Simulation of Oil Palm Shell Pyrolysis to Produce Bio-Oil with Self-Pyrolysis Reactor

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Abstract. A new self-pyrolysis reactor was designed to reduce the utilization of electric heater due to the energy saving for the production of bio-oil from oil palm shell. The yield of the bio-oil was then evaluated with the developed mathematical model by Sharma [1] with the characteristic of oil palm shell [2]. During the simulation, the temperature on the combustion chamber on the release of the bio-oil was utilized to determine the volatile composition from the combustion of the oil palm shell as fuel. The mass flow was assumed constant for three experiments. The model resulted in a significant difference between the simulated bio-oil and experiments. The bio-oil yields from the simulation were 22.01, 16.36, and 21.89 % (d.b.) meanwhile the experimental yields were 10.23, 9.82, and 8.41% (d.b.). The char yield varied from 30.7 % (d.b.) from the simulation to 40.9 % (d.b.) from the experiment. This phenomenon was due to the development of process temperature over time which was not considered as one of the influential factors in producing volatile matters on the simulation model. Meanwhile the real experiments highly relied on the process conditions (reactor type, temperature over time, gas flow). There was also possibilities of the occurrence of the gasification inside the reactor which caused the liquid yield was not as high as simulated. Further simulation model research on producing the bio-oil yield will be needed to predict the optimum condition and temperature development on the newly self-pyrolysis reactor.

1. Introduction

The increase of crude palm oil production in Indonesia results in the increase of waste production, one of which is oil palm shell (OPS), considerably potential to be one of the renewable energy resources due to its woody characteristics similar to coconut shell. Each fresh fruit bunch (FFB) processed at least consists of 6% OPS. OPS can be converted into renewable energy resources through fast pyrolysis process, producing either bio-oil or syngas depending on the temperature and the reaction time. Fast pyrolysis is a biomass decomposition process in the absence of oxygen, with high heating rate and usually takes place of ground feedstock in a constant temperature (±500°C), with short vapor residence time (<2s) [3].

Fast pyrolysis decomposes biomass into parts of gases (condensable and noncondensable), liquid, and char. The production of pyrolysis liquid takes place cooling and condensation of the primary pyrolysis vapor with short residence time, and results in dark-brown liquid able to obtain half of the conventional fuel heating value [4]. This pyrolysis liquid is commonly called bio-oil or bio-crude which is very sensitive to the change of temperature, and able to have calorific value up to 17 MJ/kg (compared to conventional fuel that is able to have calorific value 42-44 MJ/kg) [5] and produced in
medium temperature (around 500°C) [6]. This liquid also called bio-oil, is also able to be utilized as the fuel for gas turbine and diesel machines [7]. Bio-oil production usually utilizes fluidized bed reactor for its process, with the heat sourced from either electric or induction heater [8,9]. The use of fluidized bed reactor with electric heater usually needs a high amount of electricity (~5 kW) [9]. This recent study focuses on the design of fixed bed reactor for oil palm shell pyrolysis forming in the self-pyrolysis heated reactor. Applying the principle of pyrolysis which is heated deformation, the source of the heat in this reactor will come from the stove-like zone at the bottom of the reactor, with fuel coming from the oil palm shell itself, supplying heat to the pyrolysis chamber. Controlled air flow will be used in the combustion zone using a blower to achieve an optimum temperature for the pyrolysis process. The pyrolysis vapor will then be condensed using a cross-flow condenser, resulting in the final product of bio-oil.

The production system will be in batches, aiming to be able to be used a home-industry effort by the local people of the CPO factories. Expected that this method can reduce the abundant waste of oil palm shell, this reactor also is designed to achieve a total 10% yield of bio-oil (%biomass d.b.). Numerical simulation will take place to predict the yield from the process, using the developed model from Sharma [1]. This model focuses on the volatile composition of a pyrolysis process, which will be the basis of the bio-oil yield prediction.

2. Objectives
This study aims at designing, manufacturing, and evaluating the performance of a reactor by predicting the yield of the bio-oil product from oil palm shell pyrolysis using the developed simulation model by Sharma [1].

3. Research methods

3.1. Materials and sample preparation
Iron pipe with a diameter of 15 cm was utilized to manufacture the reactor, with an iron plate with a thickness of 2 mm for its upper end. The cross-flow condenser was made from iron plate with a thickness of 2 mm, and copper pipe with a diameter of 0.5 inches.
The performance tests were conducted using a blower, CA-type thermocouples, anemometer, and also AUTONICS recorder. The feedstock was raw oil palm shell (water content of 15% w.b.) without grinding.

