Hydrothermal treatment of municipal solid waste into coal-like fuel

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Abstract. Hydrothermal process is a thermochemical process used to convert wet biomass waste become a coal-like material with higher carbon content called hydrochar. In this study, performance test of hydrothermal reactor was done. Stirred reactor was made of SS-304 with volume of 1 L and electric heater as a heating mantle. The hydrothermal carbonisation reactor was utilized to perform the carbonisation of three materials (paper, banana peel, and sawdust) as substrates. The substrates represent major component of biomass waste in Bandung, Indonesia. Process was operated in batch-mode at varying temperatures (190 °C, 210 °C and 230 °C), holding time (30 and 60 min), and solid load (1:3, 1:5, and 1:10). The results suggested that the hydrothermal conversion of biomass waste to solid fuel gave high heating value with value of 24.6, 21.2, and 20.1 MJ/kg for sawdust, paper, and banana peel respectively after product dried naturally. The study showed that chemical and physical properties of several feedstock and hydrochar varied as a function of reaction temperature.

Keywords: hydrothermal treatment; municipal solid waste; coal-like fuel

1. Introduction

Waste treatment still becomes a serious problem in many developing and developed countries due to the limited lifetime of final waste disposal facilities. It has been known that urban communities yield more solid waste than rural. Culture of the nation, seasons, life style, and even government policy give more influence to the composition of municipal solid waste (MSW). More than 50 % of solid waste composition in Indonesia is dominated by wet biomass waste such are food-left garbage, wood, paper and plastics [1].

Along with the advance of technology, the perception of waste should be changed. Recently biomass waste issue become interesting. It becomes a valuable resource since it can be processed into fuel or fertilizer. Refuse-derived fuel (RDF), for instance, is a fuel produced by combusting or dehydrating municipal solid waste (MSW) with a waste converter equipment. One of environmentally beneficial waste treatment process is hydrothermal carbonisation process (HTC). HTC becomes one of technologies that can handle wet biomass better than other thermochemical process such as incinerator and gasification.
HTC is a chemical pre-treatment process which is able to produce coal-like material from biomass in the shorter time compare to natural process. Water is critical element in this process. Biomass is carbonised in the subcritical water condition in the temperature region of 180 to 350 °C [2], although the effect of carbonisation is still able to reach at temperature below 350 °C [3]. HTC involves a series of reactions such as hydrolysis, decarboxylation, demethylation, dehydration reactions, and polymerisation [4-7].

Unlike landfilled and biological approaches which produce greenhouse gas emission, during HTC process, solid and liquid phases are formed with small fraction of gases [8]. The other advantages of this technique include large volume reduction of the wastes, odourless, and no need MSW moisture removal unlike incineration and gasification. The moisture contained within MSW is used as a heating medium, stream, to decompose MSW [7]. Unfortunately, the facts about the chemistry of HTC is still complicated and highly feedstock dependent [9].

In this research, we performed hydrothermal treatment under low temperature condition to produce solid fuel from several components of MSW. Paper, banana peel and sawdust were prepared as the main components of MSW. Banana is popular fruit in Asia. At least 50 % of the production of bananas in Asia is harvested in Indonesia [10], and approximately 90 % of banana production is used for domestic consumption. Decomposition characteristics of each MSW component and yield and composition of obtained char were investigated.

2. Materials and Methods

2.1. Materials

Several individual feedstocks that represent major fractions of municipal solid waste were evaluated in this study: mixed office paper, banana peel, and sawdust (Table 1). Before use, the office paper were shredded manually and represents cellulose component. Sawdust represent lignocelluloses material and was obtained from local woodworking industry. The size of the sawdust is about 1 mm. Banana peel was conditioned as cellulose and hemicellulose source. It was collected from local market.

| Material       | Description       | Amount     |
|----------------|-------------------|------------|
| Office paper   | mixed 70 and 80 gsm in weighing | 50 gram    |
| Banana peel    | Musa sp           | 50 gram    |
| Sawdust        | Albizia chinensis | 50 gram    |
| Solid load     | biomass/aquadest  | 1:3, 1:5, 1:10 |

2.2. Experimental apparatus

HTC of both every single component was performed via 1 L SS-304 reactor. The reactor, operated in batch mode, was equipped with electrical heater and agitator. In order to evaluate the effect of process parameter on feedstock, the HTC test was implemented at different parameter; residence time (30 and 60 minutes) and solid load 1:3, 1:5, 1:10. Since hydrolysis process could be happened at temperature below 200 °C [11], temperatures were set at 190, 210, and 230 °C. Nitrogen gas was used to purge the reactor to release oxygen in the reactor. Figure 1 showed HTC experimental apparatus.

