Process Modeling of Drying and Torrefaction of Oil Palm Trunk (OPT)

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Abstract. This paper concerns on process modeling of drying and torrefaction of oil palm trunk (OPT), abundant biomass resources coming from replantation of oil palm. The processes are very crucial in treating of OPT before utilization for energy source due to high level of water content and volatile matters in the biomass. Modeling with Aspen Plus is performed to predict the composition of product in mass in fastest way without doing experiment. The study uses Flash Dryer Model and Reactor Model available in Aspen as tool box for modeling the drying process and torrefaction process. Objective of the paper is to validate the process model with experimental results from that of Prasetyo et al. (2016) in identifying final mass and calorific value of torrefied OPT. The process modeling of OPT drying and torrefaction gives the charcoal yield of 0.2972 compared to experiment yield of 0.24. The calorific value (HCV) of torrefied OPT with RGibbs is 6,901.0 kcal/kg that is similar with experiment result of 6,939.2 kcal/kg.

Keywords: calorific value, drying, oil palm trunk, simulation, torrefaction

1. Introduction

The energy demand, reported 505 quadrillion BTU in 2008, is expected to increase by 53% in 2035 [1]. Energy security and environmental sustainability are the major emerging issues in the world that can only be addressed through diversification in the energy resources and clean fuels. The promotion of indigenous renewable energy sources and the low carbon fuels could be good solution while addressing issues of the global warming and climate change. Kyoto Protocol, legally binding EU 20-20-20 targets, and volatility of oil prices have encouraged the global community to reduce dependence on oil and replace it with clean and renewable energy resources [2]. Biomass energy, one of a renewable energy, could be a good candidate for replacement of fossil fuels with prospective and emerging technologies for converting biomass through pyrolysis, gasification and torrefaction. It can be converted into three valuable products, solid (briquette, pellet, char), liquid (ethanol, biodiesel, biofuel), and gaseous (synthesis gas, biogas) [3].

Due to their availability in Indonesia, oil palm wastes such as empty fruit bunch (EFB) and oil palm trunk (OPT) are considered to be the best options for fuel generation and biochar production. Indonesia is the world’s biggest producer and consumer of palm oil, currently providing about half of world the supply. Based on USDA data, Indonesia produced 33,500,000 MT of palm oil in 2014. It gave an increase of about 8.06% from the previous year. [7]. In general, OPT are collected during replanting and can be utilized as resource for renewable chemicals as well as for renewable energy. OPT are available in significant amount before replantation is carried out and thus the utilization of OPT will increase its added value.
The commercial utilization of biomass for energy requires integration of intensive logistic system [5]. Torrefaction is regarded as an emerging thermal biomass pretreatment method aiming to produce high quality solid biomass products. It has an ability to reduce the major limitations of biomass such as heterogeneity, lower bulk density, lower energy density, hygroscopic behavior, and fibrous nature. Torrefied biomass can be efficiently used in the co-firing power plant and, in the future, is expected to replace coal in the metallurgical process and promoted as an alternative for charcoal [6]. Basically, torrefaction can be divided into two consecutive processes: drying and isothermal heating or roasting for removing volatiles through different decomposition reactions at 200-300°C in an inert environment at an atmospheric pressure.

This study is aimed to modeling the drying and torrefaction of Oil Palm Trunk (OPT). Process modeling using Aspen Plus V10 could represent laboratory experiment and ease the process to identify the torrefaction products. In addition, prior to torrefaction process, drying process was simulated to eliminate H₂O content in OPT. Modeling analysis conducted to obtain the highest calorific value of OPT. The result of this study are expected to the further research development.

2. Process Modeling

Prasetyo et al. (2016) have conducted research on drying and torrefaction of OPT. The operating temperature condition for OPT drying was 110-225°C while torrefaction temperature was 245°C. Yield of torrefied OPT from previous experiment was 24,01%. These experiment data were used as reference for process modeling.

The drying and torrefaction processes of Oil Palm Trunk (OPT) were simulated in Aspen Plus. As shown in Fig. 1, the overall process contains a drying and torrefaction processes. The simulation was designed to validate the yield of torrefaction process of OPT and calorific value of torrefied OPT. The general simulation assumptions were as follows:

1. Oil Palm Trunk had a high content of cellulose therefore it was defined and assumed as cellulose.
2. Feedstock basis was defined 10 kilograms with ash content of 5.85% and moisture content (H₂O) of 5.89%.
3. Ash in OPT was defined as a non-conventional solid with weight percentage of 5.85%.
4. The stream class used in the model was MCINCPSD that defines the particle size distribution for non-conventional and conventional solids.
5. The PENG-ROB property model was used to estimate the properties of gas phase while the IDEAL property model was used for solid and liquid phase.