3.2. Research procedures
The literature on oil palm shell, pyrolysis, and the manufacturing process are done first before the development of the numerical simulation takes place. The reactor is designed using SolidWorks Premium 2012, manufactured on the local workshop and then tested on the Renewable Energy Engineering Laboratory, Bogor Agricultural University (IPB). The oil palm shell is gathered from state oil palm factory in West Java.

3.3. Experimental set-up
The experimental set up is illustrated in figure 1. The total length of the copper pipe of the condenser is 7 m, with 20 fins. The thermocouples were set apart 15 cm from each, with the main focus on the combustion zone.

As the reactor was aimed to be one of the home-industry efforts, its capacity was set to be only 5 kg as a pilot project. Assuming that the bulk density \((\rho_{\text{bulk}})\) of the oil palm shell was 400 kg/m\(^3\) when designing, so the calculation of the reactor volume \((V, \text{in} \text{m}^3)\) was obtained through equation (1).

\[
V = \frac{m}{\rho_{\text{bulk}}}
\]  

(1)
where \( m \) is mass of oil palm shell (in kg). Considering that the fast pyrolysis must apply the principle of pressure, was then obtained a ratio of 1:5 for the diameter and the height of the reactor (15 cm and 75 cm).

![Figure 1. Reactor and condenser assembly during the experiment](image)

3.4. **Experimental procedures**

The experiment started with putting a net in the middle of the reactor, to provide enough air due to low porosity of the oil palm shell. Three kilograms of oil palm shell was then filled into the reactor, and a bit of them already pyrolyzed (and became char) was put inside the net and burnt as a fuel. After the flame was considered to incinerate enough, the reactor was then closed and sealed using ceramic wool to prevent any vapor leaks. Four CA-type thermocouples were put in places, and the temperature was measured in every five minutes.

The calculation of the bio-oil yields, char, and noncondensable gas was conducted every time the experiment ended. The bio-oil yield (mass fraction), denoted by \( Y \), was contained in a measuring beaker to measure and then weighed. The calculation of each yield was obtained through equations (2-4) [3].

\[
Y_{\text{bio-oil}} = \frac{m_{\text{bio-oil}}}{m_{\text{dryOPS}}} \times 100\% 
\]

\[
Y_{\text{ch}} = \frac{m_{\text{ch}}}{m_{\text{dryOPS}}} \times 100\% 
\]

\[
Y_{\text{ncg}} = (1 - Y_{\text{bio-oil}} - Y_{\text{ch}}) \times 100\% 
\]

where subscript bio-oil is for tar, dryOPS for dry matter, ch for char, and n cg for noncondensable gas.

3.5. **Simulation model**

Sharma [1] developed a model to predict the pyrolysis yield from woody biomass in forms of char, volatile matters, and also pyrolysis heat. This model was based on input data to predict the volatile matters of the oil palm pyrolysis process using the self-pyrolysis reactor, in some temperature levels. The calculation of the developed model was obtained from equation (5) to equation (14).

Due to the dry biomass used, the mass fraction on the dry basis of the biomass was considered to be:

\[
Y_{\text{cl}} + Y_{\text{hc}} + Y_{\text{lg}} = 1 
\]

The subscript cl stands for cellulose, hc for hemicellulose, and lg for lignin. While the char yield from the pyrolysis was considered to be:
\[ Y_{\text{char}} = Y_{\text{cl}f_{\text{char,cl}}} + Y_{\text{hc}f_{\text{char,hc}}} + Y_{\text{lg}f_{\text{char,lg}}} \]  

(6)

where \( f_{\text{char,cl}}, f_{\text{char,hc}}, \) and \( f_{\text{char,lg}} \) stand for composition fraction of cellulose, hemicellulose, and lignin, respectively. The volatile matters fraction \( (Y_{\text{vol}}) \) was then obtained from equation (7).

\[ Y_{\text{vol}} = 1 - Y_{\text{char}} \]  

(7)

Volatile matters from combustion consist of CO, CO\(_2\), H\(_2\), H\(_2\)O, light hydrocarbons (ME), and heavy hydrocarbons (tar) [11]. Light hydrocarbons in this study were then grouped into methane and ethylene, with a mass ratio of 3:1 resulting in its empirical formula of C\(_{16}\)H\(_4\). Heavy hydrocarbons (tar) was considered to be levoglucosan [12] which was vaporized and condensed at increasing temperature, with its empirical formula of C\( _6H_{12}O_{0.2} \) [11,13]. Aiming at achieving the reaction balance where char presence was needed, the char was considered to be pure carbon (C) in this study.

