PRETREATMENT OF FORESTRY RESIDUE VIA TORREFACTION PROCESS

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AYUNI BINTI MOHAMAD ALI

Thesis submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Chemical Engineering

Faculty of Chemical & Natural Resources Engineering UNIVERSITI MALAYSIA PAHANG

JUNE 2015

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Bachelor of Chemical Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedication

This thesis is dedicated to my parents and my late teacher, Ruzana Binti Manaf who have been an invaluable source of inspiration throughout my life. Thank you...

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First and foremost thankful to Allah S.W.T because I was given a chance to complete this thesis. Hence, I am Ayuni binti Mohamad Ali would like to express my biggest gratitude to Faculty of Chemical and Natural Resources Engineering of Universiti Malaysia Pahang in providing this Undergraduate Research Project as a medium for UMP students to be exposed with a research work.

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ABSTRACT

The use of biomass to produce energy is becoming more and more frequent as it helps to achieve a sustainable environmental scenario. However, the exploitation of this fuel source does have drawbacks that need to be solved. In this work, the torrefaction of forestry residues was studied in order to improve its properties as an alternative fuel for renewable energy sources. The torrefaction process was conducted at 230 °C, 270 °C and 300 °C with a residence time of 30 minutes and in the absence of oxygen. From the torrefaction experiment, characteristics such as heating value, mass and energy yield were determined. From the results obtained, the heating values of torrefied biomass increased when the temperature were increased in the range of 18 to 21 MJ/kg at various torrefaction conditions. The overall mass yield of torrefied biomass was decreased when temperature was increased from 230 to 300 °C and in the range of 84 - 93%. The energy yield for torrefied biomass increased when the temperature was increased from 230 to 300 °C and in the range of 85 to 99%. The torrefied biomass can be pelletized as an alternative to replace the usage of charcoal in commercial and industrial sector.

ABSTRAK

Penggunaan biojisim untuk menghasilkan tenaga menjadi lebih kerap kerana ia membantu untuk mencapai senario alam sekitar yang mapan. Namun, penggunaan sumber bahan api ini mempunyai kelemahan yang perlu diatasi. Dalam karya ini, pengeringan sisa perhutanan telah dikaji untuk menambah baik sifat-sifat sebagai bahan api alternatif untuk sumber tenaga boleh diperbaharui. Proses pengeringan telah dijalankan pada suhu 230 °C, 270 °C dan 300 °C dengan jangka masa 30 minit dan dalam ketiadaan oksigen. Daripada eksperimen pengeringan ini, ciri-ciri seperti nilai pemanasan, hasil jisim dan hasil tenaga telah ditentukan. Daripada keputusan yang diperoleh, nilai pemanasan biojisim kering meningkat dengan penambahan suhu, dalam lingkungan 18 hingga 21 MJ/kg pada pelbagai keadaan pengeringan. Keseluruhan hasil jisim bagi biojisim kering menurun apabila suhu telah meningkat dari 230 hingga 300 °C dan dalam lingkungan 84 - 93%. Hasil tenaga untuk biojisim kering meningkat apabila suhu turut meningkat dalam lingkungan 85 hingga 99%. Biojisim kering ini boleh dibentuk menjadi pelet sebagai alternatif untuk menggantikan penggunaan arang dalam sektor perdagangan dan perindustrian.

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LIST OF ABBREVIATIONS

e	correction in calories
EFB	empty fruit bunches
С	carbon
GHG	greenhouse gas
GW	Gigawatt
Н	hydrogen
Hg	heat of combustion
HHV	higher heating value
LFG	landfill gas
MSW	municipal solid waste
MW	Megawatt
PKS	palm kernel shell
PMF	palm mesocarp fiber
TLR	torrefied logging residue
TPC	torrefied pine chips
Ν	nitrogen
0	oxygen
POME	palm oil mill effluent
RE	renewable energy
t	temperature
W	constant in equation of heat of combustion
W _n	mass retained at sieve tray
\mathbf{W}_{t}	total mass of biomass

Subscripts

- g n + combustion size of sieve tray total mass
- t

1 INTRODUCTION

1.1 Background, Motivation and Problem Statement

Energy sources play a significant role in the world's future. It mainly used in four economic sectors, which are residential, transportation, commercial and industrial. Energy sources can be divided into three categories, which are fossil fuels, renewable sources and nuclear sources (Ciubota-Rosie et al., 2008). Fossil fuel sources such as oil, natural gas and coal used to be the global energy market. It decreases as it were consumed because the duration for fossil fuel sources to be formed in the earth takes millions of year (Roberts et al., 2014). Due to the depletion of fossil sources, biomass was chosen as an alternative renewable energy sources (Gokcol et al., 2008).

Based on the research by Srirangan et al. (2014), the usage of biomass as the alternative sources can reduce the levels of greenhouse gas (GHG) emission. GHG was resulted from the burning fossil fuels for electricity, heat and transportation. Other than that, according to Gokcol et al. (2008), biomass is clean, renewable energy source can decrease the amount of waste sent to landfills and dependent on foreign oil sources. Biomass fuels can prevent the phenomenon of acid rain from occur as it does not emit sulphur dioxide and have negligible content of sulphur (Ciubota-Rosie et al., 2008).

