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Hydrogen Gas Production from Gasification of Oil Palm Empty Fruit Bunch (EFB) in a Fluidized Bed Reactor

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Abstract

Malaysia is one of the largest producers of palm oil and this industry plays an important role in Malaysia economic growth. As this industry grows larger, a significant amount of oil palm waste is generated, creating the problem of overloading biomass waste. Since the oil palm waste has many significant uses such as empty fruit bunches (EFB), the interest in production of hydrogen gas as the renewable energy from EFB also increases. The most common and favorable thermochemical processes to produce the hydrogen gas is gasification process in fluidized bed reactor. Regardless of tremendous experimental studies done on effectiveness of using EFB for production of hydrogen, the process implementation in industry is still discouraging. This is due to lack of proven technology and high capital cost of investment. In this study, a computational modeling was developed for EFB gasification in fluidized bed gasifier using the ASPEN PLUS simulator (v. 8.8) to optimize the gasification temperature, pressure and to study the different of chemical behavior. The results indicated that increase in temperature will increases the production of hydrogen and enhances carbon conversion efficiency. The optimum temperature and pressure was 850 °C and 1.035 bar respectively. The result shows that the char was removed significantly after several gas cleaning process. The final product for purified hydrogen gas is 14.5 kg/hr which is around 21% of hydrogen yield. Based on the result, it indicates that EFB has a potential to be used as a source of energy in a future.

Keywords: Renewable energy; EFB; Hydrogen; Fluidized bed reactor; Aspen plus

1.0 INTRODUCTION

Renewable energy is a significant part of sustainable development and is crucial to the success of the industrialization process. Recently, substantial focus has been given to the renewable energy development since the conventional energy supply has become limited, fast depleting and the search of new source of gas and oil reserves becoming very challenging because of the unknown quantity of oil reserve [1]. Whereas, the use of nuclear energy has causes various devastating effect in term of cost, environment, human health and safety. It is due to the fact that radiation generated from the mechanical failures and human errors killed thousands of people only in a short period of time and effecting ten of thousand people later [2]. Beside from that, over the last few decades, the greenhouse gas (GHG) emission was increase and environmental pollution has become one of the greatest global issues. Carbon dioxide produce from the usage of fossil fuels cause a greenhouse effect and global warming. According to Pacesila, Burcea [2], in the next 50 years, the atmospheric carbon dioxide concentration will be doubled which will increase global warming from 1.8 to 6.3 degrees Fahrenheit. And among the effects of global warming are floods, heat waves, drought, loss of plant and animal, diseases and heat-related death. Therefore, it is necessary to establish energy from the renewable source as to avoid and reduce the environmental problems.

Currently, there are few countries which has already implemented the usage of renewable source as energy production with the aim of reducing the greenhouse gas emission. For example, Luxemburg and Germany had a target of reducing the greenhouse gas emission by 28% and 21% respectively. While the European Union as a whole had the average of 11.8% reduction in greenhouse gas emission by the end of the first EU-15 commitment period [3]. There is a positive growth in the renewable energy development especially in European Union to meet their 2020 target for a smart, sustainable and inclusive growth of renewable energy. As can be seen in Figure 1, there are various sources of renewable energy has been established in the European Union from 2004 to 2014. The percentage of consumption and energy generated from the renewable source has been increasing over the years. Wind turbines, solar power and solid biofuels become the largest source of the energy generated.

