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Research paper

Fast pyrolysis from Napier grass for pyrolysis oil production by using circulating Fluidized Bed Reactor: Improvement of pyrolysis system and production cost

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HIGHLIGHTS

- The pyrolysis oil production from Napier grass was studied by using circulating fluidized bed reactor (CFBr).
- The new design of pyrolysis system was developed in order to reduce the pyrolysis oil production cost.
- The comparison between pyrolysis oil yield and optimization were discussed.
- Cold efficiency and energy conversion efficiency were shown in this work.
- Comparison of pyrolysis oil production cost was also shown.

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ABSTRACT

This article focused on production cost of pyrolysis oil production of Napier Grass in Circulating Fluidized Bed Reactor (CFBr) which sand was used as bed material. The Napier grass was converted to pyrolysis oil by using fast pyrolysis process. The reactor temperature, superficial velocity (U_f) and feed rate of feedstock were adjusted in order to find the best condition of this experiment, and the Quadratic Response Model was used to predict the yield of pyrolysis oil and the optimum condition coupled with the experiment. From a results of this experiment, it was found that the maximum pyrolysis oil production was 36.93 wt% at 480 °C of bed temperature, 7 m/s of superficial velocity and 60 kg/hr of feed rate, while the result from the Quadratic Response Model indicated that the maximum pyrolysis oil production was 32.97 wt%. From the analysis of properties of pyrolysis oil, results showed that heating value, density, viscosity, pH and water content were 19.79 MJ/kg, 1,274 kg/m 2.32 cSt, 2.3 and 48.15 wt%, respectively, and the ultimate analysis was also determined. From the analysis of the efficiency of energy conversion, it was concluded that the value of cold efficiency and total energy conversion to pyrolysis oil in this system were 24.88% and 19.77%, respectively. The greatest energy consumption in this system was made by the energy from the heating process. Furthermore, from the calculation result of production cost in this study, it was concluded that a production cost of pyrolysis oil was 0.481 $/liter or 9.88 $/GJ at the 75 kg/hr of feed rate.

1. Introduction

Napier grass (Pennisetum purpureum Schumach) is a fast-growing vegetation with a harvesting round of 60 days. The grass is known for its high productivity (an average of 90–120 tons per hector), weather endurance, and low producing cost. In addition to its productivity values, Napier grass holds high protein content and offers tasty flavor (Pincam et al., 2017). This is why the plant is suitable raw material for animal food product industry (Muia et al., 2001; Shem et al., 2003). Since Napier grass is a source of high heat rate biomass, an average of 16.58 MJ/kg, it is widely used as a fuel source for industries and in electronic producing plants. Thailand is one of the countries interested in using the grass for electricity production. Based on the country's AED2013 plan, Thailand expects to produce about 3000 MW of electricity from Napier grass in the next 20 years (Waramit and Chaugool, 2014; Haegele and Arjharn, 2017).

There has been an amount of research into the exploitation of Napier grass as a substitutional energy in the productions of biogas (Sawasdee and Pisutpaisal, 2014; Janejadkarn and Chavalparit, 2014; Wilawan et al., 2014), bioethanol (Pensri et al., 2016; Ko et al., 2017; Liu et al., 2017), and pyrolysis oil (Strezov et al., 2008; Lee et al., 2010; Mohammed et al., 2017). Napier grass is more effective as a base material of the bioethanol and pyrolysis

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oil productions than it is for the biogas production since the first two energy products require simple storage and transportation, while they are applicable for more types of engines. Moreover, the heating value of bioethanol produced from Napier grass is almost two times higher than the heating value of the pyrolysis oil produced from the same grass. However, using Napier grass for bioethanol production yields less product exchange rate than what observed in the production of pyrolysis oil. The yield of bioethanol production in a study by Liu et al. (2017) was measured at 12.6 wt% while Mohammed et al. (2017) observed that the optimal production of pyrolysis oil was at 50.57 wt%. One of the primary factors for the energy production is the time it takes in the producing process. Bioethanol making process is based on fermentation, while the production of pyrolysis oil is based on a none-oxygen consumption burning, which takes as short as 0.5–2 s (Bridgwater and Peacocke, 2000). Obviously, producing bioethanol from Napier grass takes much more time than the production of pyrolysis oil. When the outcome and the production time are primary concerns in using Napier grass as an initial substance for the substitutional energy production, then Napier grass is more efficient as a base material for the production of pyrolysis oil than it is for bioethanol production.