The pyrolytic decomposition was then determined using equation (8).

\[ C_6H_{12}O_{0.2} = n_{\text{char,ashfree}}C + n_{\text{CO}}CO + n_{\text{CO}_2}CO_2 + n_{H_2}H_2 + n_{H_2O}H_2O + n_{\text{ME}}C_{1.16}H_4 + n_{\text{TAR}}C_{6}H_{12}O_{0.2} \]  

(8)

where \( n \) is mole number of the corresponding substance. Characteristics of the oil palm shell [2] were then used to put into the developed model. The characteristic was shown in table 1.

| Table 1. Fraction of oil palm shell lignocellulose [2] |
|-------------------------|-------------------|-----------------|-------------------|-------------------|
| Cellulose | Hemicellulose | Lignin | Ash+Other Extractives |
| 0.205 | 0.223 | 0.499 | 0.073 |

To obtain the volatile matters fraction, char formation characteristic was used as shown in table 2, where each of the C, H, and O balance are obtained through equations (9)-(11), respectively.

\[ 6n_{\text{DB,ashfree}}C - n_{\text{char,ashfree}}C = n_{\text{CO}} + n_{\text{CO}_2} + 1.16n_{\text{ME}} + 6n_{\text{TAR}} \]  

(9)

\[ n_{\text{DB,ashfree}}H_2 = 2n_{H_2} + 2n_{H_2O} + 4n_{\text{ME}} + 6.2n_{\text{TAR}} \]  

(10)

\[ n_{\text{DB,ashfree}}O_2 = n_{\text{CO}} + 2n_{\text{CO}_2} + n_{H_2O} + 0.2n_{\text{TAR}} \]  

(11)

where subscript \( \text{DB,ashfree} \) stand for dry biomass. Considering the ratio of water and carbon dioxide as one (H\(_2\)O = CO\(_2\)), the ratio of each volatile matters was obtained through equations (12)-(14).

\[ \frac{Y_{\text{CO}}}{Y_{\text{CO}_2}} = e^{-1.8454 \frac{7730.3}{T} \left( \frac{5019998}{T^2} \right)} \]  

(12)

\[ \frac{Y_{\text{H}_2\text{O}}}{Y_{\text{CO}_2}} = 1 \]  

(13)

\[ \frac{Y_{\text{ME}}}{Y_{\text{CO}_2}} = 5 \times 10^{-16}T^{5.06} \]  

(14)

where \( T \) is temperature of pyrolysis. The value determination from equation (12) to equation (14) was conducted in every five-minutes temperature measured where each of them was put to simulate the volatile matters producing the bio-oil from the experiments. The parameters used in the simulation can be seen in table 3.

| Table 2. Char yield fraction. |
|-----------------------------|-------------------|-----------------|-------------------|-------------------|
| Composition | Cellulose | Hemicellulose | Lignin | Reference |
| Char yield fraction | 0.05 | 0.10 | 0.55 | [14] |
| Formula | C\(_6\)H\(_{10}\)O\(_3\) | C\(_6\)H\(_{10}\)O\(_3\) | C\(_6\)H\(_{7.95}\)O\(_{2.4}\)(OCH\(_3\))\(_{0.92}\) | [15] |
Table 3. Parameters used in the simulation.

| Parameter          | Value          | Unit     |
|--------------------|----------------|----------|
| Water Content      | 15             | % (w.b.) |
| Pyrolysis Rate (ṁ)| 0.023, 0.022, and 0.024 | kg/minute |
| Tar HHV            | 41,000         | kJ/kg    |

4. Results and discussion

4.1. Experiment results

The designing of the reactor resulted in a volume of 0.0125 m³, with the total amount of starter fuel was 0.97 kg. The temperature development for every 5 minutes is shown in figure 2.

