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Process Development of Oil Palm Empty Fruit Bunch Gasification by using Fluidised Bed Reactor for Hydrogen Gas Production

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Hydrogen can store and deliver usable energy, but it does not typically exist by itself in nature and must be produced from compounds that contain it such as biomass. Hydrogen can be used as fuel which produce from gasification process that used renewable sources as feedstock. Large amount of empty fruit bunch (EFB) has been produced in Malaysia and yet has no specific used in large quantity and it is being incinerated or used as landfill material dumped in the plantation. These situations have led to increased CO_2 and other greenhouse gas (GHG) emissions in the atmosphere. During preliminary study, it shows that there are very limited studies being done in the process design development of the hydrogen production by using EFB from oil palm. Despite of tremendous experimental studies done on the 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, the drying, gasification and purification unit operations were modelled in Aspen Plus simulator for production of pure hydrogen gas and char was removed significantly after several gas cleaning processes. The final product for purified hydrogen gas is 12.3 t/h which is 16.3 % of hydrogen gas produced from the total EFB feedstock. Based on the result, the optimum temperature and pressure for gasification process is 850 °C and 1 atm respectively. Since, there is not much research have been carried out on process design of hydrogen production process by using EFB as feedstock, the understanding towards this topic can be prolonged.

1. Introduction

The used of biomass such as oil palm empty fruit bunch (EFB) for hydrogen production in Malaysia is still on the research phase even though Malaysia has been endowed with a lot of renewable energy sources. 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. Research and development efforts 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 (Lange and Pellegrini, 2013). Currently, in Malaysia, there is no commercial gasification plant employing biomass has been registered (Lahijani and Zainal, 2011). 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 to develop the gasification plant design. The process design of EFB gasification will involve the gaseous production by fluidised bed reactor, gas cleaning process and hydrogen storage. This research may speed up the commercialisation of the technology toward the aims of Malaysia in the development of renewable energy.

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Hydrogen is a vision for future cleaner energy as to replace the limited source of fossil fuels. It is a clean energy carrier which can decarbonising the industrial sector, commercial, residential and especially transport since it can be burnt in a way that it produces no harmful emission. The use of biomass become a common interest among a researchers nowadays due to several factors such as energy security, abundant of locally available energy source (wind, solar, water, waste from agriculture, animal, municipal etc.) without any specific usage, ability to reduce the greenhouse gas emission and because it also will make the energy market less dependence on the supply and fluctuation price of oil and gas (Basu, 2013). Biomass material can be used to produce hydrogen via several methods 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 (Demirbas, 2009). Hydrogen has the potential to be the next great fuel and environmentally friendly option as it only by-product 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 the future as the source to produce it can be acquired easily (Mandil, 2004). Due to that reason, the study on the production of hydrogen from EFB starting from the fresh feedstock until gas cleaning process and storage is necessary to enhance the availability of the technology in a near future.

2. Model development

Development of pilot plant for experimental study of chemical behaviour can be quiet challenging in term of material cost, time and high operating temperature (Thapa and Halvorsen, 2014). In this study, a computational model of hydrogen production process by using EFB as a feedstock has been developed by using ASPEN Plus (Advance System for Process Engineering Plus) Software. By using the Aspen Plus software for a process design development, it can reduce plant design time, help to improve current process and also various plant configuration can be tested by changing the input in the stream and unit operation condition to determine factors effecting the efficiency of the plant. It also can be used to answer “what if” question and able to identify the optimal process condition within given constrain (Schefflan, 2011). The design basically consists of a few processes which are feed drying, gasification, gas clean-up and hydrogen purification (Figure 1).

