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MICROWAVE PLASMA GASIFICATION OF OIL PALM BIOCHAR

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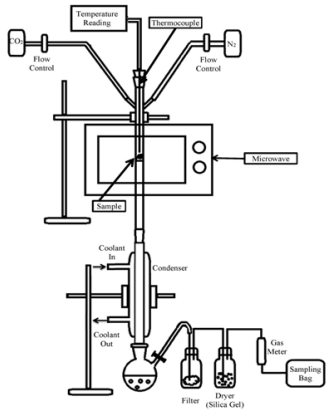
Graphical abstract



Abstract

Conventional pressurized gasification operates at higher pressure than atmospheric pressure and requires heat up time during startup. In this study, microwave plasma gasification was used to compensate this problem. The objectives of this paper is to investigate the CO_2 microwave gasification of EFB and OPS biochar, and optimizing the char reaction rate through the addition of activated carbon as the microwave absorber. A microwave plasma gasification test rig was designed to produce syngas from oil palm biochar. From the study, it was found that EFB char performed better than OPS char as gasification fuel due to its high porosity and surface area that increased the char reactivity towards CO_2. The temperature increment promoted by the addition of MW absorber using activated carbon (AC) has increased the CO composition. The optimum condition for microwave plasma char gasification of EFB was 3 lpm with 25 wt% AC that produced syngas with 1.23 vol% CH_4, 20.88 vol% CO_2, 43.83 vol% CO, 34.06 vol% H_2 and 9.40 MJ/kg gas CV. For OPS is at 2 lpm with 1.12 vol% CH_4, 35.11 vol% CO_2, 35.42 vol% CO, 28.35 vol% H_2 and 7.32 MJ/kg gas CV. As EFB char has larger BET surface areas and larger pores than OPS char, the ability to react with the gasifying gas is better than the OPS. Thus, resulting in higher carbon conversion. The best gasification efficiency was 72.34% at 3 lpm, 10% AC for EFB biochar plasma gasification with 12% unreacted carbon. For OPS biochar plasma gasification, the best gasification efficiency was 69.09% at 2 lpm, 10% AC with 18% unreacted carbon.

Keywords: Microwave plasma, gasification, biochar, oil palm biomass, syngas

Abstrak

Dalam kajian ini,gasifikasi gelombang mikro dikaji untuk menyelesaikan masalah ini. Dari kajian, didapati arang EFB lebih bagus dari arang OPS dalam gasifikasi kerana kadar keporosan dan luas permukaan yang tinggi. Kondisi optimum untuk gasifikasi gelombang plasma bagi arang EFB adalah 3 lpm with 25 wt% AC dengan komposisi gas 1.23 vol% CH_4, 20.88 vol% CO_2, 43.83 vol% CO, 34.06 vol% H_2 dan 9.40 MJ/kg CV gas. Untuk arang OPS adalah pada 2 lpm dengan komposisi gas 1.12 vol% CH_4, 35.11 vol% CO_2, 35.42 vol% CO, 28.35 vol% H_2 dan 7.32 MJ/kg CV gas. Oleh kerana arang EFB mempunyai luas permukaan BET dan liang yang lebih besar dari OPS, maka kecekapan penukaran karbonnya adalah lebih tinggi. Kecekapan gasifikasi EFB adalah 72.34% pada 3 lpm, 10% AC dengan 12% karbon tidak terbakar. Untuk OPS, kecekapan gasifikasi terbaik adalah 69.09% pada 2 lpm, 10% AC dengan 18% karbon tidak terbakar.

Kata kunci: Plasma gelombang mikro, gasifikasi, arangbio, biomas kelapa sawit, singas

1.0 INTRODUCTION

Renewable energy such as solar energy, wind energy and biomass energy are gaining more attention by the world in efforts to reduce the CO_2 greenhouse gas emissions, which are causing global warming and climate change. Biomass is used since thousand of years ago and it still contributes around 10% of world's energy supply, especially in rural and developing countries. It is unlike the situation of natural gas and coal as the source of biomass is available all around the world [1].

