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Design, fabrication and operation of continuous microwave biomass carbonization system

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A B S T R A C T

This paper presents a new design and the fabrication of biomass carbonization system using microwave heating. The heating system employs multi-feed microwave generators with 8.5 kW maximum power and 2.458 GHz frequency for uniform heating distribution in a 0.847 m^3 cylindrical low cement castable reactor. The experiment entails the carbonization of 58,800 kg of coconut shell for 7 days. Afterward, the charcoal and wood vinegar yields are analyzed; meanwhile, uncondensed gases are treated to fuel the engine-generator system. The results show that the proposed approach greatly saves the production time of charcoal yields and allows ease of temperature control.

1. Introduction

The demand for energy by a multitude of industries is rising and will be more so in the future. The increasing consumption of fossil fuels causes numerous negative impacts on the environment, examples of which are the accumulation of carbon dioxide in the atmosphere and thereby rising global temperatures. As a result, attempts have been made to use biomass as an alternative source of energy to reduce carbon dioxide emission in the atmosphere [1].

As an agricultural country with numerous kinds of biomass, Thailand produces approximately 61 million tons of biomass waste annually; however, the country hardly utilizes biomass waste to produce bio-fuel. Most biomass waste of the agriculture industry is typically burned while that from agricultural activities is left in the fields/plantations or burned [2]. It is estimated that Thailand could produce from available biomass over 20 million tons of crude oil, which is more than half of the current oil consumption of the country. Consequently, biomass waste should be greater utilized either by value adding or by translating into fuels or energy. The development of biomass conversion technology is suitable for available biomass resources of different areas thus benefits both the economy of the local community and the whole nation in the long run [3].

Biomass carbonization is a process to decompose biomass with heat in the absence of oxygen and is divided into 4 stages: Firstly, biomass is heated to 180 °C at which the water inside the gaps between cells (free water) and at cell boundary (bound water) is completely removed and transformed into non-pungent, non-harmful, pale blue vapor. Secondly, volatiles are removed by heating the biomass at the temperature range of 180–280 °C, and once the temperature reaches 280 °C, Hemicelluloses are fully decomposed. The temperature is maintained at 280 °C for an extended period of time for an optimal carbonization process whereby the heat is evenly distributed to the whole biomass inside the reactor. The yield from this stage is of pale gray color consisting of CO, CO_2, acetic acid, and methanol, all of which are nevertheless of low quantity to be of use. Thirdly, the derived biomass is then converted into charcoal. The temperature range at this stage is approximately 280–400 °C, the range at which biomass self-decomposes through the exothermic reaction. Celluloses in the biomass rapidly decompose at 280 °C and their yield is of white and yellow colors with pungent smell and gives high quality wood vinegar if condensed. Then, lignin decomposes at approximate temperatures of 310–400 °C. Beyond 400 °C biomass is entirely converted into charcoal. Finally, charcoal quality is improved at this final stage by removing tar. Although biomass becomes charcoal after approximately 400 °C, high quantity of tar remains. Tar causes the charcoal to be of low quality and, once burned, changes into benzopyrene and dibenzanthracene, both of which are carcinogenic. Therefore, charcoal is dried at 500–600 °C for a period of time to remove tar [4].

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The carbonization process is normally employed to convert agricultural biomass waste into biofuels, i.e., solid (charcoal), liquid (bio-liquid, wood vinegar, pyroligneous acid), and syngas [5]. Charcoal can be made into charcoal briquettes [6]; or induced to obtain activated carbon [7–9]; wood vinegar can be used as a substitute for the chemical pesticides [10]; and syngas can be used as a fuel in the internal combustion engines or in the electrical production [11]. Therefore, biomass waste and agricultural waste processed to add value would benefit the economy, society, and environment [12]. In addition, the employment of biomass waste materials from agriculture could be an answer to the quest for a sustainable source of renewable energy.

The carbonization process of biomass waste from agriculture is a suitable, cost-effective technology for charcoal production in Thailand because the process adds value to the biomass raw materials which are inexpensive and ubiquitous. Furthermore, the process is effective in solving the problem of biomass waste from agriculture and can be suitably and economically employed by villagers in remote areas to produce electricity for local consumption.

There have been many developments of new technologies to produce charcoal from biomass. Moreover, several countries, such as European countries, Australia, Brazil and the United States of America [13], not merely promote the utilization of biomass to produce energy but also encourage the use of energy from biomass. The carbonization process (i.e., charcoal production) has evolved since its inception hundreds of years ago to include multiple loads, new designs, etc. The existing carbonization processes of today can be categorized into two types: batch (e.g., pits, earth mound, brick and metal kilns) and continuous (e.g., drum type pyrolysers, screw type pyrolysers, and rotary kilns) [14]. The current charcoal production methods have changed little from the traditional methods.

