PRODUCTION OF BIO-OIL FROM SAWDUST AND OIL PALM FRONDS BIOMASS USING GAS FIRED PYROLYSIS SYSTEM

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THE STUDY ON PRODUCTION OF BIO-OIL FROM SAWDUST AND OIL PALM FRONDS BIOMASS USING GAS FIRED PYROLYSIS SYSTEM

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A thesis is submitted in fulfillment of the requirements

for the award of the degree of

Bachelor in Chemical Engineering (Gas Technology)

Faculty of Chemical and Natural Resources Engineering

UNIVERSITI MALAYSIA PAHANG

JANUARY 2012

SUPERVISOR DECLARATION

“I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor in Chemical Engineering (Gas Technology)

Signature

Name of Supervisor:

Position:

Date:

STUDENT DECLARATION

I hereby declare that the work in this thesis entitled “The Study on Production of Bio-oil from Sawdust and Oil Palm Fronds Biomass using Gas Fired Pyrolysis System” is the results of my own research accept as cited in references. This thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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ACKNOWLEDGEMENTS

I would like to take the opportunity to recognize several people who had a considerable influence on my ability to complete this study. Therefore without people who aided me, the thesis might not complete.

Firstly, I have readily acknowledged and thank to Allah, The Omnipotent and Omniscient who created everything and giving me the ability to start and complete this study. I would like to express my sincere gratitude to my supervisor Dr. Iqbal Ahmed for his germinal ideas, invaluable guidance, continuous encouragement and constant support in making this thesis possible. He has always impressed me with his outstanding professional conduct and strong conviction. I am truly grateful for his tolerance of my youthful mistakes and co–operation throughout the study. I also sincerely thanks for the time spent proof reading and correcting my mistakes.

My sincere appreciation also extends to all my friends in University Malaysia Pahang and members of the staff of Chemical Engineering Department, UMP who have provided assistance at various occasions. Their views and tips are useful indeed. I thank all of them, who are too numerous each of them individually.

Last but not least, I want to thank to my family especially my lovely mother Puan Zarah binti Hassan and my father Encik Ismail bin Musa for their moral support throughout my study. I would not value my education so had my parents not sacrificed so much to give it to me.

ABSTRACT

Fast pyrolysis of biomass is the most promising technology of exchanging solid biomass to liquid bio-oil as a renewable substitution of fossil resources in fuel and chemical feedstock'spurposes. Malaysia with abundant biomass resources allows an ideal platform for the growth of this thermal conversion technology. Biomass fast pyrolysis is rapidly developing interest in Malaysia as it is considered to offer efficient logistical and hence economic advantages over other thermal conversion process. In this study, pyrolysis of sawdust and oil palm fronds were investigated under various heat distribution and pyrolysis temperature in gas fired reactor. The heat distribution was done in different setting of fuel and air of gas burner. The setting are 16mbar of fuel with 7.5 air, 19mbar of fuel with 2.5 air and 19mbar of fuel with 5.0 air. The best setting of fuel and air ratio is the setting 19mbar of fuel with 2.5 air ratio where it give shortest time to reach 400^{o}C of the temperature of the reactor. The temperatures of pyrolysis were varied in range of 400^{o}C-600^{o}C. The products obtained from pyrolysis of waste furniture sawdust and palm oil stem were bio-oil, char and gas. The maximum bio-oil yield was obtained at temperature 500^{o}C. This study provides better insight on heat distribution and temperature of the reactor.

ABSTRAK

Proses pirolisis biojisim merupakan teknologi yang menjanjikan pertukaran biojisim daripada pepejal kepada cecair yang boleh diperbaharui sebagai bahan ganti sumber fosil dalam bahan api dan sebagai bahan mentah kimia. Malaysia sebagai sebuah negara yang mempunyai banyak sumber biojisim menyediakan platform ideal untuk pertumbuhan teknologi penukaran terma ini. Proses pirolisis biojisim di Malaysia semakin pesat membangun dimana ia dianggap menawarkan kelebihan logistik yang cekap dan dengan itu memberi kelebihan ekonomi atas proses pengubahan terma lain. Dalam kajian ini, pirolisis habuk kayu dan pelepah pokok kelapa sawit telah disiasat di bawah berbagai-bagai pengedaran haba dan suhu dalam reaktor pirolisis. Pengedaran haba telah dilakukan pada persekitaran bahan api dan udara penunu gas yang berbeza. Persekitaran ditetapkan pada 16mbar bahan api dengan 7.5 udara, 19mbar bahan api dengan 2.5 udara dan 19mbar bahan api dengan 7.5 udara. Persekitaran terbaik bahan api dan pengudaraan adalah pada persekitaran 19mbar bahan api dengan 2.5 udara dimana ia memberi masa terpantas untuk mencapai suhu reaktor pada 400^{o}C. Suhu-suhu pirolisis diubah dalam julat 400^{o}C hingga 600^{o}C. Produk-produk yang diperolehi daripada proses pirolisis habuk kayu dan pelepah pokok kelapa sawit merupakan minyak, arang dan gas. Hasil minyak maksimum telah diperolehi pada suhu 500^{o}C. Kajian ini menyediakan wawasan yang lebih baik keatas pengedaran haba dan suhu reaktor.