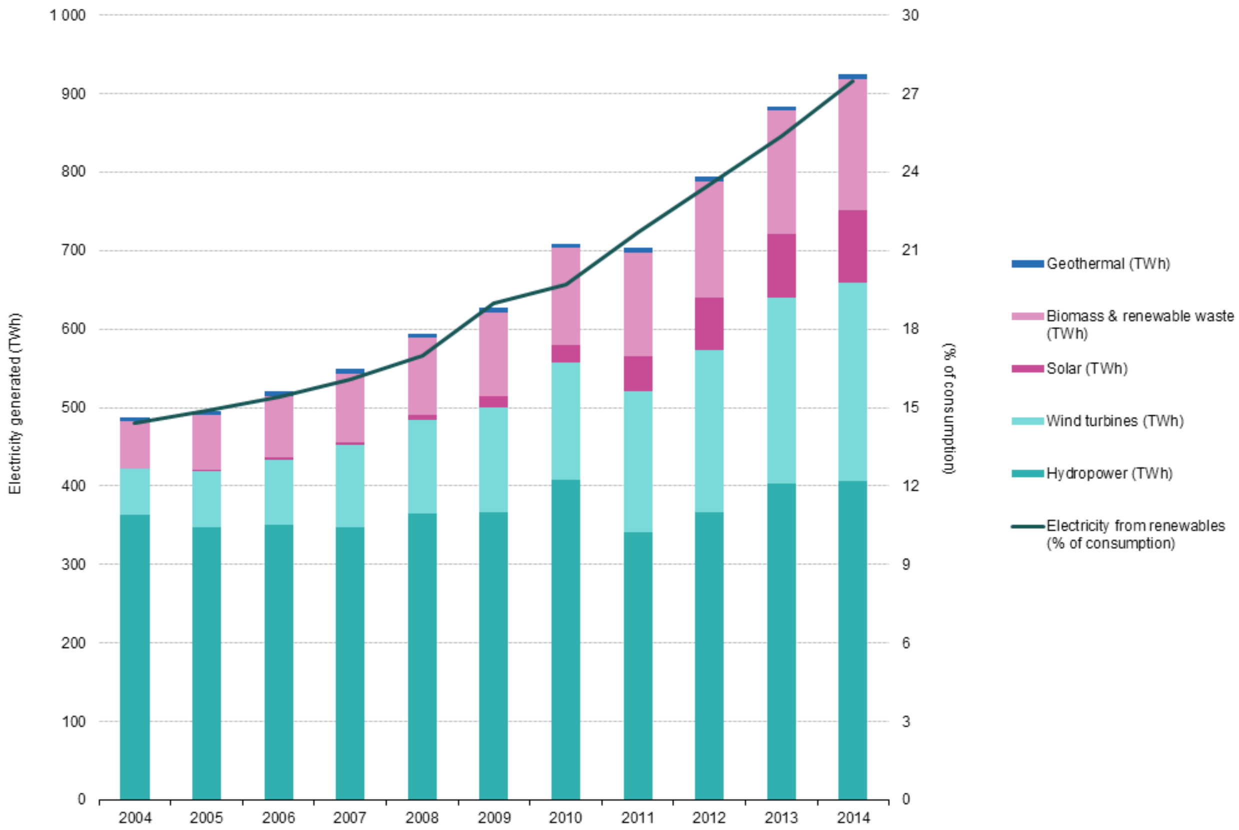

Figure 1. Electricity generated from renewable energy sources, EU-28, 2004–14 [4]

Figure 2 shows the long term trend of primary energy production from renewable sources which has been increased from 1990 to 2015. The renewable energy in European Union countries has shown a positive trend by producing a million tons of oils every year. Renewable wastes shows the highest contribution of energy production followed by geothermal energy, solar energy, wind power, hydro power, liquid biofuels, biogas and wood and other solid biofuels. Nevertheless, the primary production of renewable reduce by 2.2% in 2011 due to reduction in the biomass combustion and annual variation in hydropower production (Eurostat, 2017). Furthermore, the renewable energy production from biomass growth significantly as the Spanish Bioenergy (AVEBIOM) has coordinated the Biomasud Plus project under the Horizon 2020 Program. The program involves several countries such as Spain, Portugal, France, Greece, Italy, Turkey and Croatia. It aims to fully optimize the utilization of biomass by implementing a quality and sustainability certification system for biofuels [5]. Among the programs under this project are to identified the potential biomass exist and identify how much biomass available in each country involve. Olive stones, olive tree pruning, vineyard prunnings, woodchips and nutshells are among the biomass that been used to produce energy.

