Thermochemical Conversion of Waste Papers to Fuel Gas in a Microwave Plasma Reactor

Parin Khongkrapan, Nakorn Tippayawong, and Tanongkiat Kiatsiriroat

***Abstract*—In this work, a microwave plasma reactor for conversion of waste papers to generate fuel gas was developed and presented. Experiments were carried out with different air flow rates, focusing on product gas yield and composition. From the results obtained, it was shown that, at a constant input power of 800 W, average gas yield and maximum carbon conversion obtained were 2.10 m^3/kg and 59%, respectively. On a nitrogen free basis, total content of CO and H_2 in the gas product was 31-43%, which can be used as synthetic gas.**

***Index Terms*—Biomass, gasification, microwave plasma, renewable energy, solid waste.**

I. Introduction

Wastes are generated on a daily basis, ranging from simple garbage to complex industrial waste. Amount of waste generated is very alarming. Total solid waste production in Thailand was over 35 kilotons/day. The per capita generation of municipal solid waste in the country was approximately 0.5 – 1.0 kg/day, with average value of 0.65 kg/day [1]. For a big city, total waste generated can be 1,000 t/day or higher. The need to manage these municipal and industrial solid wastes is well recognized. Generally, technological strategies for disposal of solid wastes can be classified as (i) land-filling, with possibility of biogas recovery, (ii) incineration with recovery of energy, (iii) sorting of the wastes to recover materials that are recyclable, fermentable, or combustible, (iv) advanced approaches that aim at energy valorization. In most countries, emphasis has been placed on utilization of solid waste for generation of energy and electricity as an attractive alternative to landfills [2]. Waste-to-energy conversion in modern facilities with adequate and careful environmental monitoring has been shown to be a safe and cost effective technology. This is usually conducted with thermal technology such as combustion, gasification or pyrolysis because they can reduce the waste volume, toxicity, and produce a stream for further utilization [3].

Recently, plasma treatment of waste has emerged to offer a strong potential in waste disposal due to its fast process and ability to eliminate harmful substances. Plasma is the fourth state of matter. When the bonds between the electrons and ions are broken, the gas becomes electrically conducting plasma. The energetic species (electrons, ions, atoms, and free radicals) initiated in the plasma may enhance desired chemical reactions. Plasma assisted reaction is a technologically advanced and environmentally friendly method to dispose of waste, converting it to commercially usable by-products, as well as fuels. Most plasma applications to waste management have so far been associated with thermal plasma [4]-[6]. Traditionally, plasma process uses arc plasma torch as the heat source. It requires high electrical energy to keep high temperatures in the plasma discharge. High energy consumption and low selectivity of some chemical processes are the main drawbacks of arc plasma. Non-equilibrium or non-thermal plasma technologies can offer alternative solutions.

Microwave plasma is non-thermal, easy to control and requires low power [7]. Microwaves are electromagnetic waves that have frequency range between 0.3 – 300 GHz. Microwave generation technology has been well established and widely commercialized. The microwave plasma can be generated using magnetron in typical household microwave ovens. It is simple, compact, robust and economical [8]. Many applications for microwave plasma have been reported, such as sterilization of germs, and surface modification of materials. However, there is still rather limited number of works reporting on microwave plasma and energy generation [9].

In this work, a microwave plasma reactor was developed for gasification of biomass. Waste paper was used as a feedstock. Effect of carrier gas flow rate on production of fuel gas via partial oxidation was investigated.

II. Methodology

A. Feedstock

Waste paper was the major component of combustible fraction of solid waste. In this work, the feedstock used was dry, shredded paper. It was sorted to uniform size. Composition of the sample paper [10] was shown in Table I.

TABLE I: Composition of Paper Samples Used

Component	Quantity (% w/w, dry basis)
Carbon	45.0
Hydrogen	6.1
Oxygen	42.4
Nitrogen	0.3
Sulfur	0.3
Ash	6.0

B. Microwave Plasma Reactor

The microwave plasma system in this work was modified

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from a commercial microwave oven. It consists of the 800 W, 2.45 GHz microwave generator, a cylindrical tube reactor, and auxiliary electrical equipment. The microwave radiation generated from the magnetron passed and guided through the oven cavity, and entered the discharge quartz tube centrally located inside the oven cavity. The plasma generated inside the tube was stabilized by injecting a carrier gas, which entered the tube from the bottom as a turbulent flow.

