Bioresource Technology 254 (2018) 130–138

Contents lists available at ScienceDirect

Bioresource Technology

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

Application of biomass pyrolytic polygeneration by a moving bed: Characteristics of products and energy efficiency analysis

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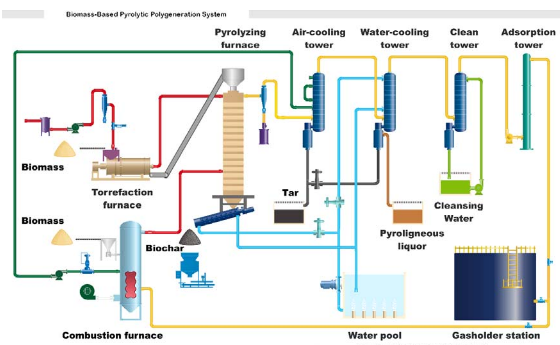
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Biomass
Agricultural waste
Pyrolytic polygeneration
Demonstration project

ABSTRACT

In order to overcome the shortcoming of batch production in the retort and improve the quality of three-state products, a moving bed as pyrolysis furnace and torrefaction pretreatment were both used in a demonstration of biomass pyrolytic polygeneration. The bench and demonstration scale experiments were both investigated in this work. The results show that when the pyrolysis temperature between 550 °C and 750 °C, it can not only maintain the relative stability of the tri-state products yield, but also guarantee the quality. When the demonstration ran at this temperature, it can continuously deal with biomass for about 7E + 03 kg/h, and reach 5.42E + 07 kg/yr, which can be converted into 1.12E + 07 Nm^3 of bio-gas, 3.78E + 06 kg of tar, 7.63E + 06 kg of vinegar and 1.14E + 07 kg of biochar. The lower heating value of bio-gas and biochar were respectively 12.5 MJ/m^3 and 30.5 MJ/kg, which showed the great potential as gas and solid fuel.

1. Introduction

Biomass, which is a renewable source of energy and the only renewable source of carbon, is inexhaustible and can be converted into fuel gas, solid char and liquid oil or other chemicals (Chen et al., 2016b; Chen et al., 2017a; Guo and Bi, 2015; Iribarren et al., 2012; Zhang et al., 2010; Zhang et al., 2014; Zhang et al., 2017). In China, there are a large amount of agricultural straw wastes to be produced annually, over 703 million tons in 2007 alone (Chen et al., 2014). However, these biomass resources are not well utilized. Farmers on-site burning is a main method to remove the agricultural straw in harvest season, which plays an important role to cause severe environmental pollution, such

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https://doi.org/10.1016/j.biortech.2018.01.083
Received 7 December 2017; Received in revised form 15 January 2018; Accepted 17 January 2018
0960-8524/

as haze.

The method of biomass resources utilization can be divided as biochemical process and thermo-chemical conversion, the later can be sub-divided into combustion, gasification, pyrolysis, etc. (Xin et al., 2013). The biomass combustion for electricity is the quickest but dirtiest approach to use its thermal energy, the potential air pollution in the form of particulates and the huge cost of collection, transport and store have been restricting the development of the combustion. In addition, due to the very low efficiency of biomass and dated means of biomass in China, the majority of them are burned on spot though policies limiting or banning biomass burning have been widely enacted (Wang et al., 2014). Compared with the combustion focusing on heat generation, the purpose of gasification is to create valuable gaseous products (e.g. H_2, CO, CO_2, CH_4, etc.) with specific heating values in the presence of a partial oxygen (O_2) supply (typically, 35% of the O_2 demand for complete combustion) or suitable oxidants such as steam and CO_2 (Zhang et al., 2010). The product of gasification, syngas, is a gaseous form of bioenergy that can be used directly for combustion, or be stored for other applications. The biomass gasification technology has been utilized commercially in China, and there have been more than 70 biomass gasification systems for household cooking in the 1990s (Zhou et al., 2012). However, the heat value of the biogas generated from the current air-gasification technology is only 3–5 MJ/m^3, which is not sufficient for the energy requirements, and there is so much tar in biogas generated during air gasification, which is bad for its use. In addition, the economic benefits of gasification is low due to the single product (Chen et al., 2012; Yang et al., 2014). In contrast to combustion and gasification, pyrolysis takes place in the absence of oxygen to convert biomass into solid biochar, liquid (bio-oil), and biogas at high temperatures. No gasification medium is required in the pyrolysis process, so the heat value of pyrolysis biogas is higher than the gasification (Aysu and Küçük, 2014; Biswas et al., 2014; Bridgwater, 2012; Demirbas and Arin, 2002). In addition, the products of pyrolysis are diversified, which is beneficial to their utilization and economic efficiency (Tinwala et al., 2015; Xin et al., 2013). Therefore, pyrolysis is considered to be an industrially realized process for biomass conversion, and plays a crucial role in biomass thermochemical conversion.

