Simulation analysis of bio-oil from slow pyrolysis using palm empty fruit bunch

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Abstract. This study analyses the slow pyrolysis process of Palm Empty Fruit Bunches (EFB) from a temperature of 400-650°C in producing bio-oil in the Aspen Plus simulation. The study involves the effect of excess air for the combustion process to supply heat to be used by the pyrolysis process. From the analysis, it was found that the value of energy in the form of heat is present in high amounts if the excess air is around 40%. Heat is then used to heat the biomass, producing syngas, which then passes through a heat exchanger with a copper pipe with a length of 10 m in 200 liters of water. The bio-oil mass flow rate will decrease as the pyrolysis working temperature increased, from 0.38 kg/hour to 0.121 kg/hour, or 0.387 liters/hour to 0.124 liters/hour. The bio-oil heating value will increase with increasing pyrolysis temperature from 8713.68 J/kg to 27,130.92 J/kg, at 400 °C to 650°C, respectively. The amount of bio-oil mass-produced in the simulation compared to the yield during the experiment, and it was found that the simulation results were higher, around 39.08%. That is due to there is some bio-liquid stored at the bottom of syngas storage.

1. Introduction
The development of bio-energy as a new alternative energy source is very prospective, considering the abundance of natural resources in Indonesia. Along with the development of science and technology, bio-energy is transformed into a more modern form. Bio-energy, as we know it today, has two forms, traditional and modern bio-energy. The traditional bio-energy that we often encounter is firewood. Meanwhile, more modern ones include bio-ethanol, bio-diesel, or bio-gas. The bio-energy can be produced by converting biomass into another fuel type with a specific process, such as a thermochemical process [1]. Although biomass can be used directly or indirectly by converting it into a liquid or gas state [2], the use of biomass as an energy source has not increased significantly in modern times [3].

Indonesian oil experts stated that Indonesia's oil production from 2004 was at the lowest level compared to previous years [4]. Crude oil production in the first quarter of 2004 was only around 0.98 million barrels per day or around 360 million barrels per year, while in 1999, oil production was still around 1.4 million barrels per day [5, 6]. It is also known that the world price of fuel oil is increasing...
rapidly. This problem has resulted in an increase in the selling price of fuel oil, including Indonesian kerosene.

Biomass as the primary basis for alternative energy, has its uniqueness, which cannot be separated from the biomass commodity of each country so that energy utilization is adjusted to the biomass advantages of each region. Examples of existing biomass are rubberwood. In terms of the availability of raw materials, according to data from the Central Statistics Agency [7, 8, 9], the area of rubber plantations in Indonesia is included in the large plantation scale, only less than oil palm plantations for the period between 1995-2010 [10, 11, 12].

One uses of the pyrolysis process for the purpose of generating electrical energy has been carried out in the framework of simulation in the form of exploiting exhaust heat during the pyrolysis process to drive the Organic Rankine Cycle expander [6, 13]. In connection with the fact that oil palm plantations are still very extensive, it is necessary to develop the pyrolysis technology to produce bioenergy in the form of biochar, syngas, and bio-oil from palm oil mill waste. For this reason, in this study, an analysis of the bio-oil production process using the slow pyrolysis method was carried out by performing simulation and experimental processes. The empty fruit bunches (EFB) used in this study come from Pabatu Palm Oil Mill as one of the plantations in North Sumatra province.

2. Simulation Section

The development of simulation analysis for the Bio-oil production process is carried out in three stages, namely: Heat Supply, Pyrolysis, and Condensation. The flowsheet of the simulation is shown in Figure 1. The EFB raw material was analyzed in the form of proximate and ultimate analysis after the pretreatment process. The properties of EFB and Wood can be seen in Tables 1-2.