Non-conventional solids in Aspen Plus was assumed that do not participate in phase and chemical equilibrium calculations [21].

![Figure 1. A process flow diagram for drying and torrefaction of Oil Palm Trunk (OPT).](image)

2.1. Overview of Process Modeling

Figure 1 shows the general layout of a OPT drying and torrefaction process. The process configuration consists of OPT drying using contact dryer to remove moisture content (H₂O) and heater to increase the temperature of OPT. A flash separator is required to separate gases and dried OPT. Torrefaction reactor
is a reactor to convert dried OPT to charcoal, carbon dioxide, water, and hydrogen gas. Carbon monoxide is assumed not present in torrefaction product. Torrefaction product enters a splitter to separate H₂O as vapor phase and torrefied OPT as solid component.

The reaction of OPT torrefaction is given as:

\[
\text{OPT} \rightarrow \text{Charcoal}_{(s)} + \text{CO}_2 + \text{H}_2\text{O} + \text{H}_2
\]  

(1)

2.2. Contact Dryer

Moisture content in Oil Palm Trunk was removed as vapor phase using dryer. The contact dryer was selected from the available solid unit operations in Aspen Plus. Air was used as an inlet gas in dryer with mass flowrate of 15 kg/hr and temperature of 132°C.

Table 1. Dryer specification for OPT drying.

| Parameter                                             | Unit         | Value |
|-------------------------------------------------------|--------------|-------|
| Heat transfer coefficient between wall and solids     | Watt/sqm-K   | 400   |
| Heat transfer area wall/solids                        | sqm          | 10    |
| Wall temperature                                      | °C           | 170   |
| Heat transfer coefficient between gas and solids      | Watt/sqm-K   | 10    |
| Heat transfer area gas/solids                         | sqm          | 3     |

2.3. Heater and Flash Separator

Before entering the torrefaction reactor, heater model was used to increase the temperature of dried OPT while flash separator was used to separate vapor phase in solid phase. The operation conditions for heater and flash separator are 225°C and 0.5 atm.

2.4. Torrefaction Reactor and Splitter

Torrefaction reactor are modeled by Reactor Yield and Reactor Gibbs, shown in the Fig. 1, as RYield and RGibbs. In the RYield, data of product yield of OPT torrefaction process is specified and showed on Table 2. Yield value of charcoal is obtained from previous experiments [19] while for CO₂ and water is obtained from literature [20]. The process parameter that needs to be studied in this research is yield of torrefaction product to obtain calorific value.

Table 2. RYield specification for Torrefaction of OPT.

| Component | Basis | Yield  | Reference               |
|-----------|-------|--------|-------------------------|
| Water (H₂O) | Mass  | 0.1397 | Haryadi et al (2009)    |
| Charcoal (C) | Mass  | 0.24   | Prasetyo et al (2016)   |
| CO₂       | Mass  | 0.042  | Haryadi et al (2009)    |

RGibbs works based on excess Gibbs value in order to predict the products of torrefaction. Moreover, RGibbs is a reactor that performs reaction by minimizing Gibbs energy and calculate the product composition based on the properties of chemicals which involved in chemical reaction. The chemical reaction that occurred in RGibbs as torrefaction reactor referred to Eq. (1). The principle of RGibbs depends on chemical and phase equilibrium by specifying temperature in chemical system. The temperature conditions for RGibbs are 245°C according to previous experiment of OPT torrefaction process [19].

Splitter is used to separate solids products from gases or liquids. In this simulation, split fraction of H₂O component as gases is 1. The products of splitter model are torrefied OPT and torrefied gas. Validation are performed by comparing yield and calorific value of torrefaction product from simulation result with previous experiment.
3. Results and Discussion

3.1. Comparison of Simulation and Experimental Results of OPT Drying using Contact Dryer and Torrefaction

In this simulation, Oil Palm Trunk was assumed as cellulose and charcoal was used as torrefied product. Contact dryer was able to remove water (H$_2$O) and air as exhaust gases while the dried OPT entered the heater and flash separator. Table 3 and Table 4 showed the simulation results of OPT Drying and Torrefaction Process using RYield and RGibbs. The operation temperature of reactor was set to 245°C. From the simulation, Gibbs Reactor produce H$_2$O and CO$_2$ mass flowrate higher than Yield Reactor produced. In contrast, it yields lower mass flowrate of charcoal as torrefied product. Moreover, Gibbs Reactor produce H$_2$ in torrefaction reaction.