C. Experimental Setup and Procedure

The experimental setup is shown schematically in Fig. 1, equipped with gas cylinders for air and argon, connected to gas flow regulators.

A gas collection module was used for fuel gas conditioning and tar capture. It consists of a series of filter, impinger bottles containing a solvent for tar absorption placed in cold baths, and a moisture trap. Each impinger bottle was filled with approximately 100 ml of isopropanol. The gas flow rates were measured with flow meters. The cool, dry, clean gas was sampled using gas bags and analyzed on a Shimadzu model GC-8A gas chromatography fitted with a ShinCarbon ST Micropacked column and a thermal conductivity detector, for measuring volumetric concentration of H_2, O_2, N_2, CH_4, CO, CO_2. Standard gas mixtures were used for quantitative calibration.

Test and operating conditions were summarized in Table II. Initially, the quartz tube was loaded with shredded paper mass of 5 g, before mounted inside the oven. Carrier gas was fed from the bottom of the reactor, varying between 1 - 4 lpm. The microwave generator was then switched on to start the reaction, and run for 4 min. Gas collection was continually carried out. Solid residues were collected and weighed after each run. Each test was repeated in triplicate. Average values were reported.

D. Data Analysis

The following parameters are calculated [11];
Specific gas yield:

$$SGY = V_{gas} / W_B \tag{1}$$

Carbon conversion efficiency:

$$n_c = \frac{V_{gas} \times \sum x_i \times (12/22.4)}{W_B \times (1 - C_A) \times C_c} \times 100\% \tag{2}$$

Lower heating value:

$$LHV = \sum x_i LHV_i \tag{3}$$

where V_{gas} is total volume of product gas generated, W_B is converted mass of solid material, x_i is volume fraction of fuel component of product gas, C_A is carbon content in residue, C_C is carbon content in biomass, and LHV_i is the corresponding heating values of the gas component.

III. Results and Discussions

A. Reactor Operation

The microwave plasma reactor was operated at atmospheric pressure. The microwave was powered by a 2.45 GHz generator, whose continuous output power was constant at 800 W. The discharge takes place inside a quartz tube with internal/external diameters of 27/30 mm and length of 250 mm, inserted vertically and perpendicularly to the oven cavity. The plasma can be observed in the quartz reactor tube.

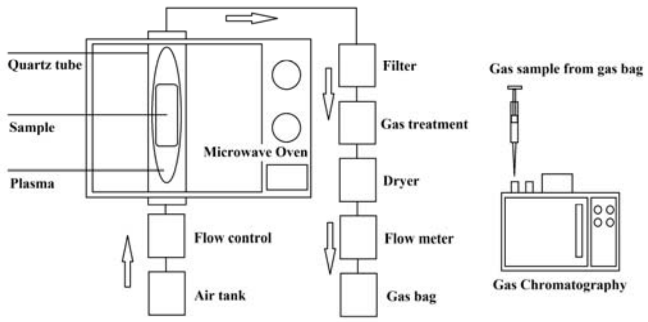

Fig. 1. Schematic of the microwave plasma reactor setup for gasification of waste papers.

TABLE II: Operating Conditions of Microwave Plasma Tests

Parameter	Condition
Input power	800 W
Frequency	2.45 GHz
Pressure	101 kPa
Mass of paper	5 g
Air flow rate	1, 2, 3 and 4 lpm
Reaction time	4 min

TABLE III: Product Gas Generated

Air flow rate (lpm)	Gas yields (m^3/kg paper)	Carbon conversion (%)	LHV (MJ/m^3)
1	0.87	19.6	1.86
2	1.71	38.8	1.93
3	2.53	58.6	2.29
4	3.29	51.1	1.56