With the global awareness on sustainability, biomass becomes one of the attractive searches for an alternative resource for renewable energy and downstream product. As a source of renewable energy, biomass has its own disadvantages. Raw biomass has a low energy density and high moisture content compared to fossil fuel (Chew and Doshi, 2011). It also has relatively high content of oxygen, low calorific value and has a hydrophilic nature (van der Stelt, 2011). The mentioned problems have resulted into higher cost for feedstock preparation, handling and transportation, since the raw biomass has high potential to undergoes biodegradation, and reduce the competitiveness of biomass (Chew and Doshi, 2011). Hence, to overcome the aroused problems, raw biomass need to undergo a pre-treatment process before it can be used as co-firing biomass to generate electricity and other potential applications, known as torrefaction process.

1.2 Objective

The objective of this research is:

• To investigate the properties of torrefied biomass using forestry residue via torrefaction process.

1.3 Scope of Research

The following are the scopes of this research:

- The torrefaction characteristics of three different biomasses from forestry residue source.
- The properties of torrefied biomass at different temperatures.

2 LITERATURE REVIEW

2.1 Introduction

Biomass can be defined as a biological material that comes from various sources. It can be derived from plant and animal which include agricultural residues, wood and wood wastes, animal waste or municipal solid wastes (Zamorano et al., 2011). Biomass can be used to create energy with different technologies: biological, thermochemical or chemical processes (Arias et al., 2007). However, direct use of raw biomass as fuel sources is usually difficult because it has poor energy characteristics such as low heating value, high moisture content and low density causing high costs during transportation, handling and storage (Chew and Doshi, 2011). Torrefaction appears to be an attractive option of upgrading biomass to a product which retains about 90% of its energy (Nunes et al., 2014).

2.2 Biomass

Biomass is an important renewable source of energy and has been used to provide energy to human activities. Harvesting and milling agricultural products produced residues that can be utilised as fuel for energy generation. Biomass differs from coal in many important ways, including organic, inorganic, energy content and physical properties. Relative to coal, biomass generally has less carbon, more oxygen, more silica and potassium, less aluminium and iron, and lower density and friability (Chuah and Azni, 2003).

2.2.1 Properties of Wood

Wood is composed of cellulose, lignin, hemicelluloses and 5 - 10% of extraneous materials contained in a cellular structure. Variations in the characteristics and volume of these components and differences in cellular structure make woods to have different weight, flexibility and hardness (Miller R. B., 1999). Generally, woods are divided into two broad classes:

(a) Hardwoods

Hardwoods can be found on the plants with broad leaves and it contains vessel elements. It starts as wide cells with large cavities, arranged one above the other and

serves as a sap in the tree. Timbers with vessels are sometimes called pored timbers and the arrangement of the vessels in a cross-section is a useful aid to identifying different timbers. Strength in broad-leaved trees is imparted by other types of cells, called fibres. These are similar to conifer tracheids but are shorter in length and usually thickerwalled. Fibres make up the bulk of the wood in broad-leaved trees and, like tracheids, the walls of these cells are made of cellulose and neighbouring cells are held together by lignin. Examples of hardwood trees include alder, balsa, beech, hickory, mahogany, maple, oak, teak, and walnut.

(b) Softwoods

Softwoods were known as non-pored wood. The bulk of softwood is made up of long narrow cells, or tracheids, that fit closely together. The cell walls of tracheids are made of cellulose and the centres are hollow. Tracheids lie alongside each other and another substance, lignin, is deposited between the touching cell walls. This helps to hold the tracheids firmly together. Conifer tracheids can be up to four millimetres long, and serve both to transport sap and to strengthen the stem of the tree. Pits in the cell walls of the tracheids enable sap to pass from cell to cell as it moves up the stem. Examples of softwood trees are cedar, Douglas fir, juniper, pine, redwood, spruce, and yew.

A cross section of hardwoods and softwoods is shown in Figure 2-1.



Figure 2-1 Cross section of (a) hardwoods (b) Softwoods

2.2.2 Utilization of Biomass in Malaysia

Biomass in Malaysia contributes about 14% of the approximately 340 million barrels of oil equivalent of energy used every year. The biomass industry represents several different industries brought together by the utilization of renewable organic matters including timber waste, oil palm waste, rice husk, coconut fibers, municipal waste and sugar cane waste. The renwable organic matters are shown in Figure 2-2. These organic materials have the potential to be used in the manufacturing of value-added ecoproducts (Chuah et al., 2006).