Table 3. Simulation result of OPT Drying and Torrefaction Process with RYield.

| Stream | Units | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Mass Flows | kg/hr | 10.000 | 15.000 | 15.589 | 9.411 | 9.411 | 0.000 | 9.411 | 9.411 | 2.462 | 6.652 |
| H$_2$O  | kg/hr | 0.589 | 0.000 | 0.589 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 2.462 | 2.462 | 0.000 |
| Charcoal | kg/hr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 4.230 | 0.000 | 4.230 |
| CO$_2$  | kg/hr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.837 | 0.000 | 1.837 |
| Ash    | kg/hr | 0.585 | 0.000 | 0.000 | 0.585 | 0.585 | 0.000 | 0.585 | 0.585 | 0.000 | 0.585 |
| Cellulose | kg/hr | 8.826 | 0.000 | 0.000 | 8.826 | 8.826 | 0.000 | 8.826 | 0.000 | 0.000 | 0.000 |
| Air    | kg/hr | 0.000 | 15.000 | 15.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Table 4. Simulation result of OPT Drying and Torrefaction Process with RGibbs.

| Stream | Units | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Mass Flows | kg/hr | 10.000 | 15.000 | 15.589 | 9.411 | 9.411 | 0.000 | 9.411 | 9.411 | 3.096 | 6.314 |
| H$_2$O  | kg/hr | 0.589 | 0.000 | 0.589 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 3.096 | 3.096 | 0.000 |
| Charcoal | kg/hr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 2.797 | 0.000 | 2.797 |
| CO$_2$  | kg/hr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 2.686 | 0.000 | 2.686 |
| Ash    | kg/hr | 0.585 | 0.000 | 0.000 | 0.585 | 0.585 | 0.000 | 0.585 | 0.585 | 0.000 | 0.585 |
| Cellulose | kg/hr | 8.826 | 0.000 | 0.000 | 8.826 | 8.826 | 0.000 | 8.826 | 0.000 | 0.000 | 0.000 |
| Air    | kg/hr | 0.000 | 15.000 | 15.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| H$_2$  | kg/hr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.246 | 0.000 | 0.246 |

Table 5 shows the yield comparison of OPT torrefaction process from the simulation and experiment. Based on the simulation result, yield of charcoal at end of torrefaction process is 0.2972 compared with experiment yield of 0.24 (Prasetyo et al, 2016). It could be concluded that the simulation results represent the real behavior and relatively close to the experimental results.

Table 5. Yield Comparison and Validation of OPT Torrefaction process.

| Mass Flows | Units | Torrefied Gas | Torrefied OPT | Yield Simulation (RGibbs) | Yield Experiment (Prasetyo et al, 2016) | OF |
|------------|-------|--------------|--------------|--------------------------|----------------------------------------|----|
| H$_2$O     | kg/hr | 3.0960       | 0.0000       | 0.3290                   | 0.2400                                 | 5.6810$^{-2}$ |
| Charcoal   | kg/hr | 0.0000       | 2.7970       | 0.2972                   | 0.2400                                 | 5.6810$^{-2}$ |
| Component          | Simulation | Experiment | Reference of Experiment |
|-------------------|------------|------------|-------------------------|
|                   | HCV (kcal/kg) | LCV (kcal/kg) | Calorific Value (kcal/kg) |               |
| Cellulose         | 2,920.0    | 2,570.3    | n/a                     | Prasetyo et al, 2016 |
| Non processed OPT | n/a        | 5,232.1    |                         |               |
| Torrefied OPT at 245°C (RYield) | 6,547.0 | 6,939.2 |                         |               |
| Torrefied OPT at 245°C (RGibbs) | 6,901.0 | 6,627.4 |                         |               |
| Banana plant trash | 3,401.2    |            |                         | Sahito et al, 2013 |
| Barley straw      | 4,048.5    |            |                         |               |
| Canola straw      | 3,874.2    |            |                         |               |
| Coconut coir      | 3,907.6    |            |                         |               |
| Corn cob          | 3,972.1    |            |                         |               |
| Corn stover       | 4,225.3    |            |                         |               |
| Cotton gin waste  | 3,422.7    |            |                         |               |
| Cotton stalks     | 3,833.5    |            |                         |               |
| Groundnut shell    | 4,390.1    |            |                         |               |
| Mango wood        | 4,318.4    |            |                         |               |
| Millet stalks      | 3,976.9    |            |                         |               |
| Neem wood         | 4,781.8    |            |                         |               |
| Rice husk         | 3,587.5    |            |                         |               |
| Rice straw        | 3,463.3    |            |                         |               |
Saw dust 3,960.1
Soybean straw 3,876.5
Sugarcane straw 3,726.1
Sunflower stover 3,747.6
Sunflower seed shell 4,079.6
Wheat straw 3,597.1
Wood chips 4,757.9

4. Conclusions

The drying process using contact dryer helps to remove H2O content in OPT prior to torrefaction process. Torrefaction is a promising process for processing OPT as it leads to higher heating value and improved energy quality. The process modeling of OPT drying and torrefaction gives the charcoal yield of 0.2972 compared to experiment yield of 0.24. The calorific value (HCV) of torrefied OPT with RGibbs is 6,901.0 kcal/kg that is similar with experiment result of 6,939.2 kcal/kg.