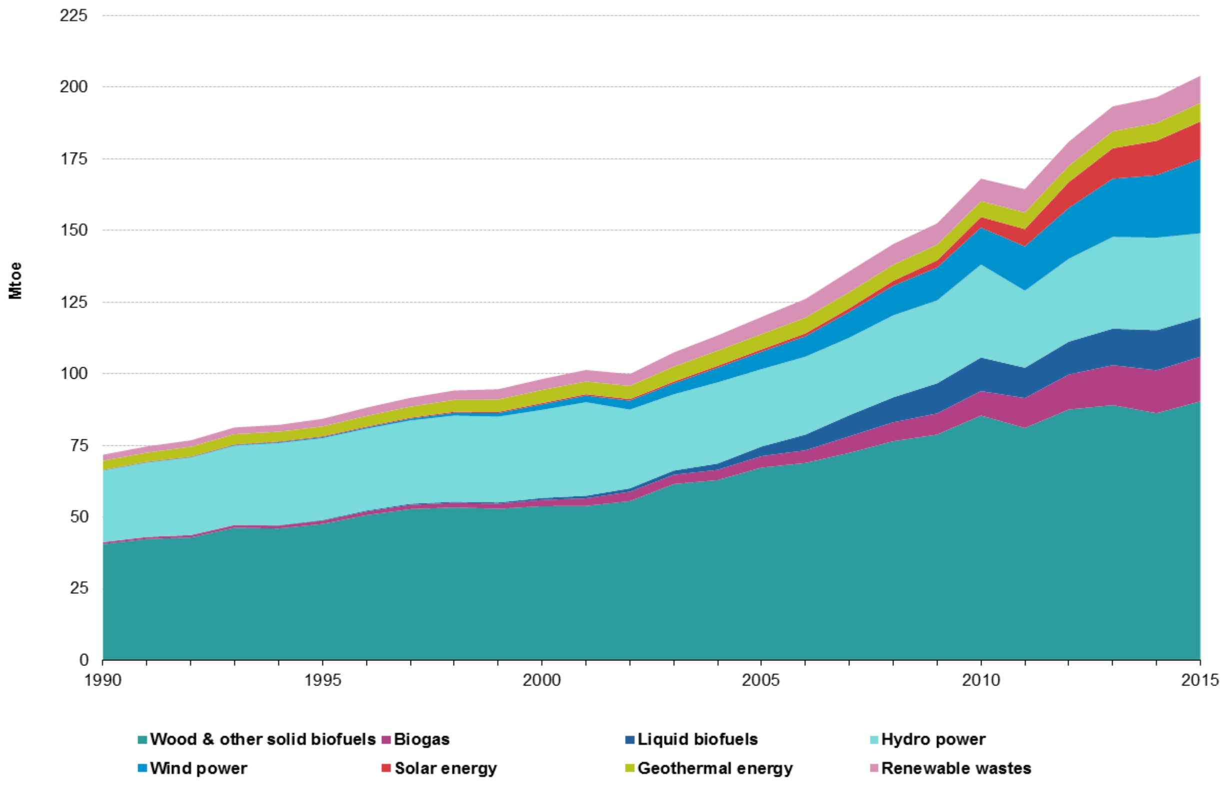

Figure 2. Primary production of energy from renewable sources [6]

In the developed country such as Germany, the hydrogen production technology from their biomass was already established. In contrast, the used of biomass such as empty fruit bunch (EFB) in Malaysia is still on the research phase. Even though Malaysia has been endowed with a lot of renewable energy sources, but currently it is not been fully utilized yet. Among the renewable energy sources that available in Malaysia are forest residues, oil palm biomass, solar thermal, mill residues, hydro, solar PV, municipal waste, rice husk and landfill gas. Table 1 shows the energy value in the various type of renewable energy in Malaysia.

Table 1. Renewable energy sources in Malaysia and its energy value [7]

Renewable energy source	Energy value in RM million (annual)
Forest residues	11,984
Oil palm biomass	6379
Solar thermal	3023
Mill residues	836
Hydro	506
Solar	378
Municipal waste	190
Rice husk	77
Landfill gas	4

Research and development effort in this area is significant to enhance the development of the renewable energy plant in Malaysia and support Malaysia Small Renewable Energy Power Plant Program which aiming to reduce 40 % of greenhouse gases emissions by 2020 [8]. Figure 3 shows the scope of biomass initiatives. The aim is to collect the residue harvesting and produce energy and fuel via several techniques such as enzymatic hydrolysis, pyrolysis, gasification and so on. Currently, in Malaysia, there is no commercial gasification plant employing biomass has been registered [9]. Study on the complete process of hydrogen production from EFB is necessary to speed up the application of such technology for renewable energy production. Throughout this study, data from the literature will be used and transformed into the process plant design. The process design of EFB gasification will be developed involving the gaseous production and gas cleaning process until the pure hydrogen storage. This research may speed up the commercialization of the technology toward the aims of Malaysia in the development of renewable energy.

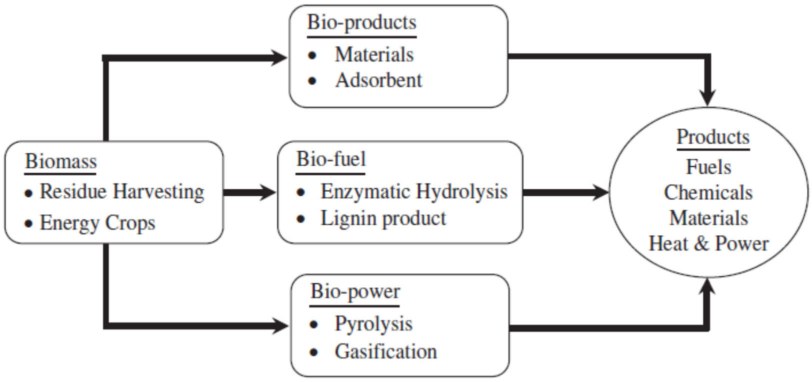

Figure 3. The scope of biomass initiatives as renewable energy source [10]

1.1 Hydrogen Energy

Hydrogen is a vision for future cleaner energy as to replace the limited source of fossil fuels since it is a clean energy carrier which can decarbonizing the industrial sector, commercial, residential and especially transport due to the fact that it can be burnt in a way that it produces no harmful emission. The use of biomass to produce hydrogen become a common interest worldwide due to several factors such as the abundant of locally available energy source (wind, solar, water, waste from agriculture, animal, municipal etc.), ability to reduce the greenhouse gas emission and make the energy market less dependence on the supply and fluctuation price of oil and gas [11]. Biomass material can be used to produce hydrogen via several method such as thermochemically, biochemically, biologically and biophotolytical. Among the current thermochemical processes to produce hydrogen from biorenewable feedstocks are steam reforming of bio-oils, steam gasification, supercritical water gasification (SWG), pyrolysis and gasification of the biomass [12]. Hydrogen has the potential to be the next great fuel and environmentally friendly option as it only byproduct is water and the source to produce it is easily available worldwide. Even though currently, the price of hydrogen gas is currently more expensive than a conventional energy sources since the cost for hydrogen gas production is about twice as natural gas and about three times the cost of coal but the technology will come to the maturity and it will be cheaper in future as the source to produce it can be acquired easily [13]. Due to that reason, the study on the process design of hydrogen production from EFB starting from the fresh feedstock until gas cleaning process and storage is necessary to enhance the commercialization of the process technology in a near future.