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The challenge to overcome the decimation of fossil fuels especially the petroleum based fuels is the critical issue of this century. Petroleum fuels have been considered as a key component in the crucial energy and natural resources sector which drives the economic progress. Almost the human activities depend heavily on this physical resource. Aside from transportation and power generation, mass quantities of petroleum and petroleum derived chemicals are necessary for manufacturing, food processing, medicine and all other industries as raw materials and fuels. Nature may have been kind to human but the size of these physical mineral resources is limited. All the reservoirs that exist in this planet will be recovered sooner or later (Lim Xin Yi, 2008 and Mabro, 2003). Although International Energy Agency (IEA, 2004) reported that the Earth's petroleum resources are more than sufficient to meet demand until 2030 and well beyond, they also pointed out that there would be uncertainties about how much it will cost to extract them and deliver them to consumers. In other word, oil reserves are not running out but it will become more difficult and expensive to recover it without any significant breakthrough in extraction tecnology or discovery of new oil feilds.

In the decimation of petroleum and the increasing of demand for alternative resources, biomass is receiving higher attention as it is one of the most available renewable energy resources that can be use to decrease the dependency on fossil resources (Lim Xin Yi, 2008 and Williams et. al., 2000). Agricultural waste is one form of the biomass which is generated consistently in large amount from the agriculture activities. Some of these agricultural wastes are be used as fuel for energy recovery scheme to generate the heat and electricity required for the milling processes. However, theuseage of biomass for energy conversion through combustion is still regarded limited due to its poor fuel properties such as high moisture, ash contents, low bulk density and low energy content. These properties leading to difficulties in storage, handling and transport which restrictions the biomass application as commodity fuels. Exceed biomass yielded not only created waste disposal problems but also regarded as waste of primary resources.

Biomass iswidely considered as a sustainable source of renewable energy particularly in countries where is plentiful agricultural activities.The use of these materials will depend on a safe state of the art, economics and technologies that are used to transform them into manageable products (Sensoz et.al,2006). Over the last two decades,special attention to the conversion of residual biomass and renewable materials into bio-oil. Bio-oil is renewable and biodegradable. Moreover, it does not contribute to a net rise in the level of CO_2 in the atmosphere and consequently to the greenhouse effect. Energy production can be produced from biomass in several ways from old direct burning to modern gasification and fast pyrolysis. For the recovery of maximum energy from a particular biomass, the technically and economically viable process should be selected (H.L.Chum and R.P. Overend,2001). By direct combustion, the biomass will completely transformed into heat which only 10-15% is effectively heated the target. Thus the commercial energy production by this process is not economically viable at present. The fast pyrolysis and gasification are the modern techniques for the conversion of biomass into combustible liquid (pyrolysis oil) and gaseous fuels.

Pyrolysis is one of the most promising technologies for biomass utilization (Bridgwater et.al,1999; Kawaser et.al,2004) , which converts biomass to bio-oil, char and gases depending on the pyrolysis conditions. Pyrolysis can be described as a thermal degradation of materials in the complete absence or inadequate presence of oxygen. Pyrolysis oil can be used for the production of renewable or sustainable energy and chemicals (D.R. Huffman et.al,1995).An ages ago, it was used to produce charcoal from wood for heating and smelting metals from various ores. Charcoal for barbecues has been produced on a small scale in Malaysia at present time. Modern pyrolysis technology is developing for the maximum liquid production instead of merely charcoal and coke. Pyrolysis processes offers several options for upgrading biomass to increase the overall applicability of biomass for large scale production. The amount and nature of the end products of pyrolysis will depend on the operating temperature, the heating rate, the residence time and the compositions of the biomass.

Malaysia is blessed with abundant natural resources and bears a favorable climate for commercial cultivation of crops such as oil palm.Agriculture and forest products industries produce food, feed, fiber and a wide range of require products like shelter, packaging, clothing and communications. Yet, biomass is also a source of a many variety of chemicals and materials and of electricity and fuels (Chum and Overend, 2001). In Malaysia, the organic or naturalwastes were available almost free-of-charge andcontributes towards the environmentally cleandisposal of organic or natural waste.

In the wood based industry, the removal of wood waste isan important activity where it can gives a certain extentaffects the productivity and profitability of the milloperation. In a typical Malaysian sawmill, the waste are loaded in a specially constructed bin or rack andremoved by forklift to the waste collection site orincinerator. In sawmilling, the sawdust generated is approximately 8% of the total volume of log input. Generally it is assume that the volume of sawdust is about three timesthe volume of wood which it is made up of. The rate of sawdust being generated is about 18m^3/day.

In Malaysia the overall plantation area of oil palm was 4,487,957 ha in 2008. It has been reported that in 2005 there was 423 palm oil mills having production capacity of approximately 89 million tonnes of fresh fruit bunches per year (R.P.Singh et.all, 2010) .Oil palm solid wastes are low-priced and abandonedmaterials formed in palm oil milling process.About 80%of solid wastes are used as boiler fuel in industrywhile the remaining 20% are abandoned (Pensamut et.al,2003). It isalso estimated that approximately 1.18 x 106 tons oforganic waste was produced from the palm oil mills.