Figure 2-2 Renewable organic matters: (a) timber waste, (b) oil palm waste, (c) rice husk, (d) coconut fiber, (e) municipal waste and (f) sugar cane waste

(a) Wood fuel

Generation of electrical power using wood waste material is considered costcompetitive with the tariffs charged by the electric utility companies. Basically, there are four types of forest residues: logging, sawmilling, plywood and veneer, and secondary processing residues. About 2.18 million tonnes of wood waste per year generated in Malaysia, with the potential to generate 598 GWh, with 68 MW of total installed capacity (Chuah and Azni, 2003). 7% of total renewable energy (RE) consumption were used for wood energy in Malaysia. A comprehensive study on utilization of woodfuel was also reported by Ali and Hoi (1990). However, data on woodfuel use by households are not available. Biomass energy is mainly used for cooking in the domestic sector. Currently, with the emergence of alternative uses for wood waste materials, wood residue volumes as a source of fuel are decreasing. Emphasis in this sector will be not so much on expansion of capacities, but rather on higher efficiencies in existing industries. The other reason biomass waste from forestry, logging and timber industries in Malaysia as a potential fuel is the lack of interest from wood mill owners to include power generation in diversifying their businesses. There is also a problem in securing long-term supply agreements from the mills.

(b) Oil palm waste

More than 2.8 million hectares of land in Malaysia involved the oil palm cultivation. The waste from the palm oil mills is utilized on-site to provide energy for the mill as well as electricity exports to the grid. In 1995, there are some 281 palm-oil mills in operation with an aggregate installed capacity of around 200 MW. All this capacity is installed to meet the captive power demand. A total of 42 million tons of fresh empty fruit bunches (EFB) were estimated to produce in Malaysia yearly. For low-pressure systems, 7,000 GWh could be generated with an assumed conversion rate of 2.5 kg of palm oil waste per kWh. However, the EFB has found an alternative use, such as medium density fibreboard in furniture making. These competing alternatives may eventually result in waste shortages at palm-oil mills (Chuah and Azni, 2003). Palm oil mill processing also produces palm oil mill effluent (POME), which was treated in tanks and released into the water table, but could be utilised as a source of biogas. 17,980,000 tonnes per annum biomass available in 2000, with the potential to generate 3,198 GWh, with a potential capacity of 365 MW. The mills are estimated to produce 31,500 million m³ of POME per year, with a potential to generate 1,587 GWh, with a capacity of 177 MW.

(c) Rice paddy cultivation

639,000 hactare of land were used for paddy cultivation in 1996, which is mainly located in the state of Kedah and Selangor. The amount of rice produced was 2.128 million tones. Types of residue left from the paddy cultivation are paddy straw and rice husk. Based on 1996 production statistics, 1.06 million tones of paddy straw were produced giving an energy potential of 2.54 million boe; meanwhile 1.03 million tones of rice husk were produced with an energy potential of 3.04 million boe. The total energy potential for rice straw and rice husk is 3.56 million boe, which would account

for 1.5% of the country's energy consumption in 1996. It is estimated that rice mills produce 424,000 tonnes per year, with the potential to produce 263 GW hours, with a capacity of 30 MW. One successful energy project that developed in rice sector in Malaysia is at Ban Heng Bee rice mill, Alor Setar. The total investment, excluding civil and structural works, for equipment is about RM 330,000 (USD 92,000). Based on the consumption and price of fuel oil, the annual savings from reducing fuel oil purchases amounts to an astonishing RM 75,000 (USD 21,000) (Ibrahim et al., 2002). Another rice husk cogeneration plant, Titi Serong Edar Sdn Bhd., located in Parit Buntar, Perak, is also reported to successfully generate between 700 and 1500 kW of electricity. The 1.5 MW plant is designed to cover the steam and electricity requirements of the drying process of rice milling (COGEN3, 2004). Even though the energy potential from rice straw and rice husk is relatively high, it is not well developed due to the difficulty of handling paddy wastes. Another problem is seasonal supplies because rice is only produced 1 to 3 times a year.

(d) Coconut cultivation

Waste from coconut cultivation can be divided into three categories (PTM, 1999):

1. Coconut fronds and debris that are shed throughout the year. It is estimated that based on 1995 data, 0.583 million tonnes of fronds with a potential energy of 1.747 million boe is produced annually and about 0.528 million tones of these are being used for fuel in rural villages by burning.

2. Shell, husk and copra wastes are generated from the processing and consumption of coconut fruits. 0.747 million tonnes of shells and 0.374 million tonnes of husks were produced annually. This amount corresponds to 1.99 million boe and 1.12 million boe respectively. The copra produced was 0.35 million tonnes with an energy potential of 1.18 million boe.

3. Wastes generated during replanting. Energy extracted from the leaves and trunks is estimated at 207.6 boe per hectare. There is no detailed study being carried out on the utilization of coconut waste as fuel in Malaysia. It may be due to the location of coconut plantations, which are usually located in the rural area with poor infrastructure. Moreover, coconut plantations are not as energy intensive compared to the palm oil industries.