1.1 Malaysia Biomass Resources

In Malaysia, there are over 23,000 tonnes of solid wastes being produced daily and by the year 2020, the number of solid wastes generated is expected to increase up to 31,000 tonnes per day [2]. Major agricultural crops grown in Malaysia are rubber (39.67%), oil palm (34.56%), rice (12.68%), cocoa (6.75%) and coconut (6.34%). As one of the world's major producers of oil palm, it produced 17.73 million tons of palm oil, contributed about RM 65.19 billion in Malaysia's exports for the year 2008 and accounts for 41% of the world's palm oil production [3]. Presently, millions of hectares of land in Malaysia are occupied with oil palm plantations; generating huge quantities of biomass source, which have no economic value. Although some of the solid wastes were being used for municipal landfill, somehow it still causes pollution to the environment, for example groundwater contamination, methane gas released by decayed organic waste and so on [2]. This industry appears to be a very promising alternative source of raw material for extraction either by gasification conversions into more valuable and usable forms of energy. Besides, it can also avoid open burning of biomass from emitting greenhouse gases into atmosphere [4].

In general, the fresh fruit bunch contains (by weight) about 21% palm oil, 6–7% palm kernel, 14–15% fibre, 6–7% shell and 23% empty fruit bunch (EFB) [5]. Producing a kilogram of palm oil, results in roughly another 4 kg of dry biomass [6].

1.2 Carbonaceous Solid Gasification

Biomass energy conversion technologies, especially pyrolysis and gasification have been substantially studied to promote renewable energy utilization and partially solving some of the environmental issues. Various types of gasification systems have been developed and some of them are commercialized [7]. Biomass gasification converts biomass into gaseous fuel or chemical feedstock, which is useful in our daily routine. It has emerged as a promising technology to fulfil the increasing energy demands of the world as well as to significantly reduce the volume of biomass wastes generated in developing societies [8].

Bricka and Swalm [9] stated that coal was the first feedstock to be used in the gasification process, but due to demands of sustaining earth resources, other types of feedstock are being used. Biomass such as corn stover, sawdust, wood and food waste are in use at the moment. Feedstock undergoes several chemical reactions to produce syngas, whereby some of it are exothermic and some are endothermic [10]. Kabalan et al. [11] claimed that the gasification technology has the advantage of obtaining energy for low cost and uses wastes as raw materials and recycle it at the same time.

Gasification is a thermo-chemical process by which carbonaceous (hydrocarbon) materials (coal, petroleum coke, biomass, etc.) can be converted into synthesis gas (syngas) or producer gas by means of partial oxidation with air, oxygen and/or steam. The device that performs this work is known as a gasifier. The gasifier is a chemical reactor where various complex chemical and physical processes take place.

A hydrocarbon feedstock (biomass) is fed into a high-pressure, high-temperature chemical reactor (gasifier) containing steam and a limited amount of oxygen. As biomass flows through the reactor it gets dried, heated, pyrolysed, partially oxidized and reduced. Under these "reducing" conditions, the chemical bonds in the feedstock are severed by the extreme heat and pressure thus producer gases are formed. The main constituents of producer gas are hydrogen (H_2) and carbon monoxide (CO). In short, the task of a gasifier is to pyrolyse the biomass to produce volatile matter, gas and carbon and also to convert the volatile matter into permanent gases, CO, H_2 and CH_4 [12].

However, there are some weaknesses on the existing conventional gasification technology, as it is not suitable to be applied to low grade coal in which high pressure is needed and leads to the requirement of special apparatus to allow the operation to run under the high pressure. It also requires a longer time for the heating up process at the start-up stage. But, plasma gasification is able to compensate those weaknesses because plasma gasification operates under atmospheric pressure and also takes a shorter time to elevate to higher temperatures using external electric energy [13]. As such, costs can be cut on high pressure apparatus set up; this also applies to operation costs since only external electric energy is applied such as microwave generators hence lowering the overall project cost.