There are two different types of hydrogen production process from biomass that is frequently utilized which are thermochemical and biological processes. Thermochemical process consist of several methods such as pyrolysis, gasification and torrefaction which applied temperature and controlled atmosphere to generate chemical changes in the structure of biomass. It produces gasses that in more or less quantity including hydrogen. On the other hand, hydrogen production from biological processes utilized the presence of microorganisms either bacteria or algae to ferment biomass. The biological process can be further separated into light-dependent or light-independent. Figure 4 shows the summary of hydrogen production process from biomass.

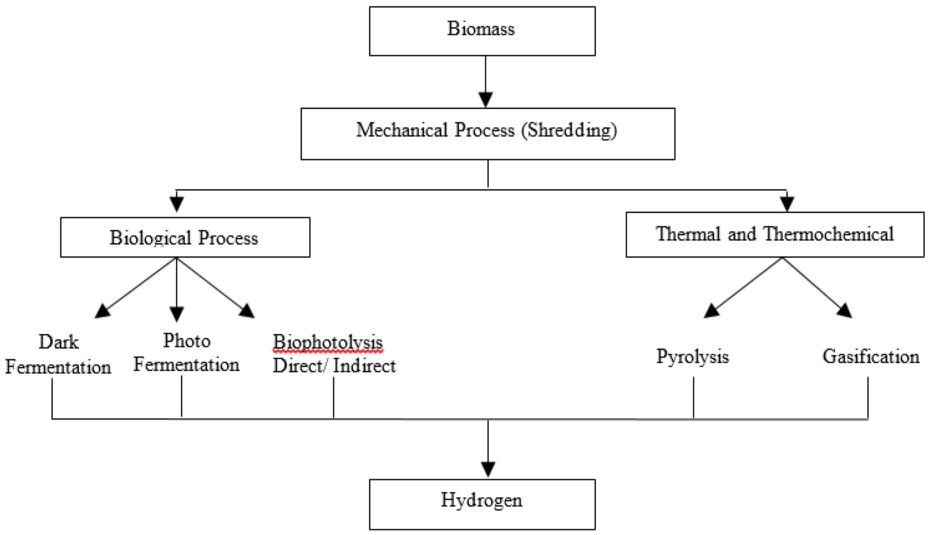

Figure 4. Hydrogen production processes from biomass

Hydrogen production process by using biological technology is a promising process which can minimize waste as well as to recover energy [14]. In biological process of producing hydrogen, it mainly includes bacterial hydrogen fermentation which considered as one of the alternatives for friendly environment. It also regards as one of the method for fulfilling the future hydrogen demand. In Malaysia, there are several research works have been done for hydrogen production via fermentation. For instance, using oil palm mill effluent (POME) in the presence of mix microflora population to produce hydrogen [15]. This process can be further divided into three processes which are dark fermentation, photo fermentation which required the light or also called as light dependent and two stage processes combining dark fermentation with either photo fermentation or bio-electrogenesis in microbial fuel cell [16]. Bacteria hydrogen fermentation process mainly depends on microorganism types and the temperature level. Dark fermentation is an attractive option for hydrogen production because it can be done in a wide range of operational temperature and pressure conditions and produce high hydrogen production rates [17].

Pyrolysis is the thermal decomposition occurring in the absence of oxygen. Gases, liquids (bio-oil) and solids are the products yield from the pyrolysis process. The related processes include slow pyrolysis where it used low temperature with long residence time and fast pyrolysis where it used moderate temperature with short residence time [18]. The liquid fraction of the product should be developed properly and could be applied to produce hydrogen. The fast and slow pyrolysis were determine according to its operating circumstances. The fast or also call as flash pyrolysis generates low temperature tar and high temperature gas whereas slow pyrolysis or conventional pyrolysis is associated with high charcoal continent [19]. In pyrolysis process, the required temperature in the absence of air is between 352°C and 502°C. Hosseini, Wahid [19] stated that in fast pyrolysis process, the products include gaseous products (CH_4, H_2, CO, CO_2 and other gases based on the organic nature of the biomass feedstock), liquid products (tar and oils such as acetic acid and acetone, which are liquid at room temperature), and solid products (composed of char and pure carbon plus other inert materials).

On the other hand, gasification is a process that usually implement high temperature with long residence time to increase the yield of hydrogen. Gasification produce high percentage of gaseous as compared to the pyrolysis process. Air or oxygen is used in combustion or partial oxidation process in the gasification process. The process could be applied in fluidized bed or fixed bed reactor [19]. Biomass gasification has gained lots of interests due to its high conversion efficiency. Energy production from biomass waste by using gasification and pyrolysis can be considered as promising technology. The partial oxidation of the feedstock occurs at high temperatures (800 – 1800 °C) in the presence of a gasifying medium such as air, oxygen or steam. Biomass gasification occurs in four stages which are drying, pyrolysis, char gasification and combustion [20]. Table 2 shows the percentage of hydrogen yield in various condition of thermochemical process.