Each running, fifty grams of biomass and certain ratio of water were loaded into HTC reactor. Reactor was pre-heated up until reached at desired temperature and hold for 30 and 60 minutes. After process completed, let temperature of reactor be dropped into room temperature. Gaseous products were discharged under fume hood. A qualitative filter paper was used to separate hydrochar in liquid product. In this study, the chemical composition of gas and liquid were not evaluated. Sun-drying were used for reducing the moisture content of solid fuel (hydrochar).
2.3. Analysis of hydrochar

Proximate and ultimate analysis were applied for both sample and hydrochar. Proximate analysis such as volatile matter, ash content, and fixed carbon was determined using Leco TGA-601. Elementar Vario Macro was used for ultimate analysis. This analysis gave the percentage of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulphur (S) content. High heating value (HHV) was determined by using bomb calorimeter. SEM (XL-30, Royal Philips Electronics, Amsterdam, The Netherlands) was used for structure observation. All of analysis was done at Research and Development Center of Mineral and Coal Technology. Equation 1-3 below were used to express three parameters; mass yield (Eq. 1), energy densification ratio (Eq. 2), and energy yield (Eq. 3):

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\text{Mass yield} = \frac{\text{mass of dried hydrochar}}{\text{mass of dried feedstock}} \times 100\%
\] (1)

\[
\text{Energy densification ratio} = \frac{\text{HHV of hydrochar}}{\text{HHV of raw feedstock}} \times 100\%
\] (2)

\[
\text{Energy yield} = \text{mass yield} \times \text{energy densification ratio}
\] (3)

3. Results and Discussions

3.1. Effect of process condition on energy and mass yield

The effect of three different process conditions; solid load, reaction time and temperature on mass and energy profile from HTC of each paper, banana peel, and sawdust were shown in Table 2 and Figure 2. Mass yield tended to increase when reaction time was short and decreased as reaction time increased. Short reaction time gave less impact on energy yield of product. Reaction time of less than 1 hour showed that HTC process results in cracks on biomass surface (Figure 3). The reaction time more than 3600 minutes could produce microsphere of carbon and decreased O/C and H/C ratio. Temperature is a key factor in hydrochar formation. The properties of subcritical water are depended on it. Furthermore, when the temperature exceed can spur dehydration, hydrolysis, decarboxylation, and polymerisation simultaneously happened. The results suggested that energy yield and HHV increased as temperature raised [7]. In this research, when the temperature increased from 180 to 230 °C, the mass yield decreased 20% for paper and 6-8% for sawdust and peel. This decrease was credited to a series of reaction which causes O/C and H/C ratio decreasing when high temperatures were employed. As expected, not only mass and energy yield, HHV was also influenced by carbon content ratio (Figure 2).

Table 2 also showed that the effect of solid load on the mass and energy yield from HTC. The more feed to water ratio, the wider the carbonisation area of feedstock. Paper was the feedstock that showed the lowest mass yield. It was easiest to decompose during hydrothermal treatment. Since it has cellulose and hemicellulose content higher than lignin, paper has lowest thermal stability than others. Hydrolysis of biomass could start at temperature 180 °C [11]. Hemicellulose was almost decomposed at temperature below 200 °C [13]. Lignin started to decomposed at temperature 250 °C [11,14]. HTC of biomass at temperature 230 °C for 60 minutes presented HHV of 20.1, 21.2, 24.6 MJ/kg for banana.
peel, paper, and sawdust, respectively.