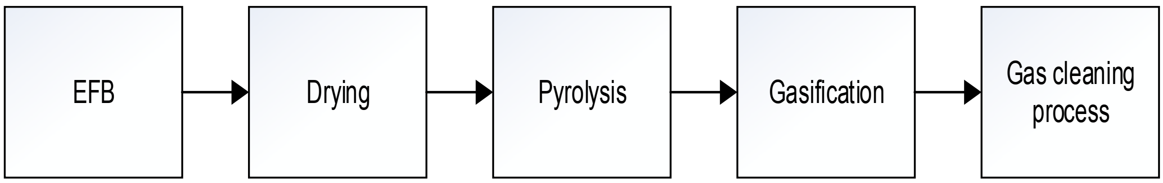

Figure 1: Reaction sequence of EFB gasification process

The Redlich-Kwong-Soave (RKS) cubic equation of state with Boston-Mathias alpha function (RKS-BM) method was used to derive the basic thermodynamic properties of the system. The RKS-BM property method was selected for this process design since it is recommended for gas processing, refinery and petrochemical applications (Eikeland et al., 2015). EFB is a nonconventional type of material, the proximate and ultimate analysis data were used as input. The non-stoichiometric model which is Gibbs free energy minimisation was used with the gasification reaction as shows in Table 1 (Gupta, 2008).
The database of proximate and ultimate analysis has been developed previously and the best technology to produce hydrogen from EFB has been identified (Shahlan et al., 2017). Data of proximate and ultimate analysis of OPEB done by Mohammed et al. (2011b) was selected for this study since the hydrogen yield and other operation condition of this simulation were compared with their experimental analysis result. Since EFB is a nonconventional component, it did not participate in chemical or phase equilibrium. The EFB enthalpy and density were calculated in this simulation by using the HCOALGEN and the DCOALIGT models. The proximate as well as the ultimate analysis data was inserted in the required component attribute field for EFB. Component attribute is used by Aspen Plus to calculate physical properties of nonconventional component. The plant capacity is designed to be 2,000 t/d of EFB as followed feedstock size from National Renewable Energy Laboratory of the U.S. Department of Energy (DOE) (Spath et al., 2005). In the simulation system, a defined FOTRAN subroutine with the specified yield distribution is used to calculate the yield and FOTRAN subroutine water calculator was used to reduce the moisture from feed material before entering the combustion zone.

Table 1: EFB gasification reaction

Reaction	Physical process and chemical formula
R1	$C + O_2 \rightarrow CO_2$
R2	$C + 1/2O_2 \rightarrow CO$
R3	$C + H_2O \leftrightarrow H_2 + CO$
R4	$CO_2 + C \leftrightarrow 2CO$
R5	$C + 2H_2 \leftrightarrow CH_4$
R6	$CO + H_2O \leftrightarrow CO_2 + H_2$
R7	$CO_2 + 3H_2 \leftrightarrow H_2O + CH_4$

3. Result and discussion

In this study, the gasification process by using fluidised bed reactor was selected for process design since the analysis from the literature shows that gasification process of EFB by using fluidised bed reactor is favourable and produce high amount of hydrogen concentration which is around 17 % (Mohammed et al., 2011a). Figure 2 shows the process flow diagram for the combustion and gasification process of EFB.