Table 2. Product yield from various thermochemical processes of biomass in different condition [21]

Thermochemical process	Residence time (s)	Upper temperature (°C)	Product yield (%)		
			Char	Liquid	Gas
Slow pyrolysis	200	327	32-38	28-32	25-29
	120	427	29-33	30-35	32-36
	90	477	26-32	27-34	33-37
	60	577	24-30	26-32	35-43
	30	677	22-28	23-29	40-48
Fast pyrolysis	5	427	22-27	53-59	12-16
	4	477	17-23	58-64	13-18
	3	527	14-19	65-72	14-20
	2	577	11-17	68-76	15-21
	1	677	9-13	64-71	14-24
Gasification	1500	977	8-12	4-7	81-88

2.0 OIL PALM EMPTY FRUIT BUNCH

Oil palm (Elaeis guineensis) is a tropical plant which is originally come from Africa. It was first introduced in Malaysia as an ornamental plant in 1870. The planted area increase over the year which is from 1.5 million hectares in 1985 to 4.3 million hectares in 2007 and 4.917 hectares in 2011 [22]. Table 3 details the oil palm planted area (hectare) base on each state in Malaysia in 2013 [23]. It shows that Johor and Pahang represent the largest planted area which is around 56% of the total planted area in Peninsular Malaysia, while Sabah and Sarawak are the largest producers of palm oil in Malaysia which is around 51.5% from the total planted area in Malaysia. The information of oil palm planted area is necessary to plan the future commercial plant of hydrogen production from EFB. Base on Table 3, the most suitable area where the transportation cost of biomass can be reduced is around Pahang since it is located in the center of peninsular Malaysia and very near to Johor which also produce high oil palm. Beside from that, Sabah is also among a potential place to set up a new gasification plant to produce hydrogen from EFB. Additionally, Malaysia has the important role in fulfilling the growing global need for oils and fat sustainability since Malaysia currently accounts for around 39 % of world palm oil production and 44% of world exports [22]. Oil palm tree has become the most important agricultural crop in Malaysia and has become the key to the national economic expansion [24]. Currently there is a strong global demand for palm oil. According to [MATRADE [25]], palm oil represent the fifth largest export of Malaysia in 2014 which is RM 46.95 Billion (6.1%) which contribute towards Malaysian Gross National Income (GNI).

Table 3. Planted area (hectare) of oil palm in Malaysia in 2013 [23]

State	Mature	%	Immature	%	Total	%
Johor	651,242	88.8	82,225	11.2	733,467	13.6
Kedah	80,767	93.7	5415	6.3	86,182	1.6
Kelantan	99,783	68.9	44,979	31.1	144,762	2.7
Malacca	49,501	93.7	3348	6.3	52,849	1.0
Negeri Sembilan	142,503	84.1	26,865	15.9	169,368	3.1
Pahang	623,269	86.6	96,344	13.4	719,613	13.3
Perak	348,794	89.6	40,370	10.4	389,164	7.2
Perlis	189	64.1	106	35.9	295	0.0
Penang	13,309	93.7	895	6.3	14,204	0.3
Selangor	126,805	91.6	11,677	8.4	138,482	2.6
Terengganu	139,410	82.5	29,538	17.5	168,948	3.1
Peninsular Malaysia	**2,275,572**	**91.6**	**341,762**	**8.4**	**2,617,334**	**48.5**
Sabah	1,355,541	89.7	155,969	10.3	1,511,510	28.0
Sarawak	1,058,208	83.8	205,183	16.2	1,263,391	23.5
Sabah & Sarawak	2,413,749	87.0	361,152	13.0	2,774,901	51.5
MALAYSIA	**4,689,321**	**87.0**	**702,914**	**13.0**	**5,392,235**	**100.0**

As the second largest producer of palm oil in the world [26], huge amount of waste which called as lignocellulosic biomass comprising palm EFB (53%), palm mesocarp fibre (32%) and palm kernel shell (15%) produce from around 368 of palm mills in Malaysia [21]. Abundant of EFB being produce every day since oil palm is the dominant agricultural crop [9]. EFB is the empty husks left over after the oil extraction from palm fruit. According to Lahijani and Zainal [9], EFB is utilized as organic fertilizer in palm processing mill, some part of EFB is also used as solid fuel in the boiler to generate steam and electricity but currently there is limited particular utilization of it in large quantities and it is burned in open air, incinerated or used as landfill material dumped in the plantation. These situations have led to increased CO2 and other greenhouse gas (GHG) emissions in the atmosphere [27]. Beside from that, several researches have aggressively been done in the technologies and potential of EFB to produce energy through thermochemical process [8]. Table 4 depicts the various process analyzed by a few researchers to know the elemental composition of EFB [28] and this data is important to be used as a basic component database in the simulation process by using Aspen Plus Software.

Table 4. Hydrogen production process from EFB as feedstock [28]