1.2 Prolem Statement

World today is facoused on renewable energy to replace fossil fuel sources. Pyrolysis process is one of the method that being used to produced renewable energy.

The conversion of heat to the pyrolysis system is an important aspect for the heat distribution. Based on the previous study, using electricity for heating is not efficient because the energy conversion of heat by electricity will only have 40% of efficiency.

Temperature of the pyrolysis process can give effect to the yields of pyrolysis products. At different temperature, the yield of liquid, gas and char will be varies.

1.3 Statement of Objectives

The objectives of the research is to find the best setting of fuel and air ratio that can achieve the pyrolysis process temperature in the shortest time.Other objectives is to study the maximum yield of bio-oil pruduct from the pyrolysis of sawdust and oil palm fronds.

1.4 Scope of the Study

This research mainly focuses on

1. Run the experiment on the system with different setting of fuel and air of gas burner.
2. Find the best fuel and air setting that can achieve the pyrolysis process temperature in the shortest time.
3. Run the experiment on two difference raw material that is sawdust and oil palm fronds at difference temperature.
4. Find the maximum yield of bio-oil and the best temperature.

1.5 Rationale and Significance

During the research, knowledge about the production of bio-oil from the pyrolysis process can be gained. Besides, the heat distribution of the gas fired pyrolysis system can be learn. The technical elements on controlling and handling the equipment such as gas burner also can be gain in this research.

Therefore, experiment to get the optimum setting of fuel and air setting of gas bernur also being run. The experiment cover on the gas burner with controlling the setting of the fuel and air setting and make sure that the temperature in the furnace nad reactor achieve the pyrolysis process temperature in the shortest time.Other than that, there are several experiments have been run such as eperiment to get the maximum bio-oil yeild for sawdust and oil palm fronds. The experiment cover on the maximum production of bio-oil and the best temperature to obtain maximum bio-oil yeild.

Hence, in the end of the experiments, the best setting of fuel and air of gas burner can be selected. Also,the maximum bio-oil yeild can be calculate and the best temperature can obtain. So, after all the aspects covered, it will accomplish this research well.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concern over the global warming and finite fossil fuel reserves have led to the realisation that a more enviromentally friendly, flexible transport infrastructure is required. While solutions with efficiencies that surpass the current combustion engine are likely to be developed, this will take time, and furthermore current consumer preferences favour liquid alkane fuels (Alonso DM *et al*,2010).Biofuels are seen as the possible solution for this problems. Global production of biofuels has increased rapidly to 83 billion litres in 2008, but still retains a small share of the transport fuel market (IEA,2009).The first generation biofuels have encountered significant criticisms over their ability to achieve meaningful substitution, climate change mitigation and economic growth. While more advanced second generation technologies do not completely overcome these problems, they are none-the-less expected to become at least a part of the solution in the shift from fossil resources in the short to medium term (IEA,2010 & Sims REH *et al*,2008). It is expected that second generation biofuels will be produced under commercially viable conditions between 2015 and 2020 (Sims REH *et al*,2008). Such technologies can be classified as biochemical or thermochemical.It is has been suggested that biochemical and thermochemical technologies could be employed synergistically in integrated biorefineries with the added benefit of increased flexibility and efficiency (Jae J *et al*,2010).Thermochemical processes depend on the relationship between heat and chemical action as a means of extracting and creating products and energy. Main biomass thermochemical conversion processes are pyrolysis, gasification, and liquefaction.Figure 2.1 shows the main biomass thermochemical conversion processes.