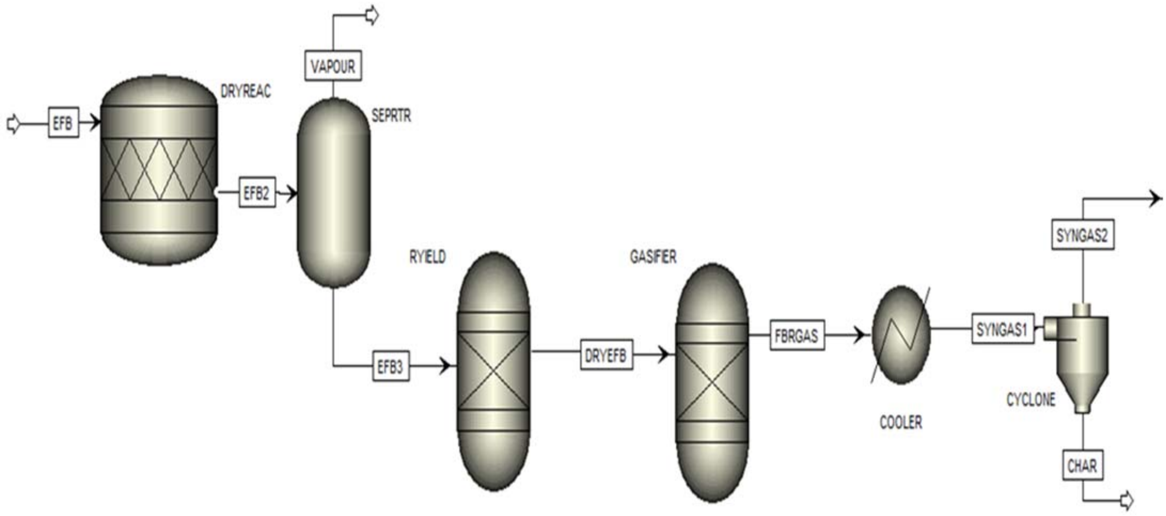

Figure 2: Process flow diagram for EFB gasification process

The wet EFB was feed into the RSTOIC and FLASH2 unit operation to simulate a single piece of plant equipment for EFB drying. RSTOIC block was used to convert EFB to form water. The chemical reaction for the drying of wet EFB shown in Eq(1)

$$\text{Wet EFB} \rightarrow 0.0555\ H_2O \quad (1)$$

The process continues with the combustion and gasification process. The heat combustion of EFB used in this simulation is 18.4 MJ/kg (Ninduangdee et al., 2015). The RYIELD model was used to convert the EFB into its constituent elements such as hydrogen, carbon, oxygen, sulphur, nitrogen and ash. The yield was identified based on the ultimate analysis of the EFB. The RGIBB reactor model was used for gasification process. Inside the reactor, the biomass was dried and devolatilised to produce gases and solid char particle (Eikeland et al., 2015). In the absence of air, the volatile reaction is assume to follow the Gibbs free energy equilibrium (Kabir et al., 2015).

The gases from the reactor was passed through the cyclone separator. The cyclone was used to remove the particle down and clean the gases from solid particles (Klass and Emert, 1981). The gases from the cyclone was sent to into a fabric filters to removes access char in the stream (Figure 3). Few gas purification processes needed to clean the gases from any particles from the gasification process (Gupta, 2008). After the gas clean-up process, the gases was sent to a separators to undergo a pressure swing adsorption (PSA) separation process. PSA is best suited for separation and purification processes for hydrogen production from EFB since it produces a very high purity product and it is less strongly adsorbs species which is required in pure form as the main product (Isalski, 1989).

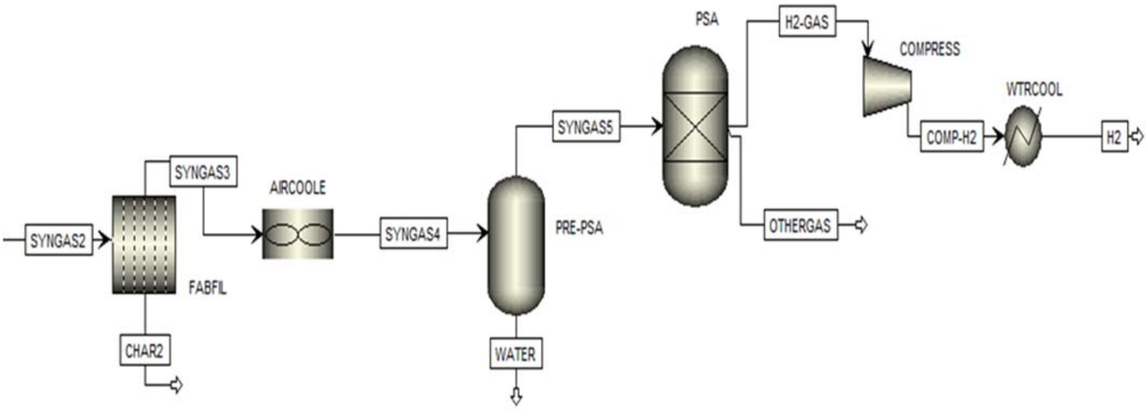

Figure 3: Process flow diagram for gas clean-up and purification of EFB gasification process