**Table 2.** The effect of operating condition on energy and mass yield

| Temp (°C) | Feed to Water Ratio | Time    | Energy Yield (%) | Mass Yield (%) |
|----------|---------------------|---------|------------------|----------------|
|          |                     |         | Sawdust | Paper | Peel | Sawdust | Paper | Peel |
| 190      | 1/3                 | 30 min  | 69.05   | 58.76 | 67.62 | 68.11   | 52.30  | 64.21 |
|          |                     | 60 min  | 69.07   | 60.79 | 68.29 | 67.59   | 51.65  | 64.11 |
|          | 1/5                 | 30 min  | 69.73   | 60.63 | 67.14 | 67.87   | 51.21  | 63.54 |
|          |                     | 60 min  | 69.21   | 60.53 | 67.47 | 66.43   | 50.49  | 63.28 |
|          | 1/10                | 30 min  | 69.37   | 59.10 | 66.42 | 66.22   | 49.78  | 62.87 |
|          |                     | 60 min  | 70.22   | 59.15 | 67.12 | 66.13   | 49.04  | 62.76 |
| 210      | 1/3                 | 30 min  | 68.58   | 61.73 | 70.56 | 66.21   | 47.54  | 63.25 |
|          |                     | 60 min  | 71.36   | 56.89 | 70.25 | 66.16   | 43.21  | 62.04 |
|          | 1/5                 | 30 min  | 71.87   | 55.54 | 69.42 | 65.59   | 42.19  | 61.43 |
|          |                     | 60 min  | 74.23   | 54.46 | 70.96 | 64.75   | 40.57  | 60.95 |
|          | 1/10                | 30 min  | 75.48   | 54.32 | 69.08 | 65.34   | 40.72  | 60.06 |
|          |                     | 60 min  | 77.56   | 53.66 | 69.99 | 64.08   | 39.75  | 59.55 |
| 230      | 1/3                 | 30 min  | 75.53   | 52.23 | 68.02 | 64.36   | 38.67  | 59.26 |
|          |                     | 60 min  | 77.92   | 50.58 | 70.47 | 63.98   | 37.11  | 59.21 |
|          | 1/5                 | 30 min  | 78.67   | 51.95 | 68.30 | 63.44   | 37.43  | 59.12 |
|          |                     | 60 min  | 78.84   | 50.47 | 68.81 | 61.89   | 35.63  | 58.86 |
|          | 1/10                | 30 min  | 78.87   | 49.91 | 67.46 | 62.37   | 34.67  | 58.46 |
|          |                     | 60 min  | 79.08   | 47.52 | 69.47 | 60.89   | 32.45  | 57.85 |

**Figure 2.** HHV from HTC biomass waste
HTC process lead to cracks the physical and chemical structure of biomass into micro molecules. During HTC, biomass has lost its structure as the removal of hemicellulose via degradation and depolymerisation reactions [5]. Figure 3 gave an example of Scanning Electron Microscope (SEM) image of sawdust under HTC at 230 °C. Before treated, the clearly structure of sawdust can be observed well. However, sawdust has lost its structure after treated. In case of the hydrochar, it showed the unwrapping and rupture of polymer bundles and opening of pores is clearly noticeable.

3.2. Proximate analysis of hydrochar

Several literatures [15-18] reported that hydrochar produced via HTC has various carbon content. Many aspects such as the different of feedstock, temperature, reaction time, pressure, reactor type, solid load, and catalyst presence have influenced the quality of hydrochar. The proximate analysis of hydrochar has been reported in this research. Fixed carbon (FC), volatile matter (VM), and ash content (AC) were the main analysis parameters. Figure 4a presented that the FC of biomass increased during HTC as process parameters increased. When FC was high, HHV become high as well. FC is the combustible residue after VM discharged. In general, biomass has high VM content and low FC. Increasing of VM and FC will lead to rise HHV.

Figure 4b presented that low VM in hydrochar might lead to increase FC and HHV. This is because VM is combustible compound. It can be seen that VM in biomass decreased after hydrothermal process. It is because VM was possibly discharged and released into the air. In addition, it can be seen that using minimum process water will result lower VM in sample. Figure 4c showed that except sawdust, AC tend to increase after process for other biomass. It could be influenced by high lignin content in sawdust. Lignin is likely to be decomposed at high temperature (>250 °C) [11]. AC is the inorganic residue remaining after the sample is completely burned. Higher AC can trigger slagging, fouling, erosion, and corrosion in reactor.
Figure 4. (a) Proximate analysis of hydrochar from sawdust, (b) Proximate analysis of hydrochar from paper, and (c) Proximate analysis of hydrochar from banana peel.
4. Conclusion

The HTC reactor was utilized to perform the carbonisation of paper, banana peel and sawdust. The study showed that chemical and physical properties of several feedstock and hydrochar varied as a function of process parameter such as reaction time, temperature, and solid load. The results showed that HTC represents an effective way to obtain a solid product with quite good characteristics as energy path. The resulted showed that increasing temperature, solid load and reaction time period during hydrothermal treatment tend to increasing carbon content. The results suggested that the hydrothermal conversion of biomass waste to solid fuel gave high heating value with value of 24.6, 21.2, and 20.1 MJ/kg for sawdust, paper, and banana peel respectively after product dried naturally. The study showed that chemical and physical properties of several feedstock and hydrochar varied as a function of reaction temperature.