Process	Ultimate Analysis (wt. %)					Proximate Analysis (wt. %)				Feedstock size (μm)	Upper temperature (°C)	Hydrogen yield (%)
	C	H	N	S	O	Mo-ist-ure	Volat-iles	Ash	Fixed carb-on			
Gasification (Fluidized bed reactor) [9]	43.5	5.7	1.2	0.7	48.9	7.8	79.3	4.5	8.36	0.0	1050	12.4
Fast pyrolysis (Fluidized bed reactor) [29]	49.1	6.5	0.7	<0.1	38.3	7.95	83.9	5.4	10.78	250-355	450	9.61
Gasification (Fluidized bed reactor) [30]	46.6	6.5	1.2	0.04	45.7	5.18	82.6	3.5	8.79	300	1000	38.02
Dark Fermentation [31]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	58 (pH 5.5)
Gasification (Entrained-flow gasifier) [32]	46.3	5.9	0.5	0.0	44.6	0.0	0.0	2.7	0.0	0.0	900	67-75 (H_2+CO)
Gasification (Circulating fluidized-bed (CFB)) [33]	49.5	5.9	0.5	0.1	40.6	6.8	77.4	3.3	19.3	5000	709	5
Pyrolysis (fixed bed reactor) [34]	48.8	7.3	0	0.68	40.2	8.75	79.7	3.0	8.65	<1000	900	36.36
Gasification (Fluidized Bed Reactor) [35]	61.5	10.5	2.0	0.0	26.0	5.4	25.4	0.0	54.05	500	850	27.97

3.0 RESEARCH APPROACH

ASPEN Plus (Advance System for Process Engineering Plus) Software (v8.8) was used in this study to optimize the gasification temperature, pressure and to study the different of chemical behavior. Simulation of EFB gasification can reduce the time and cost of its development by using pilot plant of experimental study [37], it also help to improve current process by changing the input in the stream and unit operation condition to determine factors effecting the efficiency of the plant [38]. In this study, the following assumption are considered in simulating the EFB gasification process:

- Gasifier is a steady-state system with uniform temperature and pressure throughout.
- Gases except H_2, CO, CO_2, CH_4 and N_2 are considered dilute.
- All gases are ideal gases, including H_2, CO, CO_2, H_2O, N_2 and CH_4, and solid phase is ash.
- Ash in biomass does not participate in chemical reactions.
- N_2 is considered as inert in the entire process.
- Steam is supplied at superheated condition at 1 bar and 400 °C.
- Char is assumed as graphitic carbon.
- The main reactions of EFB gasification considered in gasifier part are [39]:

$$3C+2O_2=2CO+CO_2 \tag{1}$$

$$C + H_2O = CO + H_2 \tag{2}$$

$$CO + H_2O = CO_2 + H_2 \tag{3}$$

$$C + CO_2 = 2CO \tag{4}$$

$$C + 2H_2 = CH_4 \tag{5}$$

$$CH_4 + H_2O = CO + 3H_2 \tag{6}$$

$$CH_4 + 2H_2O = CO_2 + 4H_2 \tag{7}$$

In this modelling, the Redlich-Kwong-Soave (RKS) cubic equation of state with Boston-Mathias alpha function (RKS-BM) was selected for this process design since it is recommended for gas processing, refinery and petrochemical applications [40]. Several EFB ultimate and proximate analysis data were collected from the literature (tabulated in Table 4) and was used for this simulation. The non-stoichiometric model which is Gibbs free energy minimization was used with the gasification reaction. Data of proximate and ultimate analysis of EFB done by Mohammed, Salmiaton [30] was selected for this study since the hydrogen yield and other operation condition of this simulation will be compared with their experimental analysis result.

4.0 RESULT AND DISCUSSION

The design basically consist of a few processes which are gasification reaction, by-product separation and gas cleaning process as illustrated in Figure 5. As feed material, EFB is nonconventional, therefore its element compositions are all need to be converted to element in RYIELD. The RYIELD block was used for the devolatilization of the feedstock and after passing through the drying and pyrolysis stage, EFBs were converted into different types of elements which are H_2, CO, CO_2, etc. After that, EFB (elements) moved down due to gravity and came in contact with air in the RGIBBS block in which balanced products under certain temperature and pressure can be determined based on the method of Gibbs free Energy Minimization. The produced gas contains some particles are then eliminated using the CYCLONE solid separator and finally hot syngas are cooled using heat exchanger aspen plus block. Table 5 shows the flow sheets of the EFB gasification system and detailed mass and energy analyses for the main streams involved which are EFB, FBRGAS, SYNGAS2, SYNGAS3, H2-GAS, OTHERGAS and H2 stream. FBRGAS is a stream that produce syngas after gasification including H_2, CO, CO_2, H_2O, and CH_4.

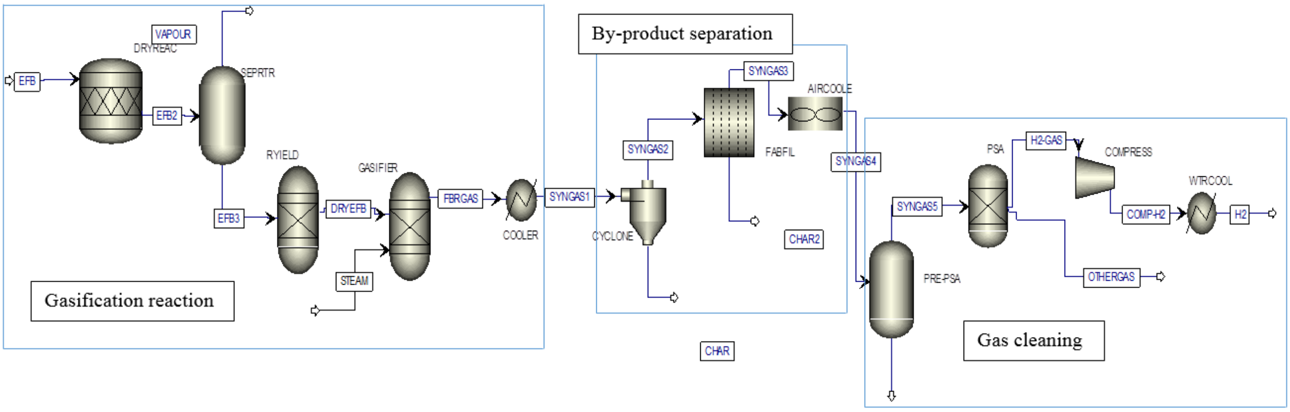

Figure 5. Aspen Plus (v 8.8) model flow sheet for EFB gasification in fluidized bed reactor