1.3 Plasma Technology

According to Fridman [14], plasma is an ionized gas, a distinct fourth state of matter. As temperature increases, molecules become more energetic and transform matter in the following sequence: solid, liquid, gas and finally plasma, which justify the title "fourth state of matter". Ionization can be induced by a strong electromagnetic field applied with a laser or microwave generator and is accompanied

by the dissociation of molecular bonds [15]. Plasma can be divided into 3 types including thermal plasma, cold plasma and warm (intermediate) plasma. Thermal Plasma has high temperature but not as high as the hot plasma in the field of astrophysics. Besides, it is an equilibrium discharge which means its' ions, neutral species, electrons, atoms all retain the same temperature and it can be produced by a direct current supply. Cold plasma is non-equilibrium plasma that allows the plasma molecule to lose heat rapidly to the surrounding environment. It is said to be low in energy levels because the transfer process of energy from electron into gas heating is very slow and the cold plasma is produced under atmospheric pressure using AC, DC or pulsed current. Lastly, the warm plasma includes microwave plasma; it is an example of plasma that allows generation under a stable condition subjected to certain external parameters. Warm plasma has a high translational temperature around 2000K and it goes through non-equilibrium discharges when energy is dissipated to the surroundings [16].

1.4 Microwave Plasma Gasification

Mountouris et al. [17] stated that plasma gasification technology is said to be "true gasification". This is because the technology involves rare occurrence of combustion, which promotes chemical reactions due to the generation of active particles including radicals and ions to reduce the reaction time [18]. The working principle of microwave plasma is such that significant amount of electrical energy tends to excite and ionise the gas under certain pressure and temperature thus generating more electrons. It will result in an increased rate of inelastic collision between electrons and atoms—at the same time generating more ions and electrons. Other than that, the significant electrical resistivity generated across the system will cause high temperature [16]. Microwave plasma gasification involves no combustion and with the addition of certain amount of continuous air and steam supply, synthetic gas or so called syngas, will be produced whereby it is mainly of carbon monoxide and hydrogen although certain percentages of carbon dioxide, methane and hydrochloride acid are also present [16].

The generating source of microwave energy will need a power supply and there are few alternative methods to generate microwaves such as using an arc; commonly applied method includes magnetron, gyrotron, klystron, and so on. With the desired output levels of 100 kW, a magnetron with frequencies of 0.915 and 2.45 GHz is presently available in the market. Ann, Ismail and Ani [19] also concluded that the use of 2.45 GHz microwave magnetron was realistic and feasible to work together with a microwave generator, directional circulator, dummy load, waveguide, 3-stub tuner and reactor. During the operation, the microwave energy will be propagated along the waveguide and plasma is obtained when coupled with the gas flow. Therefore, all the microwave energy will be confined within the waveguide and absorbed by the plasma such that there will be no safety problem regarding the radiated power during the operation. Extra microwave will be reflected back through the waveguide and a waveguide circulator will deflect those reflected microwave all the way to the water cool dump [20].

On the other hand, the microwave plasma gasification has potential in terms of syngas production because the high temperature obtained from the plasma torch will boost the rate of gasification reactions and ensures a compact reaction system whereby a more complete reaction can produce cleaner syngas to avoid several scrubber stages thus making sure the product gas is clean. It is cost saving at the same time [16, 21]. Another advantage is that the microwave plasma gasifier can operate under atmospheric condition whereas conventional gasifiers need higher strength structures to withstand the high pressure operation condition. This issue will increase the machine setup costs [21].

Since arc electrodes are susceptible to moisture, the life expectancy of electrodes are significantly reduced when applied to the plasma torch [22]. Kanilo et al. [18] claimed that microwave plasma technology is a better method for gasification because it is more resistant to moisture. At the same time, the forming of plasma flames by using microwaves as the energy source has been proved by Uhm et al. [23]. The efficiency of coupling RF energy into the plasma in the induction coupled plasma (ICP) torch is less than 40% and the efficiency drops significantly at powers higher than 100kW. Other than that, it requires more complicated safety features. Electrodeless atmospheric microwave plasma torch can be the solution to eliminate these problems [24].