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References

[1] IEO. International energy outlook 2011. U. S. Energy Information Administration 2011. Retrieved at www.eia.gov/ieo/pdf/0484 (2011).pdf, 24th October 2011
[2] Deutmeyer M, Bradley D, Hektor B, Tumuluru J S, Hess R, Nikolaisen L and Wild M 2012 Possible Effect of Torrefaction on Biomass Trade IEA Bioenergy, Task:40 Sustainable International Bioenergy Trade
[3] Koh M P and Hoi W K 2003 Sustainable Biomass Production for Energy in Malaysia Biomass and Bioenergy 25 517–529
[4] Ogawa M, Okimori Y, Takahashi F 2006 Carbon sequestration by carbonization of biomass and forestation: three case studies Mitigation and Adaptation Strategy for Global Change 11 421–36
[5] Atkinson C J, Fitzgerald J D, Hipps N A 2010 Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review Plant Soil 337 1–18
[6] Nhuchhen D R, Basu P, Acharya B 2014 A Comprehensive Review on Biomass Torrefaction International Journal of Renewable Energy & Biofuels
[7] http://www.indexmundi.com/agriculture/?country=id&commodity=palm-oil&graph=production
[8] Chan K W 2005 Best-developed practices and sustainable development of the oil palm industry Journal of Oil Palm Research 17 124–35
[9] Puah C W, Balasundram N, Choo Y M, Lim W S 2011 Malaysian oil palm industry: responding to the sustainability criteria of greenhouse gas emission savings under the European Union Renewable Energy Directive Palm Oil Development 54 5–7
[10] Goh J, Leong K H 2008 Development of pulp and paper products from oil palm fiber Proceedings of the International Conference on Oil Palm Biomass
[11] Hilstrøm T, Mikkelsen M J, Ahring B K 2005 Ethanol potential for empty fruit bunches post- treated by wet-explosion Proceedings of the international palm oil congress 348–56
[12] Yamada H, Tanaka R, Sulaiman O, Hashim R, Hamid Z A A, Yahya M K A, et al 2010 Old oil palm trunk: a promising source of sugars for bioethanol production Biomass Bioenergy 34 1608–13
[13] Mokhtar A, Hassan K, Abdul Aziz A, Wahid M B 2011 Plywood from oil palm trunks Journal of Oil Palm Research 23 1159–65
[14] Singh R P, Embrandiri A, Ibrahim M H, Esa N 2011 Management of biomass residues generated from palm oil mill: vermicomposting a sustainable option Resource Conservation and Recycling 55 423–34
[15] Loh S K, James S, Ngatiman M, Cheong K Y, Choo Y M, Lim W S 2013 Enhancement of palm oil refinery waste – spent bleaching earth (SBE) into bio organic fertilizer and their effects on crop biomass growth *Industrial Crops Production* **49** 775–81

[16] Sumathi S, Chai S P, Mohamed A R 2008 Utilization of oil palm as a source of renewable energy in Malaysia *Renewable Sustainable Energy* **12** 2404–21

[17] Deris R R, Sulaiman M R, Darus F M, Mahmud M S, Bakar N A 2006 Pyrolysis of oil palm trunk (OPT) *Proceedings of the 20th Symposium of Malaysian Chemical Engineers* **19-21** of Dec 245-250

[18] Mori Y 2007 Oil oil palm trunks as promising feedstock for biofuel and bioplastics *Presented at JIRCAS 4th BMWS*

[19] Prasetyo D, Pramudita D, Lee H W, Sitompul J P 2016 Effect of Vacuum and Atmospheric Drying on Torrefaction of Oil Palm Trunk (OPT) *International Seminar on Chemical Engineering In conjunction with Seminar Soehadi Reksowardojo*

[20] Haryadi Hardianto T, Pasek A D, Suwono A, Azhari R, Ardiansyah W 2009 The Aspen TM Software Simulation of a Peat Torrefaction System Using RYield and SSplit Block as Reactor Model *Proceedings of International Symposium on Sustainable Energy and Environmental Protection (ISSEEP)*

[21] Haydary 2004 J. Processes with Nonconventional Solids *Wiley Online Library Chapter 14*

[22] Demirbas A, Demirbas A H 2004 Estimating the Calorific Values of Lignocellulosic Fuels *Energy Exploration & Exploitation Volume 22 Number 2*

[23] Sahito A R, Mahar R B, Siddiqui Z, Brohi K M 2013 Estimating Calorific Value of Lignocellulosic Biomass from Volatile and Fixed Solids *International Journal of Biomass & Renewables*