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Production of hydrogen from rice straw using microwave-induced pyrolysis

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HIGHLIGHTS

- H_2 gas produced from the pyrolysis of rice straw is measured at different powers.
- H_2, CO_2 and CO are the main gas products in the pyrolysis of rice straw.
- The optimum concentration of the hydrogen production is 56.08% at a power of 1000 W.

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ABSTRACT

This study investigated hydrogen produced by feeding rice straw into a microwave plasma system. The conversion rate is evaluated according to the concentration of hydrogen and other gas products. When feed rice straws into the microwave plasma system at 800 W, 900 W, and 1000 W using an upstream method, the concentrations of hydrogen production were 48%, 53%, and 56%, respectively. When feed rice straws by using the downstream method, the concentrations of hydrogen production are 34%, 40%, and 45%, respectively. These results indicate that the upstream feeding method is more favorable than the downstream for hydrogen production, and an increase of power can enhance the production of hydrogen. Optimal hydrogen production is achieved when rice straws are fed into the system using the upstream method at a power of 1000 W; each gram of rice straw produced approximately 40.47 mg of hydrogen (conversion rate = 67.45%).

1. Introduction

Rice straw is a preferred bioenergy source because it is residual material resulting from rice production. The annual average of rice production was 1.6 million tons from 2001 to 2005 in Taiwan [1], and the annual average rice production from 2006 to 2011 in Pakistan is 5.93 million tones [2]. The International Rice Research Institute (IRRI) reported that the total rough rice production in the world was more than 600 million tones approximately in 2004 [3]. The use of rice straw not only saves the cost of disposal but also produces valuable bioenergy, achieving the goal of resource recovery and reuse. Biomass waste can be efficiently transformed into bioenergy by applying thermochemical methods such as combustion, pyrolysis, and gasification [4,5]. Among them, the pyrolysis process not only reduces the volume of waste considerably, but also enables the recovery of value-added products. However, because of the nature of its endothermic reactions, the pyrolysis process requires a continuous supply of heat to chemically decompose biomass.

Conventional heating methods include external heating by conduction, convection, and radiation [6]. However, these methods possess certain drawbacks, including heat transfer resistance, heat loss to surroundings, use of portions of heat supplied to biomass materials, and damage to reactor walls because of continuous electrical heating. Accordingly, a new technique of using microwaves as an alternative heating source was developed. Microwaves are currently used in several applications such as food drying and heating [7,8], chemical synthesis [9,10], digestion [11,12], and extraction [13,14]. Microwave plasma, commonly used in microwave ovens, diamond synthesis, and IC manufacturing, has the advantages of easy operation, electrodeless reactors, high plasma density, and high electron mean energy. Compared with conventional pyrolysis conducted using an electric furnace, microwave pyrolysis produces more H_2 and CO [15,16], which is the so-called syngas, or synthesis gas. In addition, microwave pyrolysis generates fewer polycyclic aromatic hydrocarbons (PAHs) and, therefore, produces fewer hazardous compounds [17,18].

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This study investigated the microwave-assisted pyrolysis of rice straw by using upstream and downstream feeding methods. Pyrolytic reactions of rice straw were implemented under different microwave powers in this study, different microwave powers present various decomposed temperatures of rice straw. Hence, the temperature profiles under different microwave power levels are studied in this manuscript. The products, pyrolysis temperature, and temperature increase rate were analyzed to obtain optimal conditions and to maximize hydrogen production.

2. Experimental section

The experimental setup, comprising an electrodeless microwave-excited atmospheric plasma system (APS) and a product analysis system, is shown schematically in Fig. 1. Details of this experimental setup are described in previous studies [19–21]. Experiments in the present study were repeated at least three times to provide evidence of reproducibility.

2.1. Pyrolysis procedure

The pyrolysis experiments were conducted in an atmospheric-pressure microwave plasma reactor at an applied microwave power of 800, 900, and 1000 W, corresponding to the temperatures of 1063, 1093, and 1121 K in the plasma zone. Approximately 1 g of rice straw at room temperature was fed into the reacting zone upstream of the cavity resonator, and N_2 was used as bath gas at a flow rate of 12 l min^{-1} (an axial flow rate of 3 l min^{-1} and a swirl flow rate of 9 l min^{-1}). The flow rate of N_2, supplied from compressed gas tanks, was maintained constant. The pyrolysis of biomass was conducted in nitrogen at a pressure of 1 atm. The reactor was made from a quartz tube, which was 35 cm in length and had inner and outer diameters of 2.9 and 3.3 cm, respectively.