1.5 Activated Carbon as Microwave Absorber

Activated carbon (AC) acts as a powerful microwave absorber as it is capable of converting microwave energy into thermal energy; which can be transmitted to solid materials [25, 26]. Activated carbon is a crude material from graphite. It has high physical adsorption forces than can adsorb higher volumes of adsorbing porosity. Activated carbon is a solid substance resembling granular or powdered charcoal and extremely porous with a very large surface area [27]. Activated carbon can act as microwave absorber and increases the reaction temperature. In the experiment by Salema and Ani [28], the temperature profiles proved that the heating characteristics of the biomass materials increase rapidly in the presence of the microwave absorber.

2.0 EXPERIMENTAL

2.1 Materials and Biochar Preparation

There are two types of oil palm biomass; the empty fruit bunch (EFB) and the oil palm shell (OPS) are obtained from the Federal Land Development Authority (FELDA) oil palm mill in Kulai, Johor. Both biomasses were dried in a conventional oven at 105°C for 24 hours to remove the water content. After that, the biomass was ground as the size of raw biomass is not suitable for pyrolysis. Grinding the biomass to a smaller size will increase the surface area for reaction to occur. EFB and OPS were ground and sieved to 1.18 to 2.00 mm. Pyrolysis of biomass was done to convert the biomass into biochar. A fixed bed furnace was used in the process. The entire system is a vertical furnace with an inlet gas flow from below. This pyrolysis rig consists of a temperature controller, heating element, reactor tube and gases. The bed furnace temperature is controlled by a programmable electronic temperature controller (Eurotherm Model – 2416). About 50 g of biomass samples were used with the pyrolysis temperature of 650°C. Nitrogen was used as the carrier gas at a constant flow rate of 6 lpm. The temperature increment of the furnace is programmed to 20°C/minute. After reaching the desired pyrolysis temperature at 650°C, which was intended to remove the volatile substances, the electronic temperature controller will hold the temperature for 60 minutes. Then, the biochar was left to cool to room temperature. This was achieved by allowing a continuous flow of nitrogen gas. Figure 1 shows the setup for the pyrolysis of biomass in a fixed bed furnace.