(e) Municipal waste

The national average of the amount of waste generated is at 0.5 - 0.8 kg/person in a day in Malaysia. However, these figures have escalated to 1.7 kg/person in a day in the cities (Kathirvale et al., 2003). An average of 2500 ton of municipal solid waste (MSW) is collected every day for Kuala Lumpur, Malaysia. There are two methods of MSW disposal in Malaysia which are landfill and incineration. Initiatives have been taken by the government and the private sectors to tap the landfill gas (LFG) for the generation of electricity. Currently, there are only a handful of properly designed and operated landfills in the country and most of them are located in the capital, Kuala Lumpur area. One of these projects is the Ayer Itam Landfill located at Puchong, Selangor which had been commissioned on April 2004, using LFG for power generation. This project was being developed by a TNB subsidiary, Jana Landfill Sdn. Bhd. (JLSB), and is under the small renewable energy power (SREP) program. The plant has a capacity of 2.0 - 5.0MW. SIRIM-Projass is another engineering group interested in developing LFG power facilities and is in the early stages of developing a municipal waste site (PTM, 2004). A few landfill gas potential studies undertaken to date have also suggested that many of the existing landfills are not currently suited to exploitation for energy production, mainly due to their small scale. As for incineration, the normal practice is that the solid waste is burnt without recovering the energy. Kathirvale et al. (2003) carried out a study to evaluate the energy recovery potential from MSW. They found that incineration gives the best returns in terms of the amount of energy recovered. Recently, the government has planned for a gasification unit with ash melting incineration system for the city of Kuala Lumpur with a capacity to incinerate 1500 ton of MSW/day and is expected to be operational by the year 2006.

(f) Sugar cane waste

In 1997, the total land area under sugarcane cultivation was 18,000 hactare, which is primarily located in the northern states of peninsular Malaysia. Sugarcane plantations derive energy from sugarcane related wastes including sugar, bagasse, dry leaves and cane top. 150,000 tonnes of dry bagasse was produced, which had an energy potential of 0.421 million boe per year. All the bagasse was used as a boiler fuel in the sugar mills. During replanting, sugar wastes such as leaves and cane tops are disposed of through burning. The total energy from these wastes is about 0.298 million boe per year (PTM, 1999). Duval (2001), reported a summary of biomass residues and wastes generated in

each Southeast Asian country by the wood and food processing industries, and the associated power generation potential. No data on bagasse fuel in Malaysia was reported.

2.3 Torrefaction Principles

The method to improve the fuel properties of biomass is the thermal pre-treatment or known as torrefaction process (Nunes et al., 2014). The thermochemical process of torrefaction is an incomplete pyrolysis process and was characterized by the parameters of reaction temperature 200 - 300 °C and heating rate < 50 °C/min with absence of oxygen. The absence of oxygen in the reactor was to ensure oxidation and ignition does not occur. Torrefaction process also conducted with the residence time less than 30 minutes at 200 °C, ambient pressure and flexible feedstock (Jaya Shankar et al., 2011).

2.3.1 Torrefaction of Biomass in Malaysia

Torrefaction of biomass has become a significant process in Malaysia, especially in Research and Development (R&D) field. A study on torrefaction of oil palm waste was conducted by Aziz et al. (2012) at Universiti Teknologi Petronas. The torrefaction behaviour of empty fruit bunches (EFB), palm mesocarp fiber (PMF) and palm kernel shell (PKS) were investigated. The study focused on the relation between the lignocellulosic constituents with torrefaction process. Two different size ranges of 250 -355 µm and 355 - 500 µm were used and the submitted to six final torrefaction temperatures of 200, 220, 240, 260, 280 and 300 °C. The process was carried out in a thermogravimetric analyzer coupled with mass spectrometry (TGA-MS). Tha results implied that torrefaction was strongly dependent on the thermal decomposition behaviour and composition of lignocellulosic constituents. The ultimate analysis showed that torrefaction increased the carbon content of torrefied solid, whilst decreased the hydrogen and oxygen content. Due to higher content of hemicellulose in EFB compared to others, EFB had been decomposed almost completely by torrefaction. From the mass spectrometry study, the percentile compositions of CO, CH₄, CO₂ and H₂ in the gases product were found to be 29 - 33, 20 - 23, 1.3 - 1.9, and 1.7 - 2.1% respectively.

A study on torrefaction pelletized oil palm empty fruit bunches (EFB) have been conducted at Universiti Teknologi Malaysia by Nyakuma et al. (2015). The results

revealed that temperature significantly influenced the mass yield, energy yield and heating value of EFB briquettes during torrefaction. The solid uniform compact nature of EFB briquettes ensured a slow rate of pyrolysis or devolatization which enhanced torrefaction. The mass yield decreased from 79.70% to 43.03%, energy yield from 89.44% to 64.27% during torrefaction from 250 °C to 300 °C. The heating value (HHV) of EFB briquettes improved significantly from 17.57 MJ/kg to 26.24 MJ/kg after torrefaction at 300 °C for 1 hour. Fundamentally, the study has highlighted the effects of pelletization and torrefaction on solid fuel properties of oil palm EFB briquettes and its potential as a solid fuel for future thermal applications.

2.4 Characteristics of Torrefied Wood

The characteristics of torrefied wood can be classified into physical properties and chemical composition. The changes physical properties consist of moisture content, density, grindability, pelletability, hydrophobicity and calorific value (Sadaka and Negi, 2009) and the chemical composition was analysed in terms of the content of carbon, hydrogen, oxygen, in the torrefied biomass.

