condensable liquids.
- The contents of acids and alcohols in condensable liquids are richer.
- The pH value of condensable liquid is close to that of bio-oil.
- Dewatering is an important process to upgrade liquid product as a fuel.

ARTICLE INFO

Article history:
Received 5 October 2014
Received in revised form 2 March 2015
Accepted 4 March 2015
Available online xxxx

Keywords:
Torrefaction
Biomass and bamboo
Water and dewatering
Viscosity
pH
Energy yield

ABSTRACT

Solid and liquid products from bamboo (*Bambusa sinospinosa*) torrefaction were analyzed in the present study. Three different torrefaction temperatures of 250, 300, and 350 °C and three torrefaction durations of 30, 60, and 90 min are taken into consideration. The properties of both solid and liquid products are sensitive to the torrefaction temperature, whereas the influence of duration is relatively slight. Among the torrefaction temperatures of 250, 300, and 350 °C, 300 °C is recommended for upgrading bamboo in that it gives a more appropriate operation to enhance the higher heating value of the biomass while the solid yield is not too low. In the liquid products or condensable liquids, acids, alcohols, ketones, phenols, aldehydes, esters, etc. are detected. The contents of acids and alcohols in the liquids are richer, and acid formation is especially significant at the torrefaction temperature of 250 °C. The pH value of the condensable liquid is in the range of 2.27 and 2.60 which is close to that of bio-oil. The water content in the liquid product is around 50% and an increase in torrefaction temperature lowers the content. After undergoing dewatering, the calorific value of the liquid product is enlarged in a significant way. The results show that dewatering is an important process to upgrade the liquid product as a fuel.

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1. Introduction

Bioenergy is an important renewable energy and it has been extensively employed worldwide, regardless of developed, developing, and under developed countries. Biomass can be consumed as energy in the solid, liquid, and gas phases. In the solid phase, biomass can be used in the forms of powder, pellet, block, and briquette, etc [1–3]. In the liquid phase, biodiesel, bioethanol, and bio-oil have been widely employed in vehicles and industries [4,5]. With regard to the gas phase, syngas from gasification [6] as well as biogas and biohydrogen [7,8] from fermentations have also received a great deal of attention for their applications in industries.

Solid biomass can be burned directly for heat and power generation [9]. Recently, the product of biochar from solid biomass has also been studied extensively [10]. The moisture and elemental oxygen and hydrogen contents as well as the volume of raw biomass are high, whereas its calorific value is low [11]. Therefore, the utilization efficiency of untreated biomass is low. After undergoing the pyrolysis process at temperatures ranging from 300 to 500 °C, the energy density of biochar is promoted greatly compared to that of raw biomass. However, the solid yield of biomass for the production of biochar is low. For example, the solid yield of mallee wood from pyrolysis at temperatures of 300–500 °C is between 25 and 55 wt% [12]. This implies, in turn, that the energy yield from biochar production is low, stemming from the pronounced weight loss of biomass.

☆ This article is based on a short proceedings paper in Energy Procedia Volume 161 (2014). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal. This paper is included in the Special Issue of ICAE2014 edited by Prof. J Yan, Prof. DJ Lee, Prof. SK Chou, and Prof. U Desideri.

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http://dx.doi.org/10.1016/j.apenergy.2015.03.022
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In recent years, numerous studies concerning biomass torrefaction have been performed and the advantages of the pretreatment method have been reported [13–15]. In brief, the properties of hygroscopicity, low atomic O/C and H/C ratio, and low calorific value of raw biomass can be improved once biomass is mildly pyrolyzed in a N_2 or oxygen-free atmosphere at temperatures of 200–300 °C for several minutes or hours [16–19]. Normally, the torrefaction duration is controlled within one hour [20]. The benefits accompanied by torrefaction also include easier grinding and storage as well as more uniform biomass products.

Solid fuels, which are made up of chars and ashes, are the prime products from torrefaction. In addition to solid products, gaseous and liquid products are also obtained from the upgrade [21]. By virtue of the release and thermal decomposition of volatiles from biomass in a torrefaction environment, the noncondensable gas products comprise primarily CO, CO_2, H_2, and small amount of CH_4 [22]; toluene, benzene, and low molecular weight hydrocarbons are also detected. The liquid products are brown or black colored, depending on the torrefaction temperature [23], and consist of condensable components, such as water, acetic acids, alcohols, aldehydes, and ketones [24]. The analysis of liquid products from gas chromatography- mass spectrometry (GC–MS) suggests that the main components in the liquid are monoaromatics; small amount of heterocyclic hydrocarbons are also obtained when the torrefaction temperature is as high as 280 °C [23].