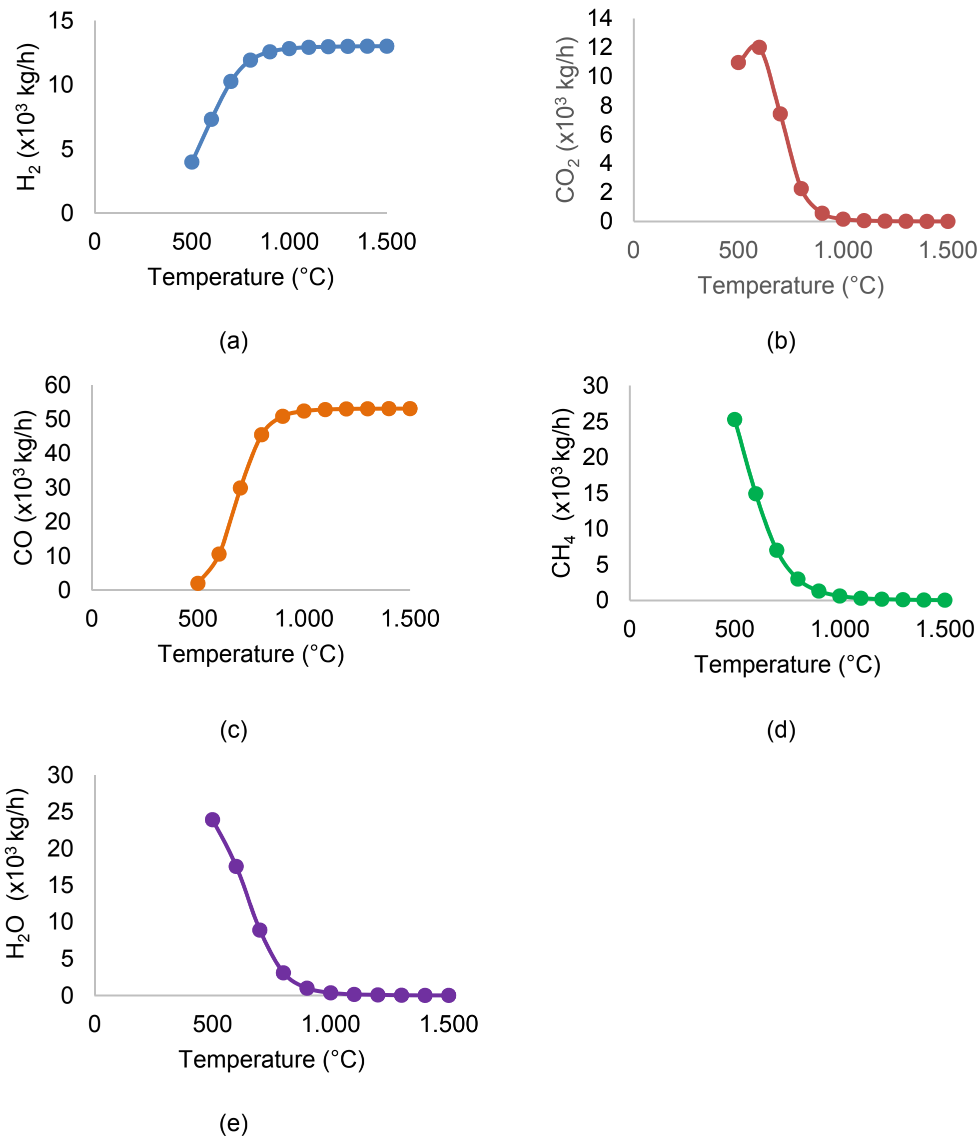

Figure 4: Effect of temperature on different gas composition

The pure hydrogen gas product was sent to the compressor to increase the pressure to 6.99 MPa and the temperature was reduced by using heat exchanger to maintain the performance since storage should not be too hot or too cold (Gupta, 2008). From the result, it shows that the char was removed significantly after several gas cleaning processes. The final product for purified hydrogen gas is 12.3 t/h with the temperature of 43.3 °C and 6.99 MPa pressure. The temperature of fluidised bed reactor used in this study was vary accordingly to determine its effect on the hydrogen production yield. Figure 4 shows the result of different temperature effect on different gas composition. It shows that, as the temperature increase, the amount of hydrogen and carbon monoxide produced were increased. However, carbon dioxide, water and methane reduced as the temperature increased while the amount of char remain almost constant. The result shows that increasing the temperature after 1,050 °C did not give a significant effect to the hydrogen yield. Based on the result, the optimum temperature for gasification process is 850 °C. It is similar with the experimental result done by Mohammed et al. (2011b). The percentage of the various product yield from the gasification process of EFB using fluidised bed reactor can be seen in the Table 2. The result shows that 16.3 % of hydrogen gas is produced from the total feedstock. Based on the result, EFB has a potential to be used as a source of energy in the future.

Figure 5 shows the effect of pressure inside fluidised bed reactor on the hydrogen yield. As the pressure increases, the mass flow of hydrogen decreases. It is because the mass transfer coefficient K_g decreases when pressure is increased (Abdelgawad, 2013). The optimum pressure of fluidised bed reactor for gasification of EFB is 0.1 MPa.