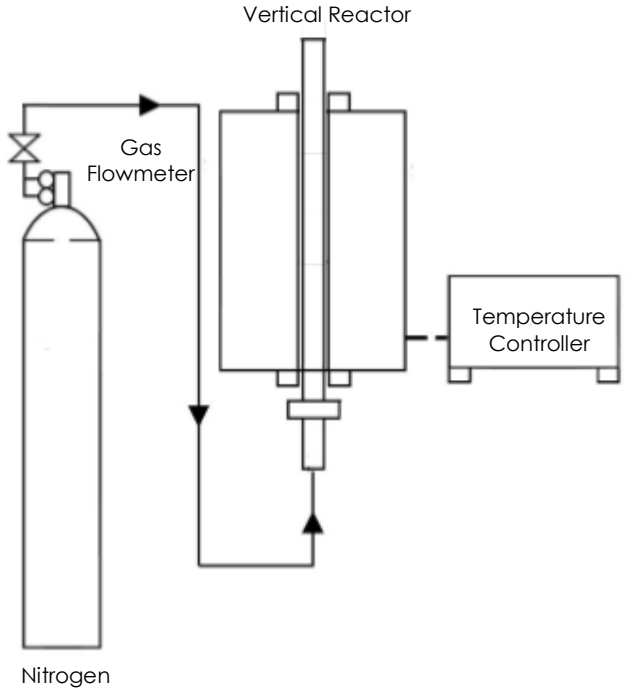


Figure 1 Setup for pyrolysis of biomass in a fixed bed furnace

2.2 Microwave Plasma Gasification of Oil Palm Biochar

The microwave plasma gasification system was modified from a domestic microwave oven. A quartz reactor of 600 mm length and 20 mm internal diameter was designed as the gasification reactor. The reactor was placed vertically inside the modified microwave oven with the sample at the center of the cavity. This is to ensure that the microwave radiated directly to the biochar sample. 5 g of sample was weighed and placed inside the reactor. CO_2 and N_2 were allowed to flow in a swirl from both the right and left sides of the reactor. The effect of microwave absorber to the reaction temperature was studied. The percentage of activated carbon added were 10% and 25%—to increase and control the reaction temperature. Further increasing the activated carbon may increase the temperature of the reaction to a high plasma temperature that can damage the quartz reactor. All experiments were repeated three times to acquire an average value. The syngas collected was analysed using gas chromatography (GC), Agilent 6890, fitted with packed column, Thermal Conductivity Detector (TCD) and a capillary column for measuring volumetric concentrations of CH_4, CO_2, CO and H_2. Inert argon gas at the flow rate of 10ml/min and TCD with front detector temperature of 473K were applied to operate the GC. Standard gas mixtures were used for quantitative calibration. The optimized condition for the experiment was selected from previous microwave gasification experiment [4]. Figure 2 shows the microwave plasma gasification rig in detail. Table 1 shows the summary of plasma gasification test conditions.

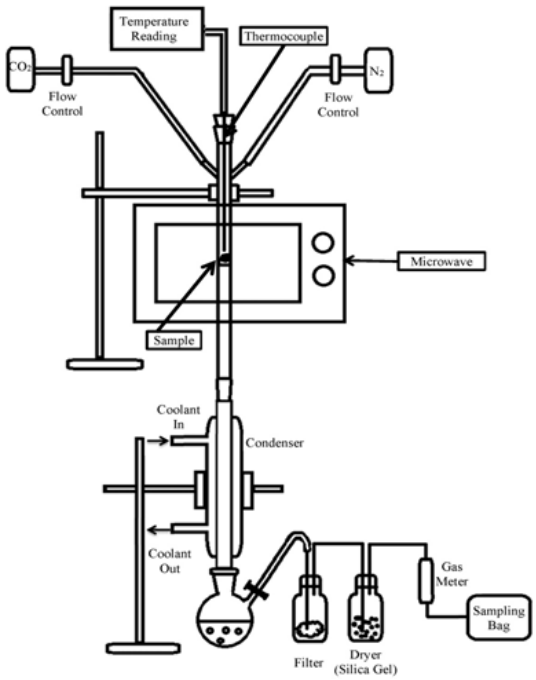


Figure 2 Microwave plasma gasification rig

Table 1 Summary of plasma gasification test conditions

Microwave Power (W)	800	
Frequency (GHz)	2.45	
Pressure (atm)	1	
Mass of biochar sample (g)	5	
CO_2 Flow rate (lpm)	EFB biochar	3
	OPS biochar	2
N_2 Flow rate (lpm)	3	
Activated Carbon (wt %)	10 and 25	
Reaction time (min)	5	

2.3 Data Analysis

The specific gas yield (SGY) was calculated using (1):

$$SGY\ (m^3/kg) = V_{gas}/(W_{before}-W_{after}) \quad (1)$$

Where, V_{gas} is the volume of gas produced (m^3), W is the weight of the sample before and after gasification (kg).

Gas heating value, HV (kJ/kg) was calculated using (2):

$$HV = \sum x_i\ (HV_i) \quad (2)$$

Where, x_i is the volume concentration of component of product gas (vol%) and HVi is the corresponding heating values of the gas component.

Gasification efficiency was calculated using (3):

$$\eta_g = (CV_{gas} \times Q_{gas}) / (CV_{solid} \times m_{solid}) \times 100\% \quad (3)$$

In which η_g is the gasification efficiency (%), CV_{gas} is the heating value of the gas (kJ/m^3), Q_{gas} is the volume flow of gas (m^3/s), CV_{solid} is the heating value of biochar (kJ/kg) and m_{solid} is the biochar consumption (kg/s).