In reviewing the published literature, it can be found that most of the studies focused on solid products and relatively little research has been carried out on gas and liquid products. The gas product typically contains 10% of the energy of biomass [22]. Because of the low heating value of the gas product, its application is limited. Though the liquid products from torrefaction have been analyzed preliminarily [23,24], the information is still insufficient. Bamboo is an abundant and fast-growing plant with high cellulose content; hence it is a feasible material for solid fuel production. In the present study, a kind of bamboo named *Bambusa sinospinosa* (*B. sinospinosa*) torrefied in N_2 will be investigated to evaluate its potential as an alternative fuel to coal. The liquid products and their properties will also be analyzed. The obtained results are able to provide a comprehensive insight into the applications of bamboo from torrefaction.

2. Experiment

2.1. Experimental apparatus

The schematic of the experimental setup is shown in Fig. 1. The system can roughly be partitioned into the following four units: (1) a gas supply unit, (2) a torrefaction unit, (3) a gas condensation and treatment unit, and (4) a solid cooling unit. Nitrogen was adopted as the carrier gas to sweep samples, and its volumetric flow rate was controlled by a mass flow controller (Alicat Scientific). The torrefaction unit comprised a cylindrical chamber and a heater (or electrical furnace). The biomass sample was placed in the chamber (i.d. × height = 125 × 440 mm), and the chamber was heated by the heater which was located outside the chamber. The torrefaction temperature was controlled by a proportional integral derivative (PID) temperature controller, and the power of the heater was controlled by a solid state relay (SSR) power controller. The condensation and treatment unit has three condensers in series followed by a conical flask. Cold water flew through the condensers to cool down the flow stream from the chamber so as to recover condensable liquids contained in the torrefaction gas. After the torrefaction the residual solid products were placed in the cooling unit until the torrefied samples were cooled down to room temperature. In the unit, the samples were placed in a vessel and the vessel was enveloped by a water jacket.

2.2. Material and experimental procedure

B. sinospinosa, a kind of bamboo, was adopted as the torrefaction material. The basic properties of the bamboo, such as fiber, proximate, elemental, and calorific analyses are tabulated in Table 1. As can be seen, the cellulose content in the bamboo is as high as 62.33 wt%. The moisture content in the biomass is also high and its value is 75.19 wt%. The higher heating value (HHV) of the

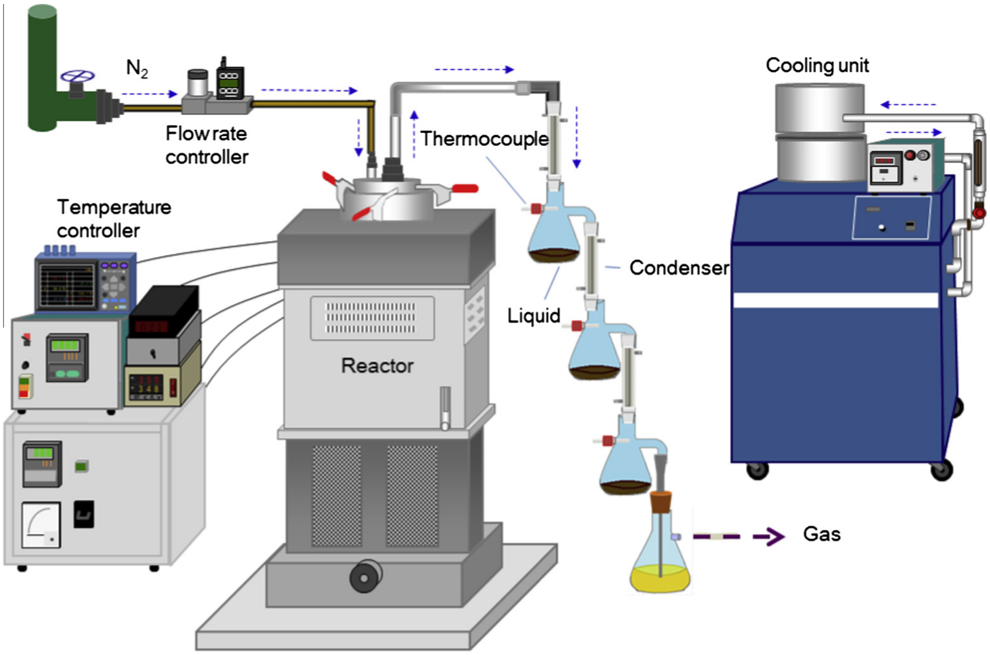

Fig. 1. A schematic of experimental apparatus.

Please cite this article in press as: Chen W-H et al. Characterization of solid and liquid products from bamboo torrefaction. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.03.022

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