![Figure 1. Pyrolysis simulation using aspen plus](image)

**Table 1. Ultimate analysis of properties.**

| Proximate analysis (wt.%) | EFB Pabatu | Wood [7] |
|--------------------------|------------|----------|
| Moisture                 | 10.64      | 12.4     |
| Ash                      | 4.52       | 11.28    |
| Volatile Matter          | 10.64      | 59.36    |
| Fixed Carbon             | 74.2       | 16.96    |
Table 2. Proximate analysis of properties.

| Ultimate Analysis (wt. %) | EFB Pabatu | Wood [7] |
|---------------------------|------------|----------|
| Moisture                  | 10.64      | 12.4     |
| Carbon                    | 42.36      | 53.24    |
| Hydrogen                  | 6.67       | 6.36     |
| Nitrogen                  | 2.3        | 0.12     |
| Sulfur                    | 0.03       | 0.14     |
| Ash                       | 4.52       | 0        |
| Oxygen                    | 44.12      | 40.14    |

The first stage is Heat Supply from the combustion process, which is to provide heat for the pyrolysis reactor. The material used for combustion is 15 kg of chipped wood, which is assisted by air in the combustion process. The second stage is pyrolysis. EFB, as the primary input material in this simulation, was introduced into Aspen Plus by entering Ultimate and Proximate values. Biomass was introduced to Aspen Plus using yield and simulated in a reactor with a temperature of 500°C, which then produced charcoal (solid) and synthetic-gas (syngas).

The last stage is the condensation process, which aims to reduce the temperature of the syngas so that the condensation process occurs and produces bio-oil. The condensation process is carried out by passing syngas through a heat exchanger with a cooling fluid in the form of 200 liters of water with a temperature of 27°C.

3. Experimental Section

The experimental for the Bio-Oil production processes consist of Pretreatment, Heat Supply, Pyrolysis, and Condensing processes. The pretreatment process stage was carried out by cutting the EFB samples into smaller pieces then drying them for three days. Pretreatment is carried out so that the raw material gets dry mass. The mass of EFB weight of 4 kg. The combustion process is to provide heat for the pyrolysis reactor. The material used in the combustion process is 15 kg woodchips, which is assisted by air with its excess value. The biomass is heated during pyrolysis processes for 3 hours in the reactor. The working temperature of the pyrolysis reached a maximum of 500°C and maintained at that value until finish the processes. During the pyrolysis processes, charcoal (solid) and synthetic-gas (syngas). The syngas is then entered the condensing process, which aims to reduce the temperature of the syngas so that the condensation process occurs and produces bio-oil, as shown in Figure 3. The cooling process is carried out by passing syngas through a coil channel in a tank of 200 liters of water with a temperature of 27°C.

Figure 2. Experimental section.

Figure 3. The bio-oil output from the experimental section.
4. Results and Discussion

4.1. The Volume of Bio-Oil Produced by Simulation and Experiment

Based on the simulation results, the quantity of pyrolysis utilizing EFB biomass as raw material at 500°C produced as much as 0.921 liters. Meanwhile, the bio-oil from the experiment resulted in 0.561 liters. The difference quantity obtained based on simulation and experimental can be calculated as below.

\[
\% \text{dif} = \left( \frac{\text{Simulation} - \text{Experiment}}{\text{Simulation}} \right) \times 100\% \\
\% \text{dif} = \left( \frac{0.921 - 0.561}{0.921} \right) \times 100\% = \left( \frac{0.360}{0.921} \right) \times 100\% = 0.3908 \times 100\% = 39.08\%.
\]

The difference that occurs between simulation and experimental is due to the remaining bio-oil in the storage tank and distribution pipe that has a length of about 17 meters. When the working pressure from the pyrolysis reactor has the same with the environment, the remaining bio-oil in the pipe is not pushed out, so it remains in the distribution pipe.

4.2. Simulation Results of Excess Air and Air Fuel Ratio in The Combustion Process Used for The Pyrolysis Process

The combustion process to provide heat for pyrolysis is assisted by air using a blower. Additional air beyond the theoretical Air Fuel Ratio is added to the combustion process to achieve complete combustion. In the simulation, which assumes that the temperature of the flue gas resulted from the combustion reactor is around 100°C, the excess air of 40% effect in generating the maximum heat for the pyrolysis reactor, as shown in Figure 4.