3.0 RESULTS AND DISCUSSION

Temperature profiles during the gasification experiment were recorded to find the reaction equilibrium. Figure 3 and Figure 4 show the result of the microwave heating profiles with the addition of 10% and 25% activated carbon into the biochar. The increment of temperature in EFB biochar plasma gasification was observed as very promising, as it drastically rises up to almost 1400°C with 10% activated carbon and almost 1800°C with 25% activated carbon. The temperature increase occured as early as the first minute of the experiment. This shows a great advantage compared to conventional heating that requires hours to reach above 1000°C [29-31]. The temperature for EFB biochar plasma gasification was higher than OPS biochar plasma gasification with maximum temperature at about 1500°C. The temperature for OPS was 920°C, on average. This was due to OPS microwave absorption ability [32]. OPS char has lower surface area than EFB char, thus reducing the absorption ability. Since EFB absorbs microwave radiation better than OPS, it results in a higher reaction temperature. The temperature profile shows a sharper peak as compared to a smoother peak without the activated carbon in previous experiments [4]. This is because the activated carbon reacts to the microwave radiation quickly and creates a sudden change in the temperature profiles. It was proven that activated carbon and other microwave absorbers can be used to increase the gasification reaction temperature [28,33,34]. Figure 5(a) shows the picture of gasification without activated carbon and Figure 5(b) shows the picture of plasma gasification with activated carbon added. The plasma flame was brighter at 1500°C when using activated carbon compared to without activated carbon at about 900°C.

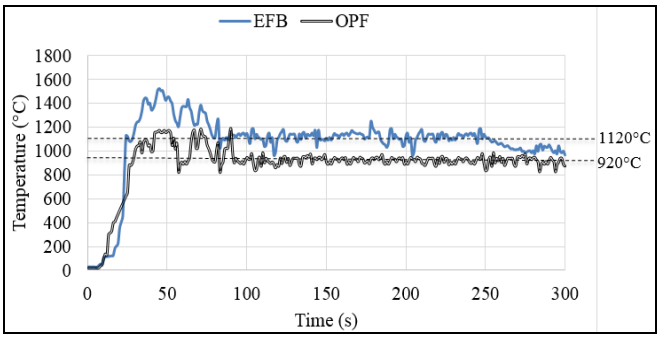


Figure 3 Temperature profile of EFB biochar and OPS biochar plasma gasification with activated carbon (10%)

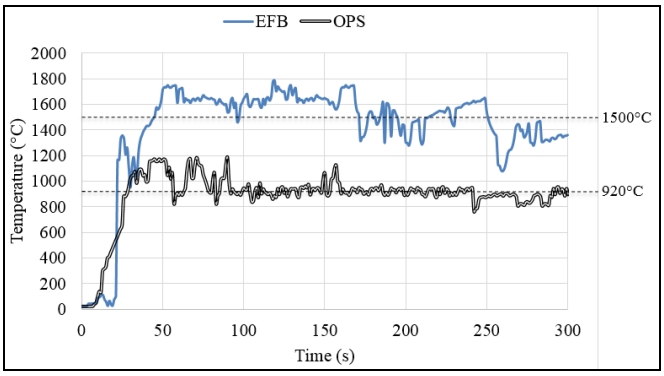


Figure 4 Temperature profile of EFB biochar and OPS biochar plasma gasification with activated carbon (25%)

Figure 5(a) MW gasification without AC

Figure 5(b) Plasma gasification with AC

Figure 6 shows the syngas composition of EFB biochar and OPS biochar plasma gasification, compared to microwave gasification. The syngas from biochar gasification with activated carbon was analysed for syngas composition. The temperature increment promoted by the addition of MW absorber AC has increased the CO_2 composition as compared to gasification without AC. The production rate of H_2 decreased after AC addition because the reaction has shifted towards a Boudouard reaction. Activated carbon is popular as an excellent microwave absorber due to its higher surface area and larger pores. By adding the activated carbon, it will absorb the microwave energy and increase the reaction temperature thus contributing to better CO production rate.