In recent studies, based on the diversity utilization characteristics of pyrolysis products, one promising thermochemical conversion technology, biomass pyrolytic polygeneration of solid biochar, liquid bio-oil, and biogas from straws, has been investigated. Chen et al. (2012) studied the process of biomass-based pyrolytic polygeneration on cotton stalk pyrolysis in a laboratory scale, and found that 650 °C was considered as the optimum operating temperature of biomass pyrolytic polygeneration. At this pyrolysis temperature, a higher calorific value (~28 MJ/kg) of biochar and a higher calorific value (8–9 MJ/m^3) of biogas can be obtained, but the quality of bio-oil is still poor. It is because that the low qualities of biomass stalks, including high oxygen content, high water content, hydrophilicity and low energy density, limit the improvement on the quality of pyrolysis products (Chen et al., 2015). Prior to the pyrolysis, torrefaction pretreatment of biomass stalks is usually considered to improve its quality for efficient energy conversion. Chen et al. (2015) discussed the effect of torrefaction on the tri-state products yield and quality of pyrolysis polygeneration. They found that the torrefaction of cotton stalk could enhance CH_4 and H_2 formation to increase the heat value of biogas in pyrolysis process. For bio-oil, it reduces acids but increases phenols content. In addition, the water content of bio-oil deceased obviously, leading to a noticeable increase in the heat value of bio-oil. However, at present, the torrefaction pretreatment of biomass stalks before pyrolysis is still in the laboratory, and it is scarce in industrialized applications.

In the existing reports, the retort reactor is a commonly used reaction unit for realizing industrially pyrolytic polygeneration. Yang et al. (2016b) introduced the application of biomass pyrolytic polygeneration technology using retort reactors. They stated that the commercial biomass pyrolytic polygeneration factory using retort reactors had high performance in converting straw to high value products. However, the structural characteristics of retort reactors determine that they can only be fed in batches, which results in its some disadvantages, such as the failure of continuous feeder, high-energy consumption, low efficiency etc.

Table 1
Ultimate and proximate analysis of raw stalks.

	Poplar chip	Bamboo chip
Ultimate analysis (wt.%)		
M_{ar}	10.87	12.13
M_{ad}	4.09	6.22
V_{ar}	76.45	75.5
A_{ar}	1.11	2.17
FC_{ar}	11.57	10.20
Proximate analysis (wt.%)		
C_{ar}	44.11	39.32
H_{ar}	5.81	5.52
N_{ar}	0.07	0.25
S_{ar}	0.15	0.14
O_{ar}[a]	37.88	40.47
LHV (MJ/kg)	17.63	16.86

ar: as received basis; ad: air dry basis.
[a] By difference.

Therefore, in order to overcome the above shortcomings of retort reactors and draw the advantages of the torrefaction pretreatment on biomass pyrolytic polygeneration, a moving bed was used as a pyrolysis furnace in the biomass pyrolytic polygeneration system to achieve the continuous production in this work. At the same time, biomass torrefaction was used as a pretreatment to improve the quality of the three-state products.

2. Materials and methods

2.1. Materials

Poplar chip and bamboo chip, obtained from Ezhou, Hubei province, China, are used as the feedstock in this study. The results of their ultimate and proximate analyses are listed in Table 1. It shows that the poplar chip contains lower moisture and oxygen content, and higher volatile and carbon content than bamboo chip, which is the reason that the poplar chip has a higher lower heating value (LHV).

2.2. Pyrolytic polygeneration system

2.2.1. Bench-scale experiment

The bench-scale pyrolysis experiment is implemented in a self-made vertical reactor, which mainly consisted of three parts: a vertical stainless steel tube with a moving silica sample-carrier, an ice cooling system for collecting liquid product, and a gas cleaning-drying system for collecting gas product (Chen et al., 2012). Prior to the experiment, the bamboo chip was first dried at 105 °C for 2 h, then crushed and sieved to obtain particles ranging from 0.1 to 1 mm in size. For each trial, nitrogen (99.99%, 1 L/min) as a carrier gas to provide an inert atmosphere, when the reactor reached the preset pyrolysis temperature (from 250 °C to 950 °C), about 3 g of bamboo chip was loaded into the sample carrier, quickly pushed into the heated zone, and held for 30 min. During the pyrolysis process, the condensable volatiles (liquid product) was collected in the ice-water condenser, and the liquid product yield was obtained by calculating the increase in weight of the condenser system. The non-condensable volatiles were filtered through a glass wool filter and dried using silica gel for collecting, and all collected gases removed the carrier gas to obtain the gas product yield. After pyrolysis, the solid product in the reactor was cooled in an N_2 atmosphere, and was weighed for calculating the solid product yield. The obtained solid product in different temperature were labeled