Three experiments showed similar trends of temperature development, as well as their temperature in the second thermocouple spot 15 cm above. These resulted in the bio-oil yield of 275 ml ($\rho = 1054.54$ kg/m³), 260 ml ($\rho = 1038.46$ kg/m³), and 255 ml ($\rho = 1019.60$ kg/m³) respectively. It showed each percentage was 10.23, 9.82, and 8.41 % (d.b.). The char yields were 39.22, 43.14, and 40.34 % (d.b.), with the process time 110, 115, and 125 minutes respectively. The pyrolysis process length using this self-pyrolysis reactor was not one of the controlled variables due to many external influential factors affecting different process conditions, such as ambient airflow velocity, and also environment temperature.
Figure 3. Volatile compositions of oil palm shell

Figure 4. Volatile composition of oil palm pyrolysis experiments

4.2. Combustion zone simulation result
Referring to the developed model by Sharma et al. (2016) with the oil palm shell characteristics from Saka et al. (2008), the volatile compositions in every temperature level is shown in figure 3.
Plotting the model to the experiment temperatures with assuming constant mass flow will result in volatile composition at every temperature level (every 5 minutes). It is assumed that the bio-oil produced was a combination of levoglucosan and H$_2$O [16,17]. Figure 3 shows that in the temperature range of 450-850 K, the H$_2$O content decreases in the increased temperature, while the gases component increases within temperature level. Also, the simulation showed that the hydrogen content of the oil palm shell is rather high, due to its high aromatic compounds [18], even if still in low level. The volatile compounds for each experiment are shown in figure 4, where the input temperature was the temperature when the bio-oil starts getting produced to when the bio-oil stop coming out of the condenser outlet. Meanwhile, the simulation temperature was the whole process temperature, starts when the reactor was closed, and the temperature was measured every five minutes. It was compared to determine the difference between the real cracking reaction occurring, and the simulated reaction.

4.3. Simulation and experiment validation

There is a significant difference between the result of the simulation and experiment yields. While the experiments resulted in 10.23, 9.82 and 8.41 % (d.b.), the simulation showed in a higher result which was 22.01, 16.36, and 21.89 % (d.b.). The comparison between simulation and experiment is shown in figure 5.

![Figure 5. Comparison between simulation and experimental results](image-url)

It was stated that the char mass fraction could be determined only from the hemicellulose, cellulose, and lignin content of a biomass [1], so the char yield from the simulation resulted in 30.7 % (d.b.), while the experiments show different values which were 39.22, 43.14, and 40.34 % (d.b.) respectively. The reaction or process condition does not count as influential factors [1] while in actual condition, the pyrolysis yield from biomass conversion is dependent to the reactor (shape, size, also optimum capacity), time, and temperature of the process. A significant difference in bio-oil yield also was indicated by the high level of CO$_2$ content due to slow heating rate, considering that the highest temperatures achieved through the process were 425, 428, and 432 °C respectively. The optimum temperature to produce the highest yield of oil palm shell bio-oil should range from 500 to 550 °C referring to [8] while usually the lignin decomposition – which contributes the most to the production of bio-oil – occurs at 650 °C [19]. The slow heating rate occasionally causes the organics reaction to occur during the process; this might also be caused by the inconstant air flow to the condenser inducing secondary reactions on the vapor formed, the vaporization of liquid, and also the gasification between the char and water [19].
The optimum size of oil palm shell particle to be pyrolyzed ranged between 1.4 – 2 mm [3], in which way any grinding was not conducted in this research. The minimum pretreatment to the oil palm shell such as grinding and drying was not conducted in this study regarding the aim of feasibility to apply this method towards local people. It also affected the result [19], biomass with very low water content can be very potential to be converted through thermochemical processes including pyrolysis. The heating rate of all three experiments also showed slow pyrolysis mechanism instead of fast pyrolysis, that resulted in higher char yield than the bio-oil yield.

The significant difference between the simulation and actual experiment results show that the process condition affects the final yield of the product including bio-oil, char, and gases formed. The simulation model which was only based on the chemical balance couldn’t still be able to reflect the real condition of a process depending on the temperature dynamic, heating rate, also the total time of reaction.

5. Conclusions

A developed model from Sharma [1] was used to predict the total yield of oil palm shell pyrolysis using its combustion chamber temperature with a self-pyrolysis method. There was a significant difference between the simulation and actual experiments due to different condition applied to both calculations. The simulation did not include external factors such as temperature fluctuation, total time of reaction, and reactor type.

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