Acknowledgment

The authors acknowledge Research and Development Center of Mineral and Coal Technology (Tekmira) for the support of his research. The author is Indonesia Endowment Fund for Education (LPDP) scholar. The works are financially supported by the Indonesian government through Ministry of Finance, Ministry of Research and Technology and Higher Education, and Bandung Institute of Technology.

References

[1] Ahmad T Y, Hirajima T, Kumagai S and Sasaki K 2010 Production of solid biofuel from agricultural wastes of the palm oil industry by hydrothermal treatment Waste and Biomass Valorization 1 395–405

[2] Axelsson L, Fränzén M, Ostwald M, Berndes G, Lakshmi G and Ravindranath N H 2012 Perspective: Jatropha cultivation in southern India: Assessing farmers’ experiences Biofuels, Bioprod. Biorefining 6 246–56

[3] Bobleter O 1994 Hydrothermal degradation of polymers derived from plants Prog. Polym. Sci. 19 797–841

[4] Garrote G, Domínguez H and Parajó J C 1999 Hydrothermal processing of lignocellulosic materials Holz als Roh - und Werkst. 57 191–202

[5] He C, Giannis A and Wang J Y 2013 Conversion of sewage sludge to clean solid fuel using hydrothermal carbonization: Hydrochar fuel characteristics and combustion behavior Appl. Energy 111 257–66

[6] Hwang I H, Aoyama H, Matsuto T, Nakagishi T and Matsuo T 2012 Recovery of solid fuel from municipal solid waste by hydrothermal treatment using subcritical water Waste Manag. 32 410–6

[7] Kardono 2007 Integrated Solid Waste Management in Indonesia Proceedings of International Symposium on EcoTopia Science vol 07 pp 629–33

[8] Lu X and Berge N D 2014 Influence of feedstock chemical composition on product formation and characteristics derived from the hydrothermal carbonization of mixed feedstocks Bioresour. Technol. 166 120–31

[9] Lu X, Flora J R V and Berge N D 2014 Influence of process water quality on hydrothermal carbonization of cellulose Bioresour. Technol. 154 229–39

[10] Lu X, Jordan B and Berge N D 2012 Thermal conversion of municipal solid waste via hydrothermal carbonization: Comparison of carbonization products to products from current waste management techniques Waste Manag. 32 1353–65
[11] Lu X, Pellechia P J, Flora J R V and Berge N D 2013 Influence of reaction time and temperature on product formation and characteristics associated with the hydrothermal carbonization of cellulose Bioresour. Technol. 138 180–90

[12] Ministry of Environment 2008 Statistik Persampahan Domestik Indonesia (Waste Management Statistics Indonesia)

[13] Pusat Data dan Sistem Informasi Sekretaris Jendral Kementrian Pertanian 2014 Outlook Komoditi Pisang 74

[14] Putra H E, Dewi K, Damanhuri E and Pasek A D 2018 Conversion of organic fraction of municipal solid waste into solid fuel via hydrothermal carbonization Int. J. Eng. Technol. 7 4030–4

[15] Ramke H-G, Blöhse D, Lehmann H-J, Fettig J and Höxter S T 2009 Hydrothermal Carbonization of Organic Waste Sardinia 2009: Twelfth International Waste Management and Landfill Symposium Sardinia 2009 Twelfth Int. Waste Manag. Landfill Symp. 1–16

[16] Sevilla M and Fuertes A B 2009 The production of carbon materials by hydrothermal carbonization of cellulose Carbon N. Y. 47 2281–9

[17] Sevilla M and Fuertes A B 2009 Chemical and structural properties of carbonaceous products obtained by hydrothermal carbonization of saccharides Chem. - A Eur. J. 15 4195–203

[18] Titirici M M, Thomas A, Yu S H, Müller J O and Antonietti M 2007 A direct synthesis of mesoporous carbons with bicontinuous pore morphology from crude plant material by hydrothermal carbonization Chem. Mater. 19 4205–12

[19] Wiedner K, Naisse C, Rumpel C, Pozzi A, Wieczorek P and Glaser B 2013 Chemical modification of biomass residues during hydrothermal carbonization - What makes the difference, temperature or feedstock? Org. Geochem. 54 91–100