![Figure 4: The heat generates based on a different value of excess air.](image)

4.3. Design Improvement of Heat Exchanger to Produce Bio-Oil

The HeatX block on AspenPlus is used to simulate the heat transfer that occurs in a condenser with a heat transfer surface area of 0.2898 m² to obtain a syngas exit temperature of 37°C. The simulation data from the inflow and outflow can be seen in Table 3. However, the usage of 200 liters of water to condense 3 kg of syngas is considered less effective. Therefore, the optimization is carried out by
using a smaller amount of water but with the same total heat transfer so that the results are as shown in Table 4.

| Parameter                  | Value         |
|----------------------------|---------------|
| Syngas mass flow rate, $\dot{m}_{\text{syngas}}$ | 3.01889 kg/hr  |
| Inlet syngas temperature, $T_{\text{in syngas}}$       | 500°C         |
| Outlet syngas temperature, $T_{\text{out syngas}}$     | 37°C          |
| Water mass flow rate, $\dot{m}_{\text{water}}$         | 200 kg/hr     |
| Inlet water temperature, $T_{\text{in water}}$         | 27°C          |
| Outlet water temperature, $T_{\text{out water}}$       | 32.56°C       |
| Heat duty, $Q$                                              | 1395.84 Watt  |
| Exchangers Area                                            | 0.2898 sqm    |

| Parameter                  | Value         |
|----------------------------|---------------|
| Syngas mass flow rate, $\dot{m}_{\text{syngas}}$ | 3.01889 kg/hr  |
| Inlet syngas temperature, $T_{\text{in syngas}}$       | 500°C         |
| Outlet syngas temperature, $T_{\text{out syngas}}$     | 37°C          |
| Water mass flow rate, $\dot{m}_{\text{water}}$         | 73.2 kg/hr    |
| Inlet water temperature, $T_{\text{in water}}$         | 27°C          |
| Outlet water temperature, $T_{\text{out water}}$       | 42.2°C        |
| Heat duty, $Q$                                              | 1395.84 Watt  |
| Exchangers Area                                            | 0.2898 sqm    |

From the Table 3 and Table 4, it can be concluded that if the design of the heat exchanger is improved, the mass flow rate of water is reduced from 200 liters to 73.165 liters, which is a 63.5% reduction in water usage with the same area size of the heat exchanger. Figures 5-6 shown the model of heat exchanger based on Aspen Plus simulation analysis.

4.4. The Value of The Mass and Volume Flow Rate Of Bio-Oil with Vary of Pyrolysis Working Temperature
Based on the Aspen Plus simulation, when the pyrolysis working temperature varied at a temperature between 400°C-650°C, the mass and volume flow rate of bio-oil will decrease, as shown in Figure 7. From Figure 7, it can be concluded that, along with the increasing working temperature of the pyrolysis process, the volume of bio-oil produced is decreasing.
4.5. Effect of Pyrolysis Working Temperature on The Heating Value of Bio-oil
After the syngas passes through the condenser, the bio-oil temperature becomes 37°C. Based on the Aspen Plus simulation, the heating value in bio-oil will be different by varying pyrolysis working temperature. Increasing pyrolysis working temperature will increase the heating value of bio-oil, as shown in Figure 8. However, increasing pyrolysis working temperature will decrease the amount of bio-liquid produced, as shown in Figure 9.

Figure 7. Bio-oil mass flow rate and volume at 400°C-650°C.

Figure 8. The heating value of bio-oil at pyrolysis working temperature of 400°C – 650°C.
Figure 9. The effect of pyrolysis working temperature on heating value and bio-oil volume flow rate.

5. Conclusion
The amount of bio-oil mass-produced in the simulation was 39.08% higher compared to the yield during the experiment due to some bio-liquid stored at the bottom of syngas storage. Furthermore, it could be concluded that the excess air needed to generate optimal heat is around 40%. The optimization of the heat exchanger is to change the model into a shell and tube model. The bio-oil mass flow rate will decrease as the pyrolysis working temperature increased, from 0.38 kg/hour to 0.121 kg/hour, or 0.387 liters/hour to 0.124 liters/hour. On the other hand, the heating value will increase with increasing pyrolysis temperature from 8,713.68 J/kg to 27,130.92 J/kg, at 400 °C to 650°C, respectively. Further research in the development of this biomass pyrolysis is being carried out.

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