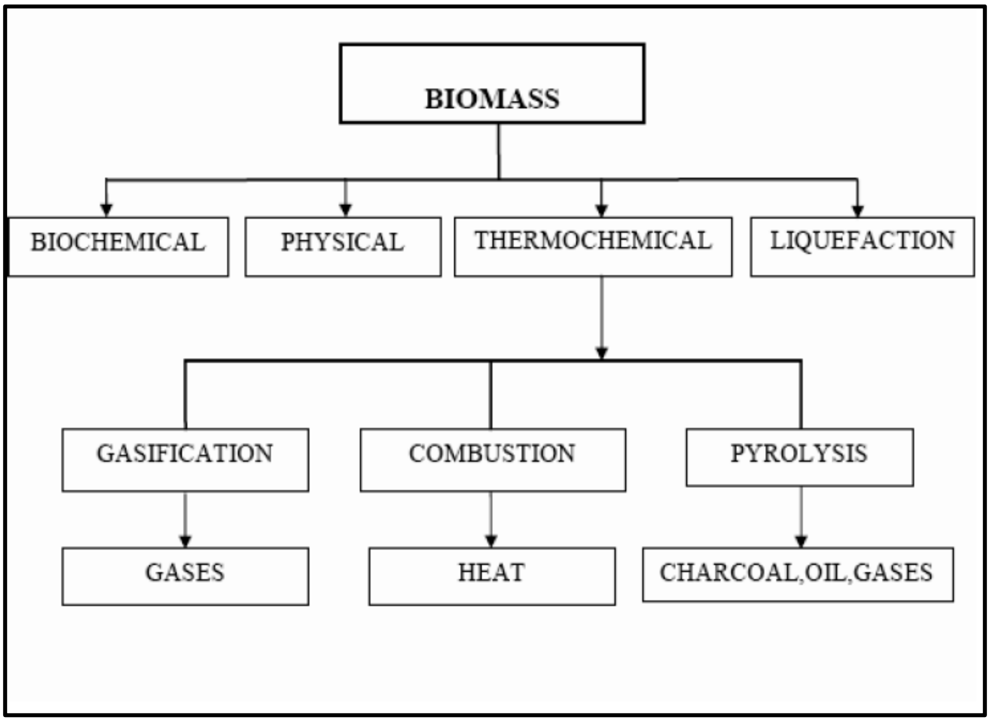


Figure 2.1 : The Main Type and Process of Biomass

(Ani 2006)

2.2 Biomass

Biomass consist of all the living matter present on the earth. It is derived from growing plants including algae, trees and crops or from animal manure (Bridgewater,1999). The biomass resources are the organic matters in which the solar energy is stored in chemical bonds. It generally consists of carbon, hydrogen, oxygen and nitrogen. Sulfur also present in minor proportions and some biomass also consist significant amounts of inorganic species. Plants, via photosynthesis, produce carbohydrates which form the building blocks of biomass (Demirbas,2001). Through photosynthesis process, biomass absord and stored the energy from the sun. The chemical energy in plants gets passed on to animals and people when they eat the plants. Biomass is a renewable energy source because trees and crops will always grow day by day and the waste will always exist. Wood, crops, manure and some garbage are some examples of biomass.

Biomass is part of the carbon cycle, where carbon in the air is converted into a biological matter using photosynthesis. Biomass is seen as more environmentally friendly and longer lasting than traditional fossil fuels. Another significant advantage of biomass over fossil fuels is that the biomass sourcescan be grown almost anywhere in the world and suitable for producing biomass and bio-fuel. Fossil fuels like petrol or gas and other traditional fuel types are only produced in certain areas of the world and takes long time to produced.

In Malaysia, biomass is one of the most important potential sources of renewable energy. Biomass resources are available from palm oil plantations, forestry and wood industry, rice husk and several other agricultural sources and agro-industries. Presently the largest fraction of solid biomass fuels is used as a boiler fuel in palm oil industry, but also to some extent in wood industries, rice mills and sugar mills (Anders Evald et al., 2005). The present utilization of solid biomass fuels takes place in industries, that have direct access to the biomass and who are used to handling large volumes of the products.

2.3 Type of Biomass

Biomass can be split into two distinct categories:

a. Waste Biomass
b. Energy Crops

Each will give different range of product either liquid, gas and char. Physical conversion involved densification more easily handled such as briquettes particles, palletized fuel and fuel logs. These involve extrusion process of biomass particles with or without binder at higher pressure and later carbonized to obtain charcoal material (Ani, 2006).

2.3.1 Waste Biomass

2.3.1.1 Forestry Residue

Forestry residues include biomass that is not harvested or removed from logging sites in commercial forests as well as material resulting from forest management operations such as pre-commercial thinnings and removal of dead and dying trees.Wood is the most commonly used biomass fuel for heat and power generation. Using these materials for electricity generation recovers their energy value while avoiding landfill disposal.Forestry waste includes logging residues, imperfect commercial trees, dead wood and other non-commercial trees that need to be thinned from crowded, unhealthy and fire-prone forests.

2.3.1.2 Animal Farming

Farm slurries is on of the example for animal farming. Farm slurry is a watery animal sewage containing a high concentration of suspended solids. Farm slurries are obtained mainly from pig farming and cattle farming. Several options for collecting and storing swine manure are available, depending on the manure form. Common storage methods include underfloor pits, outdoor structures, earthen pits, lagoons and holding ponds.The techniques for cattle farming is significantly affect the quantity and quality of manure that may be delivered to the anaerobic digestion system. The number of cows, the housing, transport, and bedding systems used by the farms determines the amount of slurry that must be used and therefore the amount of energy produced.The type of housing used determines the quantity and quality of manure that can be econom ically collected.

2.3.1.3 Organic Municipal Solid Waste (MSW)

Organic MSW is any matter collected from commercial or residential properties such as food waste, paper and others.

2.3.1.4 Slaughterhouse and Fishery Waste

At a slaughterhouse or a fish processing plant, there is a huge amount of organic waste. This has the possibility of being a danger to the environment and human or animal health.

2.3.1.5 Sewage Waste

Sewage waste is a source of biomass that is comparable to the other animal wastes previously mentioned. Energy can be extracted from sewage using anaerobic digestion, pyrolysis or drying and incineration.

2.3.2 Energy Crops

2.3.2.1 Short Rotation Coppice (SRC)

SRC is a densely planted, high-yielding varieties of either willow or poplar, harvested on a 2 to 5 year cycle, although commonly every 3 years. SRC is a woody, perennial crop, the rootstock or stools remaining in the ground after harvest with new shoots emerging the following spring. A plantation could last up to 30 years before re-planting becomes necessary.