2.4.1 Moisture Content

The moisture content of the pre-dried biomass was reduced during the drying process from 10% to less than 6% (Lipinsky et al., 2002). The moisture content of the torrefied biomass range based on weight was 1 - 6%, depends on the condition of torrefaction (Bergman and Kiel, 2005). Based on the study conducted by Phanphanich and Mani (2011) as shown in Table 2-1, when the torrefaction temperature increased, the moisture content of torrefied biomass decreased as it is stored at room temperature. The hydroxyl groups loss from biomass during torrefaction process and makes the torrefied biomass not easily absorbs moisture compared to untreated biomass. According to the study conducted on the pine sawdust by Peng et al. (2012), the weight loss differences of pine sawdust at 523 K was around 4% and 7% at 573 K. This implies that the moisture content is reduced at higher temperature of torrefaction process. The mass loss of stump wood was 34% at the highest condition of 300 °C and 35 minutes of residence time (Tran et al., 2013).

Table 2-1 Moisture content of raw and torrefied pine chips (TPC) and logging residues (TLR) by Phanphanich and Mani (2011)

Biomass	Moisture Content (%)
Pine chips (PC)	6.69
TPC-225 °C	3.30
TPC-250 °C	2.88
TPC-275 °C	2.46
TPC-300 °C	2.57
Logging Residue chips (LR)	7.94
TLR-225 °C	3.11
TLR-250 °C	2.66
TLR-275 °C	2.64
TLR-300 °C	2.36

2.4.2 Density

The biomass became more porous during torrefaction process due to the mass loss in solids, liquids and gases form. This result to the volumetric density reduced in the range of $180 - 300 \text{ kg/m}^3$, depending on the torrefaction conditions and initial biomass density (Bergman and Kiel, 2005). According to research done by Phanphanich and Mani (2011), the pine chips and logging residues have lower particle density at higher temperature of torrefaction. From Table 2-2, the oxidative torrefaction in the presence of oxygen exist in flue gas increased the particle density compared with torrefied sawdust without presence of oxygen, due to the oxidation of more light hydrocarbons in the biomass (Wang et al., 2012). Based on the study conducted by Stelte et al. (2011), the density of torrefied spruce wood decreased from 832 kg/m³ at 250 °C to 698 kg/m³ for temperature of 275 °C.

Torrefaction conditions	Particle density (kg/m ³)
Untreated dry sawdust	1441 ± 25
250 °C, 42 min, 3% O ₂ ; 30 wt%	1525 ± 18
270 °C, 25 min, 3% O ₂ ; 31.5 wt%	1521 ± 33
270 °C, 24 min, 3% O ₂ ; 29.8 wt%	1522 ± 22
290 °C, 4 min, 3% O ₂ ; 30 wt%	1541 ± 31
290 °C, 7 min, 3% O ₂ ; 36 wt%	1562 ± 50
270 °C, 12 min, 6% O ₂ ; 31 wt%	1637 ± 31
270 °C, 30 min, 0% O ₂ ; 36 wt%	1449

Table 2-2 Particle density of raw and torrefied sawdust at different torrefaction conditions by Wang et al. (2012)

2.4.3 Grindability

The biomass will shrink; becomes lightweight, flaky and fragile; and losses its mechanical strength during the torrefaction process, makes it easier to be ground and pulverized (Arias et al., 2008). Based on the study conducted by Bergman and Kiel (2005), the power consumption to grind biomass reduced in the range of 70 - 90% when the biomass was torrefied, depends on the conditions which the material was torrefied. The grindability of biomass improved with the increased in brittleness and friability of biomass reduced 10 times after the torrefaction process. The specific energy consumption was reduced 10 times after the torrefaction process (Chew and Doshi, 2011). According to Repellin et al. (2010), as shown in Figure 2-2, the grinding energy of torrefied spruce chips reduced 40% compared to the raw samples. The grindability of torrefied beechwood measured from hardgrove grindability index (HGI) was improved compared to the raw beechwood (Ohliger, 2013). The energy required and time used in grinding the stump wood decreased as the torrefaction temperature increased (Tran et al., 2013).



Figure 2-3 Grinding energy of beech and spruce at different torrefaction temperature by Repellin et al. (2010)

2.4.4 Pelletability

Uniform feedstock with consistent quality was obtained from torrefaction of the biomass before the pelletisation process. The bulk density of the torrefied pellets were produced in the range of 750 - 850 kg/m³ (Bergman and Kiel, 2005). Lignin in the biomass is considered as the basic binding agent and the pelletability of biomass is evaluated based on the amount of the lignin. The higher amount of lignin results in better binding and mild process conditions required for densification (Lehtikangas, 1999). Table 2-3 shows the study conducted by Peng et al. (2012), the energy consumption to make pellets for pine sawdust with a size of 0.81 mm was higher than 0.23 mm and 0.67 mm. The finding indicates the energy consumption is higher for the pelletability of larger sawdust sample.