This article has reviewed a number of studies into the production of pyrolysis oil from Napier grass. Strezov et al. (2008) investigated the production of pyrolysis oil from Napier grass by using Fixed Bed Reactor. In the experiment, the reactor temperature was ranged from 25 to 700 degrees centigrade, the heating accelerating rate was set at 10 °C/min and 50 °C/min. Fifty milligrams of the grass was used for each experiment. The maximum yield of pyrolysis oil production at the heating rate of 500 °C and 50 °C/min was 54.37 wt%. The experiment proved that high heat rate not only minimized the carbonization time, but it also helped diminish acid component and benzene compound in pyrolysis oil, the effects less observed in the low-temperature setting. A similar result was observed in a study by Lee et al. (2010) who conducted a research into the production of pyrolysis oil using Napier biomass and Fixed Bed Reactor. Maximum yield of pyrolysis oil product of 35.7 wt% was observed at the heating rate of 500 °C, 150 °C/min with the biomass size of 224 μm. This research showed that heating rate and size of biomass affected the acidity level in pyrolysis oil. However, the main objective of the study on pyrolysis production is finding the right factors and processes for maximizing the product. Mohammed et al. (2017) revealed that the reactor's temperature, the heating rate, the flow rate of moderating gas constituted the yield of pyrolysis oil made from Napier grass. This result is also articulated in a study by Bridgewater, who observed that the concentration of oxygen content in a reactor, a size and moisture content of biomass, feed-rate, time residence of reaction and characteristic of heat transferred to biomass have affected the quality and quantity of pyrolysis oil. The types of a reactor are crucial for the production of pyrolysis oil production. More specifically, the auger, bubbling fluidized bed reactor (BFBr) and circulating fluidized bed reactor (CFBr) are highly efficient for the production of pyrolysis oil at a large commercial scale (Bridgwater and Peacocke, 2000; Bridgwater, 2003, 2004). The importance of the type of reactors in the production of pyrolysis oil has triggered more research into a different type of a reactor in addition to Fixed Bed Reactor. Conto et al. (2016) conducted a batch experiment (each batch used 75 g of biomass) using Rotary Kiln Reactor for the production of pyrolysis oil with Napier grass and a level of 52.99 wt% yield was measured in this study. SingBua et al. (2017) conducted an experiment that was similar to Conto's study but Singbua additionally installed automatic feeding system to consistently fill the biomass to the system at the rate of 22.5 kg per hour. This system leads to the maximum of pyrolysis oil production of 14.27 wt%. In order to promote the use of Napier grass as a raw material for pyrolysis oil production in a commercial scale, it is important for the production line to be developed in order that it can continuously feed the biomass into the system while the production process should work effectively. Sousa et al. (2016) investigate the efficiency of the production of pyrolysis oil using Napier grass and Fluidized Bed Reactor with the feeding rate of 40 kg per hour. In this experiment, a system to extract water from oil and a Non-Condensable Gas (NCG) cleaning system was installed to enable big scale production. The maximum of 28.2 wt% of oil product was observed in this study. Despite the fact that the cost is one of the major factors to help decide whether Napier grass is effective raw material for the production of pyrolysis oil to serve an industrial purpose, none of the above research has investigated into this matter. Moreover, the lab scale experiments merely dictate the pyrolysis oil production capacity without mentioning the energy consumption, which is the key indicator for capital measurement in pyrolysis oil production.

Table 1
The physical properties of the experimental materials.

Properties	Napier	Sand	Units
Mean diameter (the Sauter's mean diameter)	1–3	0.249	mm
Bulk density	137.8	1524	kg/m^3
Porosity	–	42.87	%
Heating value (ASTM D240)	15.23	–	MJ/kg
Proximate analysis (Shimadzu TGA 50)			
- Moisture	12.14	–	wt%
- Volatile matter	75.37	–	wt%
- Fixed Carbon[a]	7.33	–	wt%
- Ash	5.15	–	wt%
Elemental analysis (Perkin Elmer PE2400 Series II)			
- C	40.03	–	%
- H	6.02	–	%
- N	1.69	–	%
- S	1.08	–	%
- O[a]	51.18	–	%

[a]Fixed Carbon and Oxygen were calculated by difference.

Based on the above limitations, this article proposes a system for the production of pyrolysis oil by using Napier grass with the feeding rate between 45 to 75 kg per hour. A Circulating Fluidized Bed reactor (CFBr) has been employed in this work because it offers more advantages than other reactors (Bridgwater, 2003). 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 diagram showing device placement, system's outcome, product properties, energy consumption, efficiency of energy conversion and the production cost are presented in this work as a beneficial data for the development of future research.

2. Materials devices and methods

2.1. Experimental materials

Experimental materials included: (1) Napier grass and (2) sand, which was used as the bedding material in the CFBr. The Napier grass is shown in Table 1 showed the physical properties, such as density, porosity, mean diameters, and heating values of the Napier grass and the sand, and also presented the proximate analysis and ultimate analysis of the Napier grass.

2.2. Experimental devices

As shown in Fig. 1, the experimental devices consisted mainly of a circulating fluidized bed reactor (CFBr), gas combustion, a feeder system with pneumatic conveying, a hopper, two cyclones, a gas pre-heater, and a condenser. This pilot plant was designed to produce a low cost production for obtaining pyrolysis oil. The process