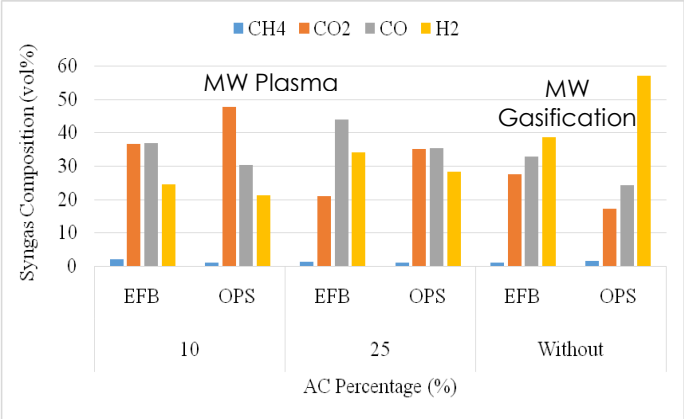


Figure 6 Syngas composition of EFB biochar and OPS biochar plasma gasification compared to microwave gasification

Table 2 SGY, CV, unreacted carbon percentage, and gasification efficiency of EFB biochar and OPS biochar plasma gasification

CO_2 Flow rates (lpm)	Char Type	SGY (m^3/kg)	CV (MJ/kg)	Un-reacted carbon (%)	η_g(%)
3 (10% AC)	EFB	1.55	7.03	12	72.34
3 (25% AC)	EFB	1.58	9.40	15	65.27
2(10% AC)	OPS	1.98	5.16	18	69.09
2 (25% AC)	OPS	2.01	7.32	20	60.20

Table 2 shows the SGY, CV, unreacted carbon percentage, and gasification efficiency of EFB biochar and OPS biochar plasma gasification. The highest CV for EFB is 9.40 MJ/kg at 3 lpm. For OPS gasification, the highest gas heating value is 7.32 MJ/kg. The heating value of syngas is the sum of volume percentage of combustible element in syngas. So, it is also affected by the reactivity of char towards CO_2. This pattern is similar to the CO production rate and carbon conversion efficiency of EFB and OPS char gasification. The gasification efficiency is dependent on the reaction of char in the gasification. The low efficiency was due to high amounts of unreacted char in the gasification experiment. Furthermore, the running time for this experiment was quite short. This may have caused unfinished burning of char that contributed to high amounts of unreacted char. By referring to the unreacted carbon percentage, it can be concluded that these parameters are dependent on each other. The best gasification efficiency is 72.34% at 3 lpm, 10% AC for EFB biochar plasma gasification with 12% unreacted carbon. For OPS biochar plasma gasification, the best gasification efficiency is 69.09% at 2 lpm, 10% AC with 18% unreacted carbon.

4.0 CONCLUSION

The amount of solid wastes generated in Malaysia increases at an alarming level every year. The increase in solid waste generation in Malaysia will not be hazardous to the environment and the general public, if it is managed properly. Treatment of solid waste is one of the many ways to manage massive amounts of generated solid wastes. As a developing country, Malaysia will be able to increase the efficiency of solid waste management by following the 3 R's: Reduce Reuse Recycle to achieve energy and material sustainability. Following this argument, a strategic approach of reusing waste materials is adopted; plasma gasification of biomass, specifically of oil palm wastes has been proven to have the potential to substitute conventional gas processing and treatments. Also, it has many other advantages such as being able to operate under atmospheric pressure, requires a short time to elevate to a higher temperature, thus helping in saving the energy for its production. Plasma technology has been proven as one of the most successful efforts in practicing cleaner technology in the industrial world. Other than processing and treating the solid waste, plasma technology can also be applied in other areas such as environmental applications, decontamination of chemical and biological warfare agents and nanotechnology. Plasma technology will help the world to become greener by lowering greenhouse gas emissions from heavy industries. Plasma gasification technology is commercially proven and viable, while also meeting all the current regulatory requirements. Plasma gasification is globally positioned to take hold as a practical, economical

and an environmentally safe alternative to the conventional forms of waste disposals and power generation.

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