PRETREATMENT OF FORESTRY RESIDUE VIA TORREFACTION PROCESS

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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 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

# TABLE OF CONTENTS

SUPERVISOR’S DECLARATION ................................................................. IV
STUDENT’S DECLARATION ..................................................................... V
Dedication ......................................................................................... VI
ACKNOWLEDGEMENT ........................................................................ VII
ABSTRACT ........................................................................................... VIII
ABSTRAK .............................................................................................. IX
TABLE OF CONTENTS ........................................................................ X
LIST OF FIGURES ................................................................................. XII
LIST OF TABLES ................................................................................... XIII
LIST OF ABBREVIATIONS ...................................................................... XIV

1 INTRODUCTION .................................................................................... 1
  1.1 Background, Motivation and Problem Statement .................................... 1
  1.2 Objective ........................................................................................... 2
  1.3 Scope of Research .............................................................................. 2

2 LITERATURE REVIEW ........................................................................... 3
  2.1 Introduction ........................................................................................ 3
  2.2 Biomass ............................................................................................. 3
    2.2.1 Properties of Wood ........................................................................ 3
    2.2.2 Utilization of Biomass in Malaysia .................................................... 5
  2.3 Torrefaction Principles ....................................................................... 9
    2.3.1 Torrefaction of Biomass in Malaysia ................................................ 9
  2.4 Characteristics of Torrefied Wood ...................................................... 10
    2.4.1 Moisture Content .......................................................................... 10
    2.4.2 Density .......................................................................................... 11
    2.4.3 Grindability .................................................................................... 12
    2.4.4 Pelletability ................................................................................... 13
    2.4.5 Chemical Composition of the Torrefied Biomass ............................ 14
    2.4.6 Particle Size Distribution and Particle Surface Area ........................ 15
    2.4.7 Mass Yield ..................................................................................... 16
    2.4.8 Energy Yield .................................................................................. 17
  2.5 Summary of Literature Review ......................................................... 19

3 METHODOLOGY .................................................................................... 20
  3.1 Materials .......................................................................................... 20
    3.1.1 Raw Materials ............................................................................... 20
    3.1.2 Chemical ....................................................................................... 20
  3.2 Methods ............................................................................................ 20
    3.2.1 Preparation of Biomass Sample ......................................................... 20
    3.2.2 Gas Catalytic Reactor .................................................................... 21
    3.2.3 Torrefaction Experiment .............................................................. 22
  3.3 Measurements .................................................................................. 23
    3.3.1 Mass Yield ..................................................................................... 23
    3.3.2 Heating Value and Energy Yield ..................................................... 23

4 RESULTS AND DISCUSSIONS .............................................................. 25
  4.1 Mass Yield ......................................................................................... 25
4.2 Heating Value and Energy Yield ................................................................. 26
5 CONCLUSION .................................................................................................. 28
  5.1 Conclusion ............................................................................................... 28
  5.2 Recommendations .................................................................................. 28
REFERENCES ..................................................................................................... 29
APPENDICES ...................................................................................................... 33
LIST OF FIGURES

Figure 2-1 Cross section of (a) hardwoods (b) Softwoods ................................................... 4
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 ....................... 5
Figure 2-3 Grinding energy of beech and spruce at different torrefaction temperature by Repellin et al. (2010) ................................................................................................. 13
Figure 2-4 Particle distributions of torrefied spruce stump chip by Tran et al. (2013) ....... 16
Figure 2-5 Weight loss of (a) rice straw and (b) pennisetum by Huang et al. (2012) .... 17
Figure 2-6 Variation in energy yield of torrefied eucalyptus by Arias et al. (2008) ...... 18
Figure 3-1 Raw samples of (a) Shorea, (b) Cratoxylum and (c) Anisoptera .................... 20
Figure 3-2 Sieve shaker .............................................................................................................. 21
Figure 3-3 Vertical reactor and other accessories ................................................................. 21
Figure 3-4 Experimental procedure ...................................................................................... 22
Figure 3-5 Torrefaction experiment setup ............................................................................. 23
Figure 4-1 Mass yield of torrefied biomass at different temperature ................................. 25
Figure 4-2 Higher heating value of raw biomass and torrefied biomass at different conditions ..................................................................................................................... 26
Figure 4-3 Energy yield of torrefied biomass at different temperature ......................... 27
LIST OF TABLES

Table 2-1 Moisture content of raw and torrefied pine chips (TPC) and logging residues (TLR) by Phanphanich and Mani (2011) ................................................................. 11
Table 2-2 Particle density of raw and torrefied sawdust at different torrefaction conditions by Wang et al. (2012) ...................................................................................... 12
Table 2-3 Properties of torrefied and control pellets made from different size of pine samples by Peng et al. (2012) .......................................................................................... 14
Table 2-4 Ultimate analysis of untreated and torrefied biomass by Bridgeman et al. (2008) ......................................................................................................................... 15
LIST OF ABBREVIATIONS

e  correction in calories
EFB  empty fruit bunches
C  carbon
GHG  greenhouse gas
GW  Gigawatt
H  hydrogen
H_g  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
N  nitrogen
O  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
W_t  total mass of biomass

Subscripts

g  combustion
n  size of sieve tray
t  total mass
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 thicker-walled. 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.
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 renewable organic matters are shown in Figure 2-2. These organic materials have the potential to be used in the manufacturing of value-added eco-products (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 cost-competitive 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 m$^3$ of POME per year, with a potential to generate 1,587 GWh, with a capacity of 177 MW.