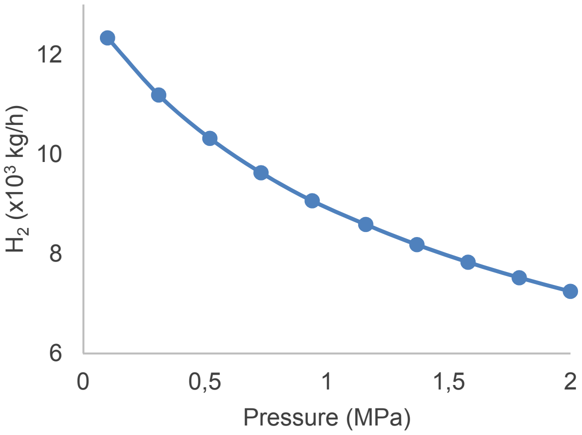

Figure 5: Effect of pressure on hydrogen yield

Table 2: Percentage of the product yield from the feedstock

Product yield	Percentage of product yield (%)
Hydrogen (H_2)	16.3
Carbon monoxide (CO)	64.8
Methane (CH_4)	2.6
Carbon Dioxide (CO_2)	1.5
Water (H_2O)	2.3
Char (C)	12.5

4. Conclusion

The Aspen Plus simulation modelling can be useful to identify the produces gas composition and determine the optimum operating condition for the process. From the process design, it is found that a feeds mass flow of 83.3 t/d can produced 12.3 t/d of hydrogen product from EFB. Several gas cleaning processes also important to ensure that the gases is clean and purify from any unwanted particles. From the result, it shows that the temperature on the gasifier has a significant impact on the product yield. After it reaches a temperature of 1,050 °C the hydrogen yield increase very slowly with only 0.1 % different. The sensitivity test was done and the temperature of fluidised bed reactor used in this study was vary accordingly to determine its effect on the hydrogen production yield. It shows that, as the temperature increased, the amount of hydrogen and carbon monoxide produced were increased. Carbon dioxide, water and methane decreased as the temperature increased while the amount of char remain almost constant. Additionally, as the pressure increased, the mass flow of hydrogen was decreased. As a conclusion, The Aspen Plus Software give a very useful design aid in evaluating a complex reacting system. The result from the simulation reveal that EFB as a good biomass source and can be an alternative for hydrogen production in Malaysia. It also can reduce the dependency on fossil fuel as well as to solve the energy problem and follow the National Biomass strategy 2020. In the future, the study on the cost benefit analysis can be done to identify the feasibility of this technology.

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