2.2. Rice straw and gas analysis

Both the pyrolysis characteristics and product distribution of rice straw were analyzed in this study. Morphological changes of the rice straw samples before and after pyrolysis were observed using environmental scanning electron microscopy (ESEM). Elemental chemical analysis (C, H, N, S, and O) of rice straw and the residue after pyrolysis was performed using an Elementary Vario Micro Cube elemental analyzer (EA). Sampling was performed by continually withdrawing gases from within the plasma zone using a micro probe with a diameter of approximately several hundred microns. Gas chromatographs (GC) equipped with capillary columns (type: SUPELCO 13821), a thermal conductivity detector (TCD), and a residual gas analyzer (RGA), were used for stable species measurements. Residual gas analyzer (RGA) provides detailed gas analysis of vacuum systems at about half the price of competitive models, the type of RGA is Extorr RGA200. Each RGA system contains a quadrupole probe, electronics control unit (ECU), and a real-time Windows software package that is used for data acquisition and analysis, as well as probe control. The RGA was used to monitor the hydrogen concentration produced throughout the entire pyrolysis process. Regarding the H_2 analyzed using the GC/TCD, the carrier gas was nitrogen and the detector oven and vaporizer temperatures were 513 and 383 K, respectively. The GC oven temperature was set to 383 K for 10 min, ramped to 473 K at 288 K min^{-1}, and maintained for 14 min. Regarding the CO and CO_2 analyzed using the GC/TCD, the carrier gas was helium and the detector oven and vaporizer temperatures were 393 K and 323 K, respectively. The GC oven temperature was set to

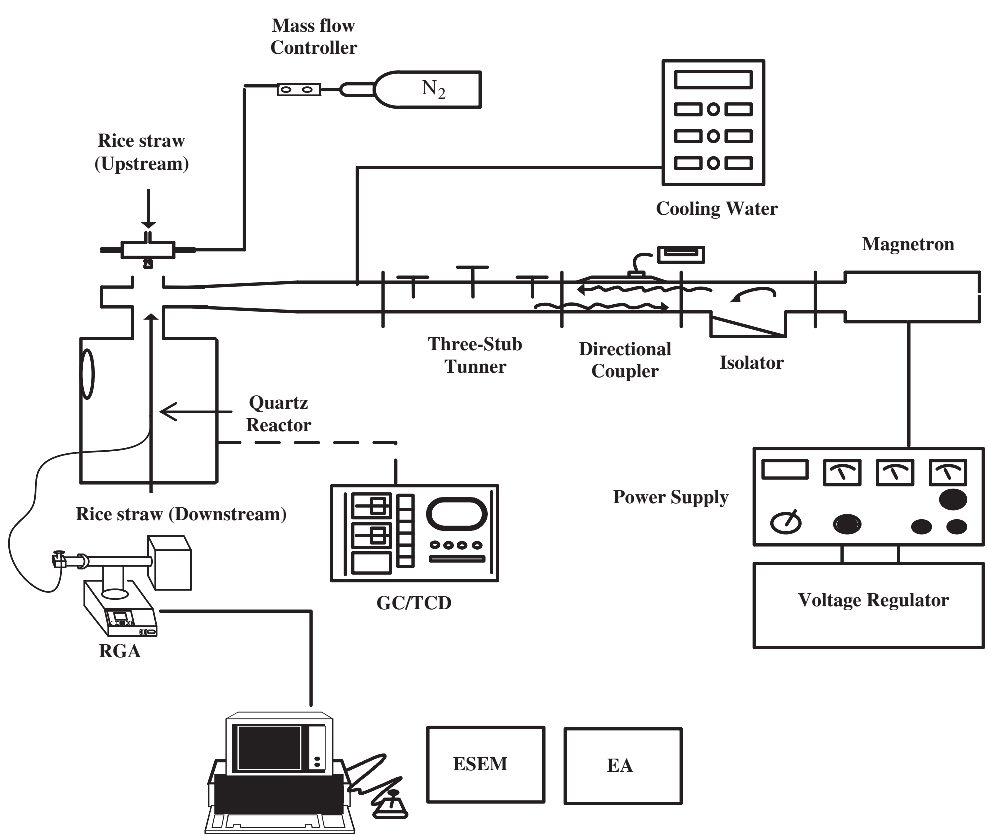

Fig. 1. Schematic of the atmospheric-pressure microwave plasma reactor.