2.3.2.2 Pellets

Pellets are a refined, solid fuel biomass with a low moisture content, which makes it easy to transport, store and convert into energy. It is manufactured from saw dust, wood chips, shaving or bark. Pellets are typically 6-8mm in diameter and 5-30 mm long. The maximum water content is 8%.The following list contains the main advantages of using pellets:

a. Pellets burns almost without any smoke development. The dust in the flue gas is very basic.
b. The ash produced is basic.
c. Less carcinogens are produced in the high temperature combustion of pellets compared with unrefined fuel.
d. It has a low heavy metal content.
e. Only small quantities of NOX oxides are formed.

2.3.2.3 Woodchips

The term woodchips refers to mechanically processed wood particles, ranging in size from 1 to 100 mm. The criteria used for woodchip quality are as follows:

a. Chip size: only the "fine" (smaller than 30 mm) and "medium" grades (below 50 mm) are suitable for small-scale installations;
b. Water content: this determines the energy content of the fuel on the one hand and its storability on the other;
c. Bulk density: this indicates the weight per cubic metre (bulk volume) and depends on wood type, particle shape, degree of compaction and water content.

2.4 Biomass Utilization

Biomass has always been a major source of energy for mankind from ancient times. Presently, it contributes around 10–14% of the world’s energy supply (Putun AE,et al., 2001). Biomass can be converted into three main types of products:

a. Electrical or heat energy.
b. Fuel for transport sector.
c. Feedstock for chemicals.

Traditionally, biomass had been utilized through direct combustion. Burning biomass produces pollutants including dust and the acid rain gases such as sulfur dioxide and nitrogen oxides but the sulfur dioxide produced is 90% less than that is produced by burning coal. The quantities of atmospheric pollution produced are insignificant compared to other pollution sources. Biomass usage as a source of energy is of interest due to the following envisaged benefits:

1.Biomass is a renewable, potentially sustainable and relatively environmentally friendly source of energy.
2. A huge array of diverse materials, frequently stereo chemically defined, are available from the biomass giving the user many new structural features to exploit [Bozell Joseph J, 1999].

3. Increased use of biomass would extend the lifetime of diminishing crude oil supplies.
4. Biomass fuels have negligible sulfur content and, therefore, do not contribute to sulfur dioxide emissions that cause acid rain.
5. The combustion of biomass produces less ash than coal combustion and the ash produced can be used as a soil additive on farms, etc.
6. The combustion of agricultural and forestry residues and municipal solid wastes (MSW) for energy production is an effective use of waste products that reduces the significant problem of waste disposal, particularly in municipal areas.
7. Biomass is a domestic resource which is not subject to world price fluctuations or the supply uncertainties as of imported fuels.
8. Biomass provides a clean, renewable energy source that could improve our environment, economy and energy securities [Othmer K, 1980].
9. Biomass usage could be a way to prevent more carbon dioxide production in the atmosphere as it does not increase the atmospheric carbon dioxide level.

Biomass can be used in many ways to obtain energy. Most of the biomass energy is consumed in domestic purposes and by wood-related industries. It is burned by direct combustion to produce steam that drives the turbine or generator to produce electricity. Gasifiers are used to convert biomass into a combustible gas which is then used to drive a high efficiency, combined cycle gas turbine. Biomass is converted to pyrolysis oil byheating. Pyrolysis oil is easier to store and transport than solid biomass material and is burned like petroleum to generate electricity.

2.5 Biomass in Malaysia

Today, about 80% of Malaysia’s total population lives in Peninsular Malaysia, the hub of the country’s economic activities. Like many other developing countries, energy has been the prime contributor towards the rapid growth of Malaysia’s economy. Malaysia is looking forward in industrial and development sector that need sustainable energy resources.

The available fossil fuels sources now only can survive for another 20 to 30 years (Hisyam, 2006). Malaysia is the largest producer and exporter of palm oil in the world, accounting for 30% of the world’s traded edible oils and fats supply. 3.88 million hectares of land in Malaysia is under oil palm cultivation producing 14 million tonnes of palm oil in 2004 (Jessada, 2007).

Malaysia government need fully supports re-biomass based power generation through various initiative and promotion program such as biogen since biomass resources is big potential for Biomass Power Co-Generation and beside that Malaysia can develop and expend the market profitability through new technology and lower production cost to overcome the challenges (Hamdan, 2004).

Energy has contributed significantly towards the rapid growth of the Malaysia economy. Energy supply infrastructure needs to be more continuously developed and being very capital intensive, it will impose tremendous pressure on the depleting resources. Successful implementation of this biomass utilization would provide the oil palm industry with an additional substantial income of over RM30 billion per year in addition to the current RM15 billion per year from the oil and its derivatives speech from Minister of Primary Industries, Dato' Seri Dr. Lim Keng Yaik in the launched the Biomass Technology Centre (BTC) and the Farm Mechanization Centre (FMC) of the Malaysian Palm Oil Board (MPOB) in Bangi, Selangor, on 5 February 2002.