Items	control	250 °C 15 min	250 °C 30 min	300 °C 15 min	300 °C 30 min	
	Initial p	oarticle size:	: 0.23 mm			
Pellet density (kg/m ³)	1210	1200	1180	1120	1120	
Specific energy consumption (MJ/t)	27.5	37.9	40.8	51.2	55.9	
Initial particle size: 0.67 mm						
Pellet density (kg/m ³)	1230	1250	1240	1170	1160	
Specific energy consumption (MJ/t)	26.7	35.4	35.3	41.2	42.9	
Initial particle size: 0.81 mm						
Pellet density (kg/m ³)	1230	1200	1170	1140	1120	
Specific energy consumption (MJ/t)	28.2	53.0	62.6	75.6	78.1	

Table 2-3 Properties of torrefied and control pellets made from different size of pine samples by Peng et al. (2012)

2.4.5 Chemical Composition of the Torrefied Biomass

From the research conducted by Zanzi et al. (2002) about miscanthus torrefaction, the carbon content was increased and decreased in hydrogen, nitrogen and oxygen content with temperature of 230 - 280 °C and residence time of 1 - 3 hours. The carbon content increased about 52% from initial value of 43.5% at 280 °C. The hydrogen and nitrogen content were decreased about 6.49 - 5.54% and 0.90 - 0.65% for 2 hours duration of torrefaction. The carbon content increased when the torrefaction temperature was higher and the hydrogen and oxygen content decreased due to the formation of water, carbon monoxide and carbon dioxide (Sadaka and Negi, 2009). According to Bridgeman et al. (2008), as listed in Table 2-4, the torrefaction process causes the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios to decrease with increasing temperature and time, resulting to less smoke and water vapor formation and reduced energy loss during combustion and gasification processes.

	D	Torrefaction temperature (K)			re (K)
	Kaw	503	523	543	563
Red can	ary grass				
C (%)	48.6	49.3	50.3	52.2	54.3
H (%)	6.8	6.5	6.3	6.0	6.1
N (%)	0.3	0.1	0.0	0.1	0.1
O (%)	37.3		37.0	37.3	36.3
Wheat s	traw				
C (%)	47.3	48.7	49.6	51.9	56.4
H (%)	6.8	6.3	6.1	5.9	5.6
N (%)	0.8	0.7	0.9	0.8	1.0
O (%)	37.7		35.6	33.2	27.6
Willow					
C (%)	49.9	50.7	51.7	53.4	54.7
H (%)	6.5	6.2	6.1	6.1	6.0
N (%)	0.2	0.2	0.2	0.2	0.1
0 (%)	39.9	39.5	38.7	37.2	36.4

Table 2-4 Ultimate analysis of untreated and torrefied biomass by Bridgeman et al. (2008)

2.4.6 Particle Size Distribution and Particle Surface Area

According to Phanphanich and Mani (2011) who studied about the torrefied pine and logging residues, smaller particle sizes are produced after torrefaction compared to untreated biomass. They also observed that the particle distribution curve was skewed towards smaller particle sizes with increased of torrefaction temperatures. An increase in particle surface area or decrease in particle size of torrefied biomass can be desirable properties for efficient co-firing and combustion applications (Mani et al., 2004). Research study has indicated that ground torrefied material results in a powder with a favourable size distribution, allowing the torrefied powder to meet the smooth fluidization regime required for feeding it to entrained-flow processes (Esteban and Carrasco, 2006). Based on the study conducted by Tran et al. (2013), in Figure 2-3, the torrefied stump wood at 300 °C pass through the 0.8 mm sieve more than 85%, while at 250 °C, about 55% torrefied stump wood passed through the sieve tray.



Figure 2-4 Particle distributions of torrefied spruce stump chip by Tran et al. (2013)

2.4.7 Mass Yield

Based on the study conducted by Kongkeaw and Patumsawad (2011), the yield of solid torrefied product decreased when the temperature and reaction time increased. Mass loss on torrefied biomass during devolatisation process as gaseous phases is detected and consists of carbon dioxide, carbon monoxide and methane. The production of carbon monoxide and methane increased and carbon dioxide content decreased at higher torrefaction temperature. The mass yield of torrefied biomass decreased as the torrefaction temperature increased. The mass yield starts to decline from temperature of 275 °C and about one-half of the original weight when temperature reaching 300 °C (Phanphanich and Mani, 2011). The mass loss was primarily due to thermal decomposition of hemicellulose and some short chain of lignin compounds (Bergman et al., 2005). The mass yield of torrefied biomass can vary from 24 - 95% of its original weight (Chew and Doshi, 2011). According to the study conducted by Rousset et al. (2012), the mass loss percentages of Eucalyptus garandis wood increased from 7 - 9% and 17 – 22% at the torefaction temperature of 240 °C and 280 °C. From Figure 2-4, the weight loss of rice straw and pennisetum at temperature of 100 °C and 250 °C was about 10% and 50% (Huang et al., 2012).