(c) Rice paddy cultivation
639,000 hectare 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 be; meanwhile 1.03 million tones of rice husk were produced with an energy potential of 3.04 million be. The total energy potential for rice straw and rice husk is 3.56 million be, 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 – 5.0 MW. SIRIM-Profass 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 hectare, 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). The 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)

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine chips (PC)</td>
<td></td>
</tr>
<tr>
<td>TPC-225 °C</td>
<td>6.69</td>
</tr>
<tr>
<td>TPC-250 °C</td>
<td>3.30</td>
</tr>
<tr>
<td>TPC-275 °C</td>
<td>2.88</td>
</tr>
<tr>
<td>TPC-300 °C</td>
<td>2.46</td>
</tr>
<tr>
<td>Logging Residue chips (LR)</td>
<td></td>
</tr>
<tr>
<td>TLR-225 °C</td>
<td>7.94</td>
</tr>
<tr>
<td>TLR-250 °C</td>
<td>3.11</td>
</tr>
<tr>
<td>TLR-275 °C</td>
<td>2.66</td>
</tr>
<tr>
<td>TLR-300 °C</td>
<td>2.36</td>
</tr>
</tbody>
</table>

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 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/m$^3$ at 250 °C to 698 kg/m$^3$ for temperature of 275 °C.
Table 2-2 Particle density of raw and torrefied sawdust at different torrefaction conditions by Wang et al. (2012)

<table>
<thead>
<tr>
<th>Torrefaction conditions</th>
<th>Particle density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated dry sawdust</td>
<td>1441 ± 25</td>
</tr>
<tr>
<td>250 °C, 42 min, 3% O₂; 30 wt%</td>
<td>1525 ± 18</td>
</tr>
<tr>
<td>270 °C, 25 min, 3% O₂; 31.5 wt%</td>
<td>1521 ± 33</td>
</tr>
<tr>
<td>270 °C, 24 min, 3% O₂; 29.8 wt%</td>
<td>1522 ± 22</td>
</tr>
<tr>
<td>290 °C, 4 min, 3% O₂; 30 wt%</td>
<td>1541 ± 31</td>
</tr>
<tr>
<td>290 °C, 7 min, 3% O₂; 36 wt%</td>
<td>1562 ± 50</td>
</tr>
<tr>
<td>270 °C, 12 min, 6% O₂; 31 wt%</td>
<td>1637 ± 31</td>
</tr>
<tr>
<td>270 °C, 30 min, 0% O₂; 36 wt%</td>
<td>1449</td>
</tr>
</tbody>
</table>

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 resulting from 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).
Pelletability

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/m$^3$ (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.

Figure 2-3 Grinding energy of beech and spruce at different torrefaction temperature by Repellin et al. (2010)
Table 2-3 Properties of torrefied and control pellets made from different size of pine samples by Peng et al. (2012)

<table>
<thead>
<tr>
<th>Items</th>
<th>control</th>
<th>250 °C 15 min</th>
<th>250 °C 30 min</th>
<th>300 °C 15 min</th>
<th>300 °C 30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial particle size: 0.23 mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellet density (kg/m³)</td>
<td>1210</td>
<td>1200</td>
<td>1180</td>
<td>1120</td>
<td>1120</td>
</tr>
<tr>
<td>Specific energy consumption (MJ/t)</td>
<td>27.5</td>
<td>37.9</td>
<td>40.8</td>
<td>51.2</td>
<td>55.9</td>
</tr>
<tr>
<td><strong>Initial particle size: 0.67 mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellet density (kg/m³)</td>
<td>1230</td>
<td>1250</td>
<td>1240</td>
<td>1170</td>
<td>1160</td>
</tr>
<tr>
<td>Specific energy consumption (MJ/t)</td>
<td>26.7</td>
<td>35.4</td>
<td>35.3</td>
<td>41.2</td>
<td>42.9</td>
</tr>
<tr>
<td><strong>Initial particle size: 0.81 mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellet density (kg/m³)</td>
<td>1230</td>
<td>1200</td>
<td>1170</td>
<td>1140</td>
<td>1120</td>
</tr>
<tr>
<td>Specific energy consumption (MJ/t)</td>
<td>28.2</td>
<td>53.0</td>
<td>62.6</td>
<td>75.6</td>
<td>78.1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Raw</th>
<th>Torrefaction temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>503</td>
</tr>
<tr>
<td><strong>Red canary grass</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (%)</td>
<td>48.6</td>
<td>52.2</td>
</tr>
<tr>
<td>H (%)</td>
<td>6.8</td>
<td>6.0</td>
</tr>
<tr>
<td>N (%)</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>O (%)</td>
<td>37.3</td>
<td>37.3</td>
</tr>
<tr>
<td><strong>Wheat straw</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (%)</td>
<td>47.3</td>
<td>51.9</td>
</tr>
<tr>
<td>H (%)</td>
<td>6.8</td>
<td>6.1</td>
</tr>
<tr>
<td>N (%)</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>O (%)</td>
<td>37.7</td>
<td>33.2</td>
</tr>
<tr>
<td><strong>Willow</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (%)</td>
<td>49.9</td>
<td>51.7</td>
</tr>
<tr>
<td>H (%)</td>
<td>6.5</td>
<td>6.1</td>
</tr>
<tr>
<td>N (%)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>O (%)</td>
<td>39.9</td>
<td>38.7</td>
</tr>
</tbody>
</table>

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.
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).