Furthermore, compare to the cost of fossil fuels that increasing by year in Malaysia, there is a strong reason to produce gases using cheaper raw material. As biomass is created by plants absorbing $CO_2$from the air, releasing this CO_2 when oxidizing biomass does not lead to a net increase in greenhouse gas (GHG) emissions if biomass is produced in a sustainable manner. Carbon dioxide has been targeted as the greenhouse gas.

Other gases, such as chlorofluorocarbon (CFC's) and nitrous oxide offer far larger positive feedbacks to global warming than carbon dioxide. The concern, however, is over the extreme levels of carbon dioxide concentration in the atmosphere, which adds immensely to the problem of global warming. Considering this factor, offsets such as this would help to significantly reduce atmospheric concentrations of carbon dioxide. This burning biomass can be used a conventional power plant built solely for the biomass is another option.

For the past decade Malaysia is dealing with serious environmental problem. The serious pollutions that occur in Malaysia are air pollution that which mainly causes by transportation and factories. Disadvantages of fossil fuel derived transportation fuels beside others problem such as greenhouse gas emissions, pollution, resource depletion adn unbalanced supply demand relations are strongly reduced or even absent with bio transportation fuels.

2.6 Biomass Technologies

There are some technologies that can convert biomass into energy and higher product value. The biochemical process leads to anaerobic digestion to produce gases and alcohol fermentation to produce ethanol. For non-biological process, it refer to thermal conversion which the main of it is converting solid waste into energy and by-product are gasification, combustion, pyrolysis and liquefaction.

Each will give different range of product either gas, solid or liquid. Physical conversion involved densification where it is more easily handled such as briquettes particles, palletized fuel and fuel logs. These involve extrusion process of biomass particles with or without binder at higher pressure and later carbonized to obtain charcoal material [Ani, 2006].

2.6.1 Liquefaction

Thermochemical liquefaction is a process similar to what occurs in nature. Only, it occurs in minutes rather than millions of years.Hydrocarbon oils and products to produce bio-fuels are the result of subjecting intense heat and pressure to organic material.Utilization of bio-oil from biomass liquefaction is given in Figure 2.2. In the case of liquefaction, feedstock macromolecule compounds are decomposed into fragments of light molecules in the presence of a suitable catalyst.Direct liquefaction of wood by catalyst was carried out in the presence of K_2CO_3 (Ogi *et al.*, 1985). Modern development of the process can be traced to the early work at the Bureau of Mines as an extension of coal liquefaction research (Appell *et al.*, 1971). Indirect liquefaction involves successive production of an intermediate, such as synthesis gas or ethylene, and its chemical conversion to liquid fuels.The heavy oil obtained from the liquefaction process was a viscous tarry lump, which sometimes caused problems during handling. For this purpose, some organic solvents were added to the reaction system. Among the organic solvents tested, propanol, butanol, acetone, methyl ethyl ketone, and ethyl acetate were found to be effective on the formation of heavy oil having low viscosity (Demirbas, 2000c).

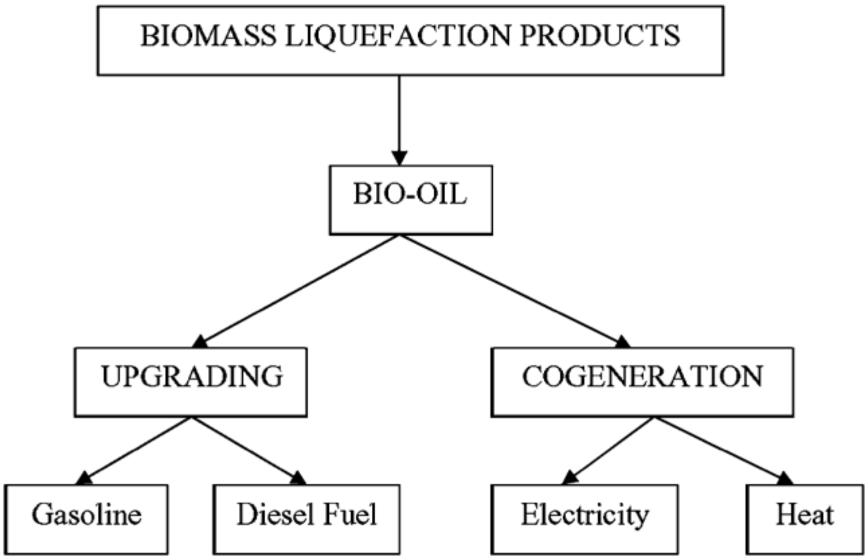


Figure 2.2 : Utilization of bio-oil from biomass liquefaction

(A. Dermibas, 2007)

2.6.2 Gasification

Biomass gasification is a process that converts carbonaceous biomass into combustible gases such as H_2 , CO, CO_2 and CH_4. Gasificationwas perfomed at high temperature range of 700–1000°C with a controlled amount of oxygen or steam where it is considered as partial oxidation. Products of gasification cannot be stored easily.Most biomass gasification systems utilize air or oxygen in partial oxidation or combustion processes. These processes suffer from low thermal efficiencies and low calorific gas because of the energy required to evaporate the moisture typically inherent in the biomass and the oxidation of a portion of the feedstock to produce this energy. The resulting gas mixture is called synthesis gas or syngas. This conversion process is expressed as:

$$\text{Biomass + heat} \longrightarrow H_2 + CO + CO_2 + CH_4 + \text{hydrocarbon + char}$$