(b)

Figure 2-5 Weight loss of (a) rice straw and (b) pennisetum by Huang et al. (2012)

2.4.8 Energy Yield

The energy yield can be viewed as an indicator of the amount of energy lost during torrefaction and based upon the mass yield and calorific value. As the torrefaction temperature increase to more than 250°C, the energy yield for woody biomass spreads from 55 to 98% (Chew and Doshi, 2011). According to the study conducted by Phanphanich and Mani (2011), the energy yield of torrefied pine wood chips ranged from 71 - 94% depends on the torrefaction temperatures. The gross calorific value increased with the increasing in temperature and residence time. In the most critical conditions of 280 °C and residence time of 3 hours, the gross calorific value of the product increased by 34% (Arias et al., 2008). In Figure 2-5, the energy yield of eucalyptus decreased as the torrefaction temperature or residence time increased. It can be seen in the results that even at low residence time, the torrefaction at 280 °C

produces large decrease in the energy yield, which does not seem possible to improve the grindability or reactivity characteristics of the biomass. The energy content of the torrefied biomass increased after the torrefaction process. Based on the study conducted by Lee et al. (2012), the energy content of torrefied softwood chip increased by 4 - 19% compared to the feedstock. The softwood chip torrefied at 280 °C has the energy value of 22.12 MJ/kg compared to the raw sample with the energy value of 18.54 MJ/kg. The heating value of beechwood chips was 21.1 MJ/kg at 280 °C and 25.3 MJ/kg at temperature of 300 °C (Ohliger et al., 2013). This indicates that the heating value of torrefied biomass increased at higher temperature and also increased in energy yield of the biomass. According to the study conducted by Huang et al. (2012), the value of higher heating value (HHV) for torrefied rice straw and pennisetum was about 30 and 56% higher than the raw samples.



Figure 2-6 Variation in energy yield of torrefied eucalyptus by Arias et al. (2008)

2.5 Summary of Literature Review

The torrefaction of biomass as a pre-treatment step has the potential to contribute to the world energy demand and a major contribution to the commodification of biomass as a renewable energy resource. The torrefied biomass that was less in moisture content and density contribute to better handling and storage of the biomass. The energy consumption for grindability of the torrefied biomass reduced because it has more brittle and friable structure. The heating value increases at higher temperature due to the removal of low carbon content hemicelluloses.

3 METHODOLOGY

3.1 Materials

3.1.1 Raw Materials

The biomass used in this study were saw dust and wood wastes, which are Yellow meranti (*Shorea (yellow*), Geronggang (*Cratoxylum*) and Mersawa (*Anisoptera*) as shown in Figure 3-1. The biomasses were obtained from sawmill in Gambang, Pahang Darul Makmur.



Figure 3-1 Raw samples of (a) Shorea, (b) Cratoxylum and (c) Anisoptera

3.1.2 Chemical

The only chemical which involved in the whole study of torrefaction process is nitrogen gas. During the process, only a small portion of nitrogen (about 0.5 L/min) is required to ensure an inert atmospheric condition by eliminating the oxygen from the torrefaction reactor.

3.2 Methods

3.2.1 Preparation of Biomass Sample

The raw biomass was ground and sieved using the sieve shaker (Figure 3-2) in order to obtain a sample with diameter of 2 - 4 mm. The sample then was dried in the oven at 105 °C until it consists about 10% of moisture content and was stored in a container for further usage. The example calculation for moisture content and sieve analysis for the raw sawdust are shown in the Appendix A-1 and A-2.



Figure 3-2 Sieve shaker

3.2.2 Gas Catalytic Reactor

A vertical reactor that was used for the torrefaction process is a stainless steel tube with an internal diameter of 22.4 mm and a length of 500 mm as shown in Figure 3-3. A plate with a hole is originally fixed and located 200 mm above the bottom of the tube. In each case a small amount of glass wool was placed above the plate to prevent biomass sample from leaking during the torrefaction process.



Figure 3-3 Vertical reactor and other accessories

3.2.3 Torrefaction Experiment

The experimental procedure is summarized in Figure 3-4.



Figure 3-4 Experimental procedure

The experiment setup for torrefaction is shown in Figure 3-4.



Figure 3-5 Torrefaction experiment setup

3.3 Measurements

3.3.1 Mass Yield

The biomass was subjected to changes in mass yield during the process. Mass yield was calculated using the equation (1) as proposed by Bergman et al. (2005).

Mass Yield (wt%) =
$$\frac{M_{\text{torrefied}}}{M_{\text{raw}}} \times 100$$
 (1)

3.3.2 Heating Value and Energy Yield

The heating value was measured using a bomb calorimeter to compare before and after the torrefaction process. The heating value was calculated using the equation (2):

$$H_g = \frac{tW - e_1 - e_2 - e_3}{m}$$
 (2)

where

t = temperature difference

 $W = 2409.26 \text{ cal/}^{\circ}C$ (heat capacity of bombcalorimeter)

- e_1 = correction in calories for heat of formation of HNO₃
- $e_2 = correction in calories for heat of formation of H_2SO_4$

e₃ = correction in calories for heat of combustion of fuse wire
= 2.3 x cm of wire consumed in firing
m = mass

The energy yield was obtained from the determination of heating value using bomb calorimeter. Energy yield was calculated using the equation (3) as proposed by Bergman et al. (2005).

