Hydrogen Gas Production Simulation Utilizing Empty Fruit Bunch of Oil Palm Pyrolysis Unit by Steam Methane Reforming Process

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Abstract. We present a simulation of the hydrogen gas production by steam methane reformer unit utilizing empty fruit bunch (EFB) of the oil palm tree by using Aspen Plus. The oil palm empty fruit bunches, as biomass, is one that can be used as an alternative energy source to generate power. This paper aims to determine the amount of hydrogen gas (H₂) can be obtained from five different EFBs samples, which are available as waste in the local area of Sumatera Utara Province. In the pyrolysis unit, the proximate and ultimate analysis of the EFB was introduced while developing the model in Aspen Plus simulation environment to get the syngas as a product from the pyrolysis process. The syngas out from the pyrolysis unit then going to a steam methane reformer unit to get hydrogen-rich gas. The results showed that, from five samples of EFBs, the H₂ obtained in the range of 0.90 kg/hr to 1.70 kg/hr.

1. Introduction
An increase in the price of petroleum, a limited amount of fossil fuels, adverse impacts on the environment, especially those related to greenhouse gas emissions, and health and safety considerations force the search for new energy sources [1-3]. Biomass is a renewable energy resource that is geographically abundant and can contribute to controlling environmental impacts such as global warming [4]. Oil palm empty fruit bunches (EFB) are the main contributors to palm oil derivative products, with 15.5-17.5 million tons per year. Most palm oil mills do not have the technology to exploit the energy potential of empty fruit bunches (EFB) [5].

The production of substitute natural gas, also known as synthetic natural gas (SNG) from biomass (bio-SNG) is the result of progress from recent research in reducing dependence on conventional (fossil) natural gas due to its composition, which is mostly methane (CH₄) [6]. Besides, SNG can contribute by extending the remaining number of production years in connection with known natural gas (R / P) reserves, which are based on various studies, limited to 52.8 years (R / P sensitive to the discovery of reserves, increases or decreases in production annual) [7].

Hydrogen is an ideal candidate system’s because hydrogen is a cleaner source of energy [8]. It holds promise as fueling a dream of the future with many social, economic and environmental benefits to its credit [9]. The hydrogen gas production from fossil fuels causes the joint production of carbon dioxide (CO₂), which contributes to increasing greenhouse gas (GHG) [10]. Hydrogen produced through various renewable primary energy sources such as wind, biomass, and solar energy is ideal for gradually replacing fossil fuels [11]. Steam reforming methods for natural gas offers an
efficient, economical, and widely used process for hydrogen production, with the efficiency of the process around 65% to 75%, and among the highest of current commercially available production methods.

Biomass pyrolysis is a promising alternative energy conversion method in producing solid (charcoal), liquid (tar and other organic), and syngas [12,13]. Depending on the operating conditions of the pyrolysis process, it can be divided into three subclasses as conventional (slow) pyrolysis, fast pyrolysis, and flash pyrolysis. Slow biomass pyrolysis is associated with continental high charcoal, but fast pyrolysis is associated with tar, at low temperatures (675-775 K) [14], and/or gas, at high temperatures [15]. At present, the preferred technology is fast pyrolysis or flash at high temperatures with short residence times [16].

Among all the techniques related to H\textsubscript{2} production, SMR (steam methane reforming) method is considered to be the most efficient and feasible procedure. The steam reforming procedure seems to be a simple procedure as product composition can be expressed by simple thermodynamics, but in reality it is a complicated procedure which includes a combination of sophisticated mechanical design, catalyst, and heat transfer.

2. Methods

2.1. Properties

Aspen Plus has proven its capability in modeling whole plant simulations such as bio-methane production via pyrolysis of biomass for bio-oil production processes [23-26]. The properties of the EFB, which is used in this study as biomass as shown in Table 1, are not included in the databank of chemical compounds of the modeling software, and thus, were defined manually into the Aspen Plus software using thermodynamic properties such as enthalpies and densities calculated using empirical correlations.

| Parameter    | EFB Adolina | EFB economic | EFB Dolok Ilir I | EFB Dolok Ilir II | EFB Tinjowan |
|--------------|-------------|--------------|------------------|-------------------|--------------|
| Proxanal     |             |              |                  |                   |              |
| Moiture      | 21.87       | 14.43        | 56.79            | 33.31             | 44.6         |
| Fixed Carbon | 6.23        | 5.02         | 2.34             | 3.2               | 3.26         |
| Volatole Meter | 9.03    | 68.26        | 34.29            | 53.44             | 42.2         |
| ASH          | 62.87       | 12.29        | 6.58             | 10.06             | 9.94         |
| Ultanal      |             |              |                  |                   |              |
| Carbon       | 54.37       | 45.94        | 24.89            | 35.18             | 26.94        |
| Hidrogen     | 6.94        | 5.64         | 3.9              | 4.8               | 3.22         |
| Sulfur       | 0.15        | 0.14         | 0.07             | 0.13              | 0.05         |
| Nitrogen     | 0.75        | 3.99         | 0                | 0                 | 0.35         |
| Oksigen      | 31.5        | 24.84        | 12.01            | 23.39             | 21.58        |
| Chlorine     | 0.06        | 0            | 0                | 0                 | 0            |

2.2. Pyrolysis Design in Aspen Plus

The pyrolysis design in Aspen Plus requires some of the modules available in the software as shown in Tables 2. In general, ultimate analysis can be calculated as the following equation,

\[
C+H+O+N+S+ASH+M=100\%
\]  \hspace{1cm} (1)