TABLE IV: Performance Comparison with Literatures

Reference	Plasma source	power	Feedstock	Carrier gas	H_2 (%)	CO (%)	CO_2 (%)	CH_4 (%)
This work	Microwave	800 W	Paper, 5 g	Air, 1-4 lpm	7.7	8.5	8.7	1.1
[12]	Microwave	4500 W	Coal, 3-50 kg/h	Air, 0-150 kg/h	2.4	8.1	9.6	1.2
[13]	Microwave	3000 W	Wheat straw, 5-30 g	N_2, 3 lpm	22.1	34.7	33.8	7.9
[14]	Microwave	600 W	Polyethylene, 1 g	0-20% steam/Ar, 3.5 lpm	14	26	12	6
[15]	Microwave	1000 W	Waste wood, 10 g	Ar, 1 lpm	-	56.9	33.8	0.5
[16]	Gliding arc	1140 W	Waste oil, 10 g	10-30% O_2/Ar, 5-16 lpm	-	0.5	2.0	-
[17]	RF, 13.6 MHz	2000 W	Sawdust, 0.3 g/min	N_2, 0.5 lpm	8.5	11	4.0	1.5

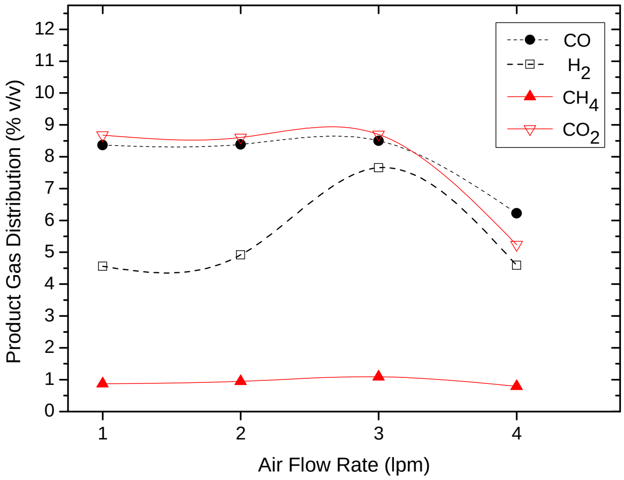

Fig. 2. Variation in concentrations of product gas generated with air flows.

The test run was performed for the microwave plasma system to confirm that the generated plasma can be achieved with our reactor. The plasma was characterized by high intensity light emission. It appeared to occupy most volume of the quartz tube inside the oven cavity.

B. Fuel Gas Production

Table III lists the gas yields, carbon conversion from those in solid material to those present in product gas, and corresponding heating values under different experimental conditions. For all test runs, there was about 1 g of solid residue left in the tube reactor. The specific gas yields obtained were found to increase with air supplied, as expected. Average gas yield was 2.10 m^3/kg paper converted. However, carbon conversion and energy content of the product gas showed initial increase with increasing flow rate, reaching maximum at 3 lpm. Further increase in air supply led to reduction in conversion efficiency and LHV of the product gas. This was contributed to the fact that combustible gas components (CO, H_2 and CH_4) were found to peak at this flow rate, and drop at higher supply rate of carrier gas, as shown in Fig. 2. The observed decline in combustible fractions at higher flow rate may be due to the fact that the flow was too fast inside the reactor, hence, less likely for biomass material and the plasma to react with each other more completely.

C. Comparison with Literature

Product gas obtained from plasmochemical conversion of waste paper in this study was compared against those obtained from other types of biomass and carrier gas in microwave plasma reactors. Results are summarized in Table IV. With air plasma reaction, gas products obtained in this work were comparable to those in the literature.

IV. Conclusion and Future Work

In this paper, a laboratory scale, microwave plasma reactor has been described. This type of plasma was highly reactive, enabling conversion of solid materials into gas. Under oxidative environment, microwave plasma was able to generate combustible gas from waste paper. This is of practical interest for utilization of solid wastes for the purpose of fuel gas production. However, tests with regards to characterization of microwave plasma generated, as well as parametric investigation of operating conditions are still required. They are planned for the next stage of this research.

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