Table 5. Detailed mass and energy analyses of the hydrogen production process by using EFB as a feedstock

Stream Name	**EFB**	**FBRGAS**	**SYNGAS2**	**SYNGAS3**	**H2-GAS**	**OTHERGAS**	**H2**
To Unit	**DRYREAC**	**COOLER**	**FABFIL**	**AIRCOOLE**	**COMPRESS**		
From Unit		**GASIFIER**	**CYCLONE**	**FABFIL**	**PSA**	**PSA**	**WTRCOOL**
Temperature C	25	850	204.4	204.4	43.3	43.3	43.3
Pressure bar	1.013	1.013	1.014	1.014	24.821	24.821	69.913
Total Mass Flow kg/hr	69.542	132.629	132.629	132.629	14.522	78.385	14.522
Volume Flow cum/hr	0.056	1097.478	466.527	466.527	7.751	2.597	2.827
Mass Flow kg/hr							
H_2	0	14.522	14.522	14.522	14.522	0	14.522
CO	0	53.603	53.603	53.603	0	53.603	0
CH_4	0	0.071	0.071	0.071	0	0.071	0
CO_2	0	24.176	24.176	24.176	0	24.172	0
H_2O	0	40.257	40.257	40.257	0	0.539	0

Simulation results in Figure 6 shows that the effect of different pressure and temperature on CH_4, CO_2, CO and H_2 gas production. The highest syngas production was obtained at pressure of 1.013 bar and slightly decreased in gas production was observed when the pressure increased to 5.875 bar and above. The temperature of fluidized bed reactor used in this study was vary accordingly to determine its effect on the hydrogen production yield. Figure 6 shows the result of different temperature effect on gases yield. It shows that, as the temperature increase, the percentage of hydrogen production yield also increased significantly. However, increasing the temperature after 1050°C did not give a significant effect to the hydrogen yield. It is similar with the experimental result done by Mohammed, Salmiaton [30]. The optimum temperature and pressure from the simulation was 850 °C and 1.035 bar respectively. The result shows that the char was removed significantly after several gas cleaning process.