The oxidant agent for gasification can be air, hydrogen, steam, CO_2 or their mixtures. Air is a cheap and widely used as a gasifying agent containing a large amount of nitrogen which reduces the heating value of the syngas produced (Wang L *et al*,2008). Usage of oxygen as a gasifying agent couldproduce a better quality syngas of medium heating value, but it requires a pure oxygen supply which leads to simultaneous problem of cost and safety (Ni M *et al*,2006). The use of CO_2 as the gasifying agent is promising because of its presence in the syngas. CO_2 with a nickelbased catalyst can convert char, tar and CH_4 into H_2or CO, thus leading to higher amount of H_2 and CO contents in the syngas produced (Gil J *et al*,1999). If steam is used as the gasifying agent, the heating value and H_2 content in the syngas can be increased, however the operational costs will also be increased due to the demand for an external heat source for steam production (Rapagna S *et al*, 1999).

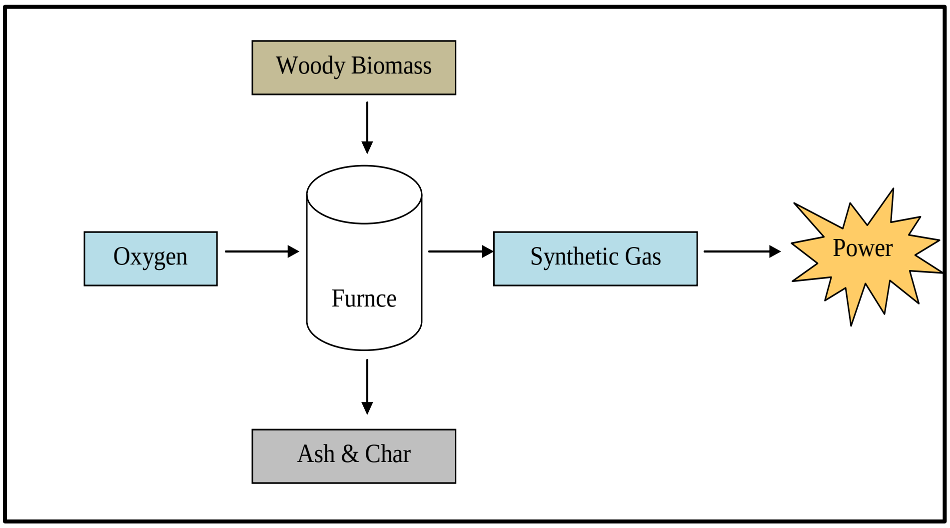


Figure 2.3: Gasification shcematic

During the gasification process a number of exothermic andendothermic reactions take place. Heating and drying are endothermicprocesses, requiring a source of heat to drive them. This heat can be supplied by an external source in a process called indirectly heated gasification. A small amount of air or oxygen is admitted for the purpose of partial oxidation, which releases sufficient heat for drying and pyrolysis as well as for the subsequent endothermic chemical reactions. During gasification, physical, chemical and thermal processes may take place sequentially or simultaneously, depending on the reactor design and the feedstock.

2.6.3 Combustion

Almost anything organic will burn. However, biomass having a lowmoisture content is best suited for combustion. Combustion refers to the rapid oxidation of the feedstock as it is exposed to high heat. Combustion is the most widely used process for biomass conversion. It contributes to over 97% of bioenergy production in the world. In some less-developed countries, combustion of traditional biomass plays an important role in people's daily lives as it is the main source of energy available for cooking and heating. Regarded as a proven low cost but highly reliable technology, combustion is relatively well understood and commercially available (Demirbas,2009 & EIA,2009). There are three main stages that occur during biomass combustion that are drying, pyrolysis and reduction, and combustion of volatile gases and solid char (IEA,2009). The combustion of volatiles gases contributesto more than 70% of the overall heat generation. It takes place above the fuel bed and is generally evident by the presence of yellow flames. Char is combusted in the fuel bed and is noted by the presence of small blue flames (IEA,2009 & Quaak P *et al*,1999). The combustion of biomass on a large scale is still considered to be a complex process with technical challenges associated with the biomass fuel characteristics, types of combustorsand the challenges of co-firing processes.Most of today's biomass-powered plants are direct-fired systems, similar to fossil fuel-powered plants.The feedstock is burned in a boiler to produce high-pressure steam that is then pumped into a turbine then a series of blades that rotate that will be powering an electric generator.

Combustion and gasification has a different concept. Generally, combustion focuses on heat generation,whereas gasification is to create valuable gaseous products that can be used directly for combustion or to be stored for other applications. In addition, gasification is considered to be more environmentally friendly because of it lower emissions of toxic gases into the atmosphere. Rezaiyan and Cheremisinoff has been provided a detailed comparison between biomass gasification and combustion and it has been summarize in Table 2.1.