Energy Yield (%) = Mass Yield
$$\times \frac{HHV_{torrefied}}{HHV_{raw}} \times 100$$
 (3)

where $M_{torrefied}$ is the mass of sample after torrefaction; M_{raw} is the mass of untreated sample; HHV is the higher heating value.

4 RESULTS AND DISCUSSIONS

4.1 Mass Yield

The mass yields at different torrefaction temperature for the three biomasses are presented in Figure 4-1. The mass yield of the torrefied biomass decreased when the temperature is increased. The mass yield for *Shorea (yellow)* decreased from 85.09% to 84.91% as the temperature increased from 230 °C to 300 °C. Other than that, *Cratoxylum* have a mass yield of 91.30%, 91.08% and 88.25% for torrefaction temperature of 230 °C, 270 °C and 300 °C, while, *Anisoptera* had decrease in mass yield from 92.17% to 88.11%. *Shorea (yellow)* has the lowest mass yield compared to others and has only slight decrease when torrefied at 230 - 300 °C. The mass yield of torrefied biomass can vary from 24 - 95% of its original weight (Chew and Doshi, 2011). The mass yield starts to decline from temperature of 275 °C and about one-half of the original weight when temperature reaching 300 °C (Phanphanich and Mani, 2011).



Figure 4-1 Mass yield of torrefied biomass at different temperature

4.2 Heating Value and Energy Yield

The heating values of the raw and torrefied biomass results were presented in Figure 4-2. The heating value for torrefied biomass increased when the temperature was increased. According to Wang et al. (2013), the heating value of torrefied sawdust is expected to be in the range of 19 MJ/kg to 27 MJ/kg depends on the type of wood used and torrefaction conditions.



Figure 4-2 Higher heating value of raw biomass and torrefied biomass at different conditions

Figure 4-3 shows the energy yields of torrefied biomass at different torrefaction temperature. The energy yield of torrefied biomass increased when the temperature increased. The energy yield of *Shorea (yellow)* increased from 85.13% to 85.57%. *Cratoxylum* had a drastic increased in energy yield from 230 °C to 270 °C, and has an energy yield of 98.32% at 300 °C. The energy yield for *Anisoptera* at 230, 270 and 300 °C are 92.40 %, 93.30% and 93.82% respectively. As the torrefaction temperature increase to more than 250 °C, the energy yield for woody biomass spreads from 55 to 98% (Chew and Doshi, 2011).



Figure 4-3 Energy yield of torrefied biomass at different temperature

5 CONCLUSION

5.1 Conclusion

Torrefaction is an effective pre-treatment method for raw biomass before it can be used as the alternative renewable energy sources. The overall mass yield of torrefied biomass is decreased at higher temperature and in the range of 84 to 93%. The heating values of torrefied biomass increased when the temperature were increased in the range of 18 to 21 MJ/kg at various torrefaction conditions. The energy yield for torrefied biomass increased when the temperature increased in the range of 85 to 99%.

5.2 Recommendations

Besides the research conducted in the present study, a few detailed investigations were recommended to have further understanding on the torrefaction characteristics:

- 1. Extension of residence time of torrefaction.
- 2. Usage of various types of sawdust and wood wastes.
- 3. Examine the chemical composition of the torrefied biomass.

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APPENDICES

A-1 Drying of Sawdust Sample

Initial mass of sawdust = 2.0409 g

Mass of aluminium foil = 0.9016 g

Temperature of oven $= 105^{\circ}C$

Time (min)	Mass of aluminium foil + sawdust after drying (g)	Final mass of sawdust (g)	Moisture content (%)
30	2.3929	1.4913	$\frac{2.0409 - 1.4913}{2.0409} \times 100 = 26.93$
60	2.3380	1.4364	$\frac{1.4913 - 1.4364}{1.4913} \times 100 = 3.68$

A-2 Sieve Analysis of Raw Sawdust Sample

Total mass of sawdust, $W_t = 120.4 \text{ g}$ Before sieve:

Sieve opening	Mass of sieve tray (g)
4 mm	389.2
2 mm	361.2
1 mm	299.8
630 µm	289.8
500 μm	294.7
Bottom tray	350.3

After sieve:

Sieve opening	Mass of sieve tray + sawdust (g)
4 mm	392.2
2 mm	404.6
1 mm	346.0
630 μm	298.7
500 μm	298.5
Bottom tray	364.5

Sieve opening	Mass of sawdust retained on each sieve, W _n (g)	Percent of mass retained (%)	Cumulative percent retained (%)		
4 mm	3.0	2.49	2.49		
2 mm	43.4	36.05	38.54		
1 mm	46.2	38.37	76.91		
630 μm	8.9	7.39	84.30		
500 μm	3.8	3.16	87.46		
Bottom tray	14.2	11.79	99.25		
$\Sigma W_n = 119.5$					

Mass loss during sieve analysis = $\frac{W_t - \sum W_n}{W_t} \times 100$

$$=\frac{120.4-119.5}{120.4}\times100$$

= 0.75 %