Both production types are nevertheless plagued with many problems, some of which are energy wastage for both types and time loss and environmental unfriendliness for batch process, all of which hinder the industrialization of carbonization [5,14]. In both processes, the conventional heating method is employed whereby the exterior of the reactors is heated and then heat is transferred to biomass inside. The heat transforms the biomass inside the reactors into biofuels, depending upon the size of the biomass and process conditions (i.e., temperature, heating rate and residence time). On the contrary, an alternative efficient heating method, microwave heating, unlike the conventional heating method, causes the heat to originate from inside of materials and migrate outward. Recent research studies on the thermochemical process of biomass with the application of microwave heating have been reported and the research results suggest that this heating method is suited to distributed conversion of large biomass particles [15–21].

The microwave carbonization of biomass is one of the novel thermochemical technologies in which biomass is irradiated with microwave. The microwave carbonization process offers several advantages over the traditional carbonization process, some of which include uniform internal heating of large biomass particles, ease of control, and saving of time and heat energy. As such, the microwave carbonization is therefore adopted by industries.

The objective of this research is to build a pilot scale continuous carbonization system of biomass using microwave heating technology to produce charcoal and wood vinegar with uncondensed gases as byproducts of the process. The organization of this paper is as follows: Section 1 deals with the introduction and Section 2 details the design of the continuous microwave biomass carbonization process. The fabrication of the process is addressed in Section 3. Experiment and results are presented in Section 4 while the conclusion is provided in Section 5.

2. Design of continuous microwave biomass carbonization system

2.1. Continuous microwave biomass carbonization system

Pulverized biomass, as large biomass particles, is conveyed by the bucket elevator to the hoper at the top to dry. A 0.847 m^3 cylindrical low cement castable reactor fixed with 10 microwave magnetrons is employed to carbonize biomass. The charcoal yield is conveyed out from the continuous microwave biomass carbonization system by a screw-conveyer and the gas yield is transported by a pipe on top of the reactor to a condensation unit in which wood vinegar is condensed. Meanwhile, uncondensed gases are transferred to a gas treatment unit to purify so that the treated gases are suitable for use to produce electricity.

To have a better picture of the carbonization process, the conversion pathway of the continuous microwave biomass carbonization system is presented in Fig. 1. The process begins with biomass waste as input and ends with three forms of product yields, i.e., charcoal, wood vinegar (bio-oils), and fuel gas. Fig. 2 shows the schematic of a full-scale microwave carbonization system.

2.2. Multi-feed microwave cavity

The prototype multi-feed microwave cavity, is designed to heat the reactor of the carbonization process as shown in Fig. 3.

Typical carbonization temperatures for most types of biomass are 200–600 °C. Design of the multi-feed microwave cavity must allow the heating rate to be optimally controlled and thereby improve heating uniformity [22–25]. Therefore, multi-mode microwave radiation is employed in this work to heat the multi-feed microwave cavity as shown in Fig. 3. The 10 rectangular-shaped openings are drilled around the cavity with each opening fixed with a microwave source each consisting of a magnetron and waveguide. The microwave sources are installed in two parallel levels of five sources for each level. At the center of the cavity vertically lies a cement castable reactor through which the biomass to be reacted is passed. The reactor is made of cement to allow penetration by microwave radiation.

In this experimental research a heating system using microwave without stirrer mechanism in which the heat can evenly distribute throughout biomass or load is designed. The absence of stirrer mechanism reduces the complexity of the design and construction of the system. The microwave reactor however disallows the installation of a stirrer because the latter would bounce off the electromagnetic wave, causing uneven distribution of heat inside the reactor.

3. Fabrication of continuous microwave biomass carbonization system

Fig. 4 shows the snapshot of the continuous microwave biomass carbonization plant used in this study. The plant is 7 m in height and covers an area of 25 square meters.

3.1. Biomass feeding system

In the feeding system, pulverized biomass are conveyed by the bucket elevator to the hoper at the top to dry. After drying, dried biomass waste is fed down to the carbonization reactor through the cylindrical steel pipe of 0.30 m internal diameter, which controls via two pneumatic stainless steel trays the amounts of dried biomass fed into the reactor and prevents gas leakage from the reactor.