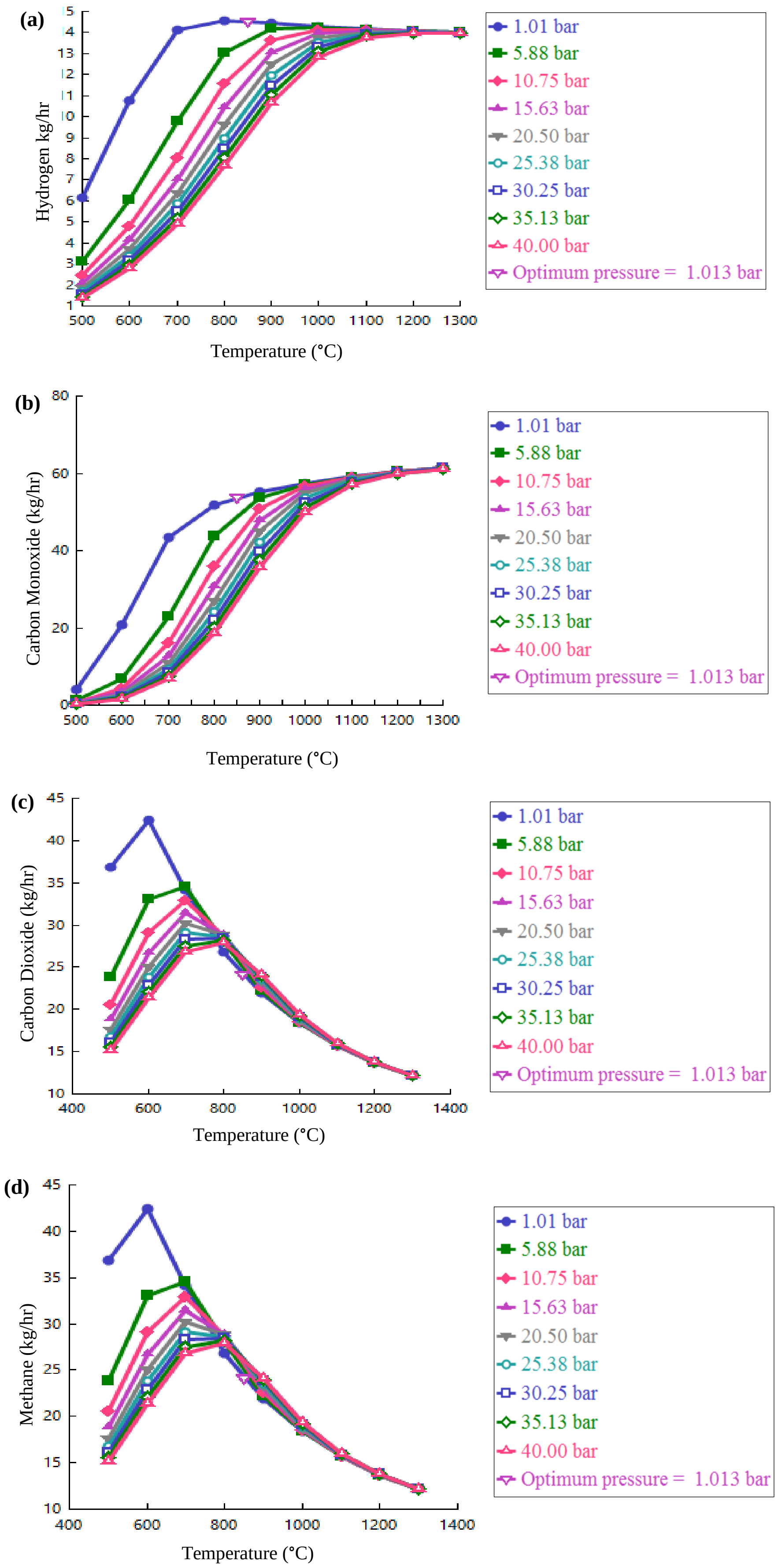

Figure 6. Effect of temperature on different gas composition

Result in Figure 6 shows that the optimum pressure of EFB gasification in fluidized bed reactor is 1.013 bar, therefore sensitivity analysis was done to observe the influence of varying temperature at 1.013 bar on gas product components. As shown in Figure 7, H_2 content increased gradually as the temperature increase from 500 °C to 900 °C and decreased with temperature increasing to above 1000 °C. The CO content also increased significantly at 700 °C while CO_2 and CH_4 decrease in its content as the temperature increasing. At 850 °C, it shows the highest yield of H_2 content which is 14.52 kg/hr, along with 53.60 kg/hr of CO, 24.18 kg/hr of CO_2 and 0.07 kg/hr of CH_4. The variation of gas product distribution may cause by the thermal cracking of gas-phase hydrocarbons at high temperature. At high furnace temperature, the gas species generated from biomass at pyrolysis zone could undergo further reactions (secondary reactions) such as tar cracking and shifting reaction, leading to much more incondensable gases (including H_2) generated. Therefore, the total yield of gases products increased significantly as temperature increased from 700 to 1000 °C. The final product for purified hydrogen gas is 14.5 kg/hr which is around 21% of hydrogen yield with the temperature of 43.3 °C and 1014 psia pressure. Based on the result, it shows that EFB has a potential to be used as a source of energy in a future.

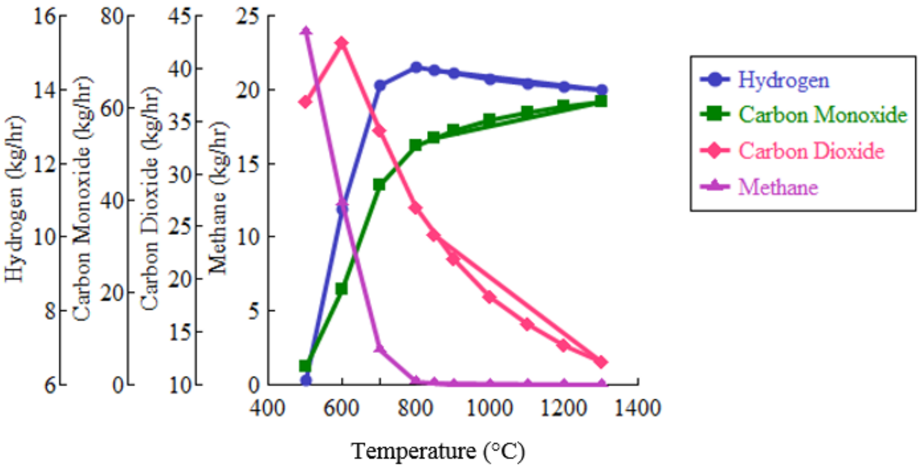

Figure 7. Effect of temperature on product gas composition at 1.013 bar

5.0 CONCLUSION

In this study, a model was developed for the gasification of EFB in fluidized bed reactor using the ASPEN PLUS (v 8.8) simulator. Several unit operation blocks were combined and model was developed using data collected from literature. Based on the result, the highest syngas production was obtained at pressure of 1.013 bar and temperature of 850 °C. Increase in temperature can improves the gasification process and also increases both the production of hydrogen and the carbon conversion efficiency. However, carbon monoxide and methane show decreasing trends with increasing temperature. The final product for purified hydrogen gas is 14.5 kg/hr which is around 21% of hydrogen yield with the temperature of 43.3 °C and 69.9 bar pressure. The findings from this study may provide an insight for future application of EFB gasification in fluidized bed reactor and result shows that EFB has a potential to be used as a source of energy in a future. Further study should be done on the cost analysis to study the feasibility of this technology.

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