For decomposer R-yield reactor, it is required that the breakdown of mass basis should be calculated as shown in Eqs. (2)-(8)

\[
\text{Basis yield } H_2, \; m_{H_2} = (1 - X_{\text{Moiture}}) \times X_{H}\hspace{1cm} (2)
\]

\[
\text{Basis yield } O_2, \; m_{O_2} = (1 - X_{\text{Moiture}}) \times X_{O}\hspace{1cm} (3)
\]

\[
\text{Basis yield } N_2, \; m_{N_2} = (1 - X_{\text{Moiture}}) \times X_{N}\hspace{1cm} (4)
\]

\[
\text{Basis yield } H_2O, \; m_{H_2O} = X_{\text{Moiture}}\hspace{1cm} (5)
\]
Basis yield $S$, $mS = (1 - X_{\text{Moisture}})X_S$ (6)
Basis yield $C$, $mC = (1 - X_{\text{Moisture}})X_C$ (7)
Basis yield $\text{ASH}$, $m_{\text{ASH}} = (1 - X_{\text{Moisture}})X_{\text{ASH}}$ (8)

Table 2. Process model in Aspen Plus.

| Name          | Model   | Function                                                                 |
|---------------|---------|--------------------------------------------------------------------------|
| Decomposer    | R-yield | decomposition of chemical compounds found in biomass                     |
| Pyrolysys     | R-Gibbs | decomposition of chemical compounds to produce syngas, char.             |
| Splitter      | SS-Split| to separating syngas from char                                           |

The main assumptions adopted in the simulation are as follows:
1. The system is in steady-state and parameters maintain constant.
2. The fuel used is oil palm empty fruit bunches.
3. The system’s working temperature is 27 °C - 650 °C.
4. The EFB oil palm flowrate is 20 kg/hour.

2.3. Design of Steam Reformer
For Steam Reformer (SR), the reactions involved are shown in Eqs. (9)-(10). The pyrolysis design in Aspen Plus requires some of the modules available in the software as shown in table 3.

\[
\begin{align*}
\text{CH}_4 + \text{H}_2\text{O} & \leftrightarrow \text{CO} + 3\text{H}_2 \\
\text{CO} + \text{H}_2\text{O} & \leftrightarrow \text{CO}_2 + \text{H}_2
\end{align*}
\]

(9) (10)

The assumptions adopted in the simulation are as follows:
1. The system is in steady state and parameters maintain constant;
2. The fuel used is syngas (H2, CO2, CO, CH4, H2O) from pyrolysis;
3. The system working temperature is 27 °C - 650 °C.

Table 3. Process model in Aspen Plus.

| Name              | Type Model | Function                       |
|-------------------|------------|-------------------------------|
| Reformer          | R-Stoic    | Converting methane from pyrolysis to hydrogen |
| Water-shift1      | R-Stoic    | Converting the pyrolysis and reformer CO into hydrogen |
| Water-shift2      | R-Stoic    | Converting the pyrolysis and reformer CO into hydrogen |
| Heat Exchanger 1  | HeatX      | Reducing the temperature of the reformer to the water-shift1 |
| Heat Exchanger 2  | HeatX      | Decreases the water-shift1 output temperature to water-shift2 |
| Separator         | Sep        | Purification of hydrogen by separating it from other gases |
3. Results and discussions

3.1. Result from Pyrolysis

From figure 3, it can be seen that the highest CH$_4$ value appears when EFB Adolina, used as raw material, producing 0.051 kmol/hr CH$_4$, while the smallest amount appears when EFB Dolok Ilir I used (0.0015 kmol/hr). A large amount of H$_2$ value appears when EFB Dolok Ilir II used as raw material which contributes around 0.521 kmol/hr, while the smallest amount appears when EFB Tinjowan used as raw material (0.374 kmol/hr). The highest CO value is EFB Dolok Ilir II which is 0.2344426 Kmol/hr, while the smallest EFB Dolok Ilir I is 0.0543811 kmol/hr. The highest CO$_2$ value is EFB Tinjowan, which is 0.2006426 kmol/hr. The highest CO$_2$ value is EFB Tinjowan which is 0.7725157 Kmol/hr, while the smallest EFB value is 0.1353571 kmol/hr.

![Figure 3. Graphic Result Syngas from Pyrolysis Process.](image)
Figure 4 shown that the largest remaining CH\textsubscript{4} is EFB Dolok Ilir II which is 0.0153383 Kmol/hr, while the smallest EFB Dolok Ilir I is 0.000361516 Kmol/hr. The biggest H\textsubscript{2} value is EFB Dolok Ilir II which is 0.8452168 Kmol/hr, while the smallest EFB Dolok Ilir I is 0.4480936 Kmol/hr. The largest remaining CO is EFB Dolok Ilir II which is 0.0370965 Kmol/hr, while the smallest EFB Dolok Ilir I is 0.00772025 Kmol/hr. The biggest CO\textsubscript{2} value is EFB Dolok Ilir II, which is 0.4038692 Kmol/hr, while the smallest is Dolok Ilir I 0.2093655 Kmol/hr. The largest remaining H\textsubscript{2}O value is EFB Dolok Ilir I which is 0.9648008 Kmol/hr, while the smallest EFB Adolina is 0.356875 Kmol/hr.

4. Conclusion
Hydrogen produced from biorenewables is a sustainable energy carrier for promising alternative to fossil fuels. Biomass-based hydrogen includes energy security reasons, environmental concerns, foreign exchange savings, and socioeconomic issues related to the rural sectors of all countries in the world. Pyrolysis Biomass and Steam reforming of natural gas will become the dominant technologies. From Simulation we found that the biggest H\textsubscript{2} value is EFB Dolok Ilir II, which is 0.845 kmol/hr = 1.704 kg/hr, while the smallest EFB Dolok Ilir I is 0.448 Kmol/hr= 0.903303 kg/hr.

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