Table 2.1: Comparison of Gasification and Combustion

Features	**Gasification**	**Combuation**
Purpose	Creation of valueable, environmetal friendly, useable products from waste or lower material value	Generation of heat or destruction of waste
Process Type	Thermal and chemical conversion using no or limited oxygen	Complete combustion using excess oxygen (air)
Raw Gas (Composition before clean-up)	H_2, CO, H_2S, NH_3 and particulates	CO_2, H_2O, SO_2, NO_x and particulates
Gas Cleanup	Syngas cleanup at atmospheric to high pressure depending on the gasifier design. Treated syngas used for chemical, fuels or power generation. Recovers sulphur species in the fuel as sulphur or sulphuric acid.	Flue gas cleanup at atmospheric pressure. Treated flue gas is discharged to atmosphere. Any sulphur in the fuel is converted to SO_2 that must be removed using flue gas primarily consists of CO_2, and H_2O.
Solid byproducts/products	Char or slag	Bottom and fly ashes
Ash/char or slag handling	Low temperature processes produced a char that can be sold as fuel. High temperature processes produce slag, a non-leachable, non-	Bottom ash and fly ash are collected, treated and disposed as hazardous waste in most cases or can be sold as a material for making concrete

	hazardous material suitable for use as construction materials. Fine particulates are recycled to gasifier. In some cases, fine particulates may be processed to recover valueable metals.	
Pressure	Atmospheric to high	Atmospheric

(Rezaiyan J & Cheremisinoff NP,2005)

2.6.4 Pyrolysis

Pyrolysis is the process of rapid thermal decomposition of biomass in the absence of oxygen. This process produces energy, liquids, gases and char. Small particles, less than a quarter inch, are delivered to a highheat reactor where essentially no combustion occurs. The fuel must be small enough to assure high heat transfer rates during the process. At about 500 degrees Celsius, the material is transformed into a vapor. In turn, it is cooled, condensed and recollected as a liquid bio-oil. Gases that are non-condensable are recycled in a reactor for co-firing, while the char is removed for fuel or used as a commercial product. To ensure a high yield of bio-oil, the processing time from introducing the feedstock to quenching is typically less than two seconds, thus the name fast pyrolysis. Figure 2.4 shows the pyrolysis schematic.

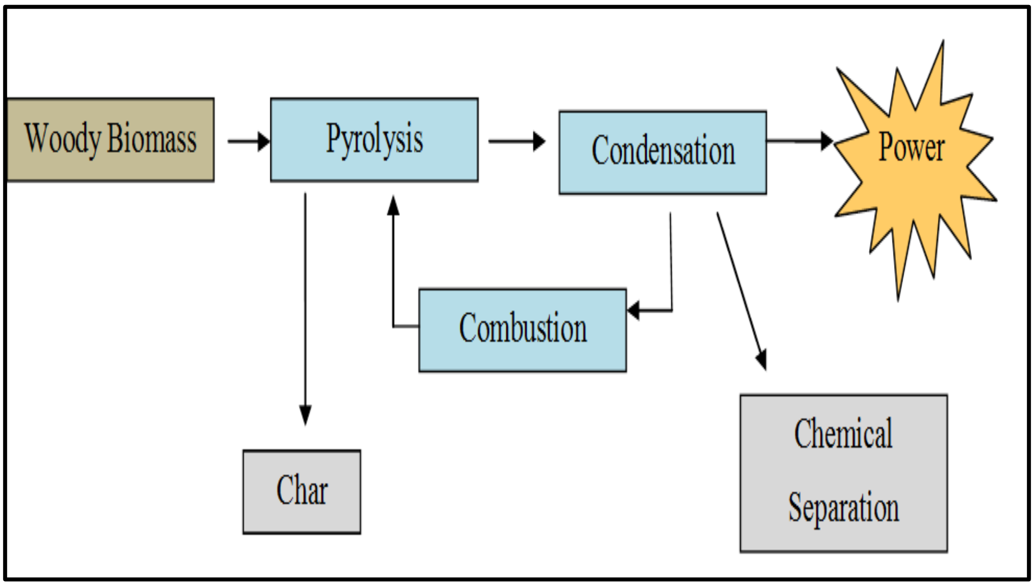


Figure 2.4: Pyrolysis schematic

2.7 Introduction of Pyrolysis

Pyrolysis is one of the most promising thermo chemical conversion routes to recover energy from biomass. During pyrolysis, biomass is thermally decomposed to solid charcoal, liquid oil and H2-rich gases under an oxygen absence condition. The yields of end products of pyrolysis and the composition of gases are dependent on the several parameters including temperature, biomass species, particle size, heating rate, operating pressure and reactor configuration.

Pyrolysis is a thermal degradation of the organic matrix in absence of oxygen to obtain an array of solid, liquid and gas [Serdar yarman, 2003]. Pyrolysis utilized heat either directly or indirectly in order to decompose waste material. Pyrolysis is usually endothermic reaction and also occurs at high temperatures. In this study, equilibrium modeling is introduced to outline the distribution of gaseous species, as a function of temperature.

There are different types of pyrolysis technology with their residence times, heating rