Fuel Processing Technology 179 (2018) 17–31

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Research article

Design and operation of a low cost bio-oil fast pyrolysis from sugarcane bagasse on circulating fluidized bed reactor in a pilot plant

Wasakorn Treedet, Ratchaphon Suntivarakorn*

Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, 123 Moo 16, Mittraphap Rd., Nai-Muang, Muang District, Khon Kaen 40002, Thailand

ARTICLE INFO

Keywords:
Bio-oil
CFBr
Low-cost bio-oil
Sugarcane bagasse
Fast pyrolysis

ABSTRACT

This article presents a design study and the development of a low-cost production process for obtaining bio-oil from sugarcane bagasse by using a Circulating Fluidized Bed reactor (CFBr). The reactor had a diameter of 4 in. and a height of 4.5 m. In addition, sand with a diameter of 249 μm was used as the bed material. Sugarcane bagasse was used as the raw material for the bio-oil production. This bio-oil production system had a feed rate of between 18 and 45 kg/h. The outstanding design of this system consisted of the production of a bio-oil with high efficiency by using the following: (1) a gas combustor used in gas turbine engine, (2) a non-condensable gas recovery for use in the process, and (3) a feeder and pre-heat exchanger before condenser unit. The experiment was performed at a superficial velocity of between 5 and 7 m/s, with a bed temperature ranging from 440 to 520 °C, and with a bed inventory at 0.5 and 4.5 kg. From the experiment, it was found that this system could produce a maximum yield of bio-oil of 78.07 wt% at the bed temperature of at 480 °C. In addition, the superficial velocity, the bed inventory, and feed rate were 7 m/s, 4.5 kg, and 30 kg/h, respectively. The properties of the bio-oil, such as its heating value, viscosity, density, and pH were measured at 18,483 kJ/kg, 24.54 cSt, 1274 kg/m^3, and 2.4, respectively. The chemical components of bio-oil were also investigated by GC–MS. In this system, the cold efficiency and total energy conversion to bio-oil production were 46.06% and 32.94%, respectively. From a cost analysis of bio-oil production, the results showed that the cost production was 0.353 $/l. In addition, the results revealed that the bed temperature, the solid re-circulating rate, and the suspension density had significantly and directly affected the yield of bio-oil production. Furthermore, the oxygen in the exhaust gas from the combustion system and the non-condensable gas from the process had been shown to have a direct effect upon the properties of the bio-oil.

1. Introduction

Bio-oil is product of the pyrolysis process. The pyrolysis process is one of the molecular thermal decomposition processes that occurs in absence of oxygen or when there is very little oxygen content at atmospheric pressure. The relationship of each thermal conversion process and the oxygen requirements are summarized in literatures [1–3]. Currently, bio-oil is used widely as an alternative fuel for many applications [4–6] because the raw materials for bio-oil production are not limited. Another reason is that, the emissions arising from bio-oil combustion have low carbon dioxide, sulfur, nitrogen, and ash contents as compared to many coals and oils [7–9], which makes them an excellent choice for reducing greenhouse gases [10]. For this reason, many countries such as USA [11], EU [12] and Thailand [13] have created a number of policies to encourage the production and utilization of bio-oil to support sustainable energy and to solve global warming in their countries.

Bio-oil has been observed as an important alternative energy and as a future replacement for fossil oil, which has a potential for raw materials, production technology, and utilization [14]. From a comparison of the results of the production cost of liquids fuel per energy unit, it was found that bio-oil had a value ratio of 4.04 $/GJ [15]. In contrast, conventional petroleum fuel and alternative fuels, such as Gasoline, Diesel fuel, Kerosene, Bio-ethanol, and Bio-diesel had shown value ratios of 10.7, 9.5, 10.3, 21.1 and 21.0 $/GJ, respectively [16]. Regarding the input costs of Bioethanol and Biodiesel, the major economic factor

* Corresponding author.
E-mail address: ratchaphon@kku.ac.th (R. Suntivarakorn).

https://doi.org/10.1016/j.fuproc.2018.06.006
Received 6 March 2018; Received in revised form 28 May 2018; Accepted 8 June 2018
0378-3820/

to be considered was the raw materials, which account for about 75–80% of the total operating costs. This differs from bio-oil because bio-oil can be produced by using agricultural residues as the raw materials. Although, bio-oil has a lower production cost than another liquid fuels, its quality needs to be improved due to the fact that it is acidic and has a higher water content and viscosity [17]. Based on this reasoning, it cannot be concluded that bio-oil has a lower production cost than other liquid fuels. For example, regarding the cost of the bio-oil upgrade with emulsification carried out by the Future Blend Company, Ltd., it was found that cost of the bio-oil upgrade had been between 0.3 and 0.48 €/l [18]. Thus, the way to upgrade the potential for using bio-oils instead of alternative fuels is to develop a production system and to improve the upgrading method in order to reduce the production costs. Accomplishing this will help to create opportunities to use bio-oil as an economic fuel.

Presently, many research studies in the literature have shown a high performance and very complicated process for low-cost bio-oil production, which are shown as operations that range in size from lab-scale to commercial scale [18–20]. The results from the study of bio-oil production have indicated that the following factors affect the quality and quantity of the bio-oil: (1) the concentration of oxygen content in reactor, (2) the size and moisture content of the biomass, (3) the feed-rate, (4) the time residence of the reaction, and 5) the characteristics of the heat transfer to the biomass [6, 21]. The time residence and heat transfer ability were set by type and operation for each of the reactors. From a review of the literature, it was found that an auger, bubbling fluidized bed reactor (BFBr) and circulating fluidized bed reactor (CFBr) have a market attractiveness that can be scaled-up for commercial usage [2, 6, 19]. Therefore, many of these reactors have been developed as commercial-scale bio-oil production systems [18–20]. However, the most important factor for yielding large quantities of bio-oil has been the reaction temperature of the biomass [22–28]. Therefore, the design of a heat generation system for the pyrolysis process is very important because the major production costs incurred in producing bio-oil has been the cost of the heat generation system. Thus, the researcher or company, who can create a method to produce the bio-oil at the lowest possible cost, will have an opportunity to create a bio-oil production system that can compete with other fuels on the market. For this reason, many researchers have created various methods to produce low-cost bio-oils. There are 5 different methods as follows:

I. Reusing a Non-Condensable Gas (NCG) as a medium to convey heat into the reactor

From a study of the bio-oil production literature, it was found that the featured processes of bio-oil production can be divided in 2 categories: 1) operating without oxygen content and 2) supplying less oxygen than is needed to ensure complete combustion. Many research studies have been carried out about bio-oil production in the complete absence of oxygen, but they have used other gases as the mediums to convey heat into the reactor, such as nitrogen [29–33], argon [34], and helium [35]. The advantages of using inert gases as the medium to convey heat to conduct the process are as follows: 1) they produce a high quality of bio-oil, 2) the bio-oil's water content is low, 3) the resulting bio-oil has a high heating value, and 4) they help to create a high value of cold efficiency for the system. However, using inert gases as the mediums for conveying heat will increase the production costs due to the high prices of these gases. Furthermore, electric energy will be the major source of energy used to transfer heat to the inert gases. For this reason, it has been difficult to develop this system on a commercial scale [1, 36]. Thus, the majority of commercial scale bio-oil production systems will need to be developed by recycling NCG back into the process. The method of reusing NCG will bring it back as a medium into the reactor, which has been shown in the details from the data in the literature [37–42]. Due to the fact that NCG has a low oxygen content, reusing NCG by putting it back into process, is more suitable option due to the high prices of inert gases.

II. Using oxygen and feedstock to produce reaction heat

The usage of low oxygen with the feedstock to create heat energy has been one method to lower the cost of heat generation. The hot gas product from this process will be directly conveyed into the reactor [43]. Even through, the oxygen composition in the pyrolysis process has a direct effect upon the quality of bio-oil. When comparing the production costs of using inert gas to this method, it can be seen that is possible to utilize this method on a commercial scale.

III. Reusing a NCG as a fuel for heat generation in the reactor

The components of NCG consist of carbon-monoxide (CO), carbon-dioxide (CO_2), hydrogen (H_2), nitrogen (N_2), and hydrocarbon compounds (HC), etc. Some gases are flammable and can be reused as fuel to generate heat. For this reason, many researchers have used NGC to generate heat in the reactor in order to reduce the production costs and to reduce emissions of NGC to the environment [44–46].

IV. Reusing charcoal as fuel for heat generation in the reactor

Charcoal is one product of the pyrolysis process from the biomass. Charcoal has a high carbon content, so it also has a high heating value (10–25 MJ/kg). Due to the fact that charcoal can be ignited in the same manner as NCG, charcoal has been used by many researchers as a fuel to generate heat in the reactor [47, 48]. However, this method has not been popular because charcoal can be upgraded as highly pure carbon, which can cause the product to have a higher cost.

V. Using Liquefied Petroleum Gas (LPG) as fuel for heat generation in the reactor

There are many advantages to using LPG to generate the heat for pyrolysis. Firstly, the cost of producing heat with LPG was lower than using electric energy. Secondly, there was a greater heating power and higher stability to combust as compared to using charcoal & NCG [44–46] and charcoal [47, 48]. Thirdly, the hot gas from combustion by LPG had a low oxygen composition in the flue gas, which can be directly used for the reactor in the pyrolysis process. As a result, heat loss from system can be absolutely reduced. For this reason, many researchers have studied the use of LPG as fuel to generate heat in the pyrolysis reactor [49–51]. However, using this method also increases the production costs.

As mentioned above, it was observed that the development of a low-cost bio-oil production system has been continuously improved for more than 30 years in order to invent a high performance system for reducing the cost of bio-oil production, which could be expanded to a commercial scale. Several researchers have shown their operations and have reported their methods to reduce costs, to improve the work mechanism, to advance the technical parameters, and to enhance the efficiency of energy conversion. However, the product's properties and the costs of production have not been presented. Thus, this article presents the design and operation of an alternative process to produce a low-cost bio-oil with a fast pyrolysis process. A Circulating Fluidized Bed reactor (CFBr) has been employed in this work because it offers more advantages than other reactors [6]. Liquid Petroleum Gas (LPG) and NCG were used as the fuels to produce heat into the reactor, and a cross flow heat exchanger was used to recover heat and to return it back into the process to save energy. The hydrodynamics of the CFBr were investigated in order to study the relationship between the hydrodynamics and the yield of any product. The stability of this plant with CFBr was evaluated in order to provide a reference for the future research studies as well. The properties of the products and energy consumption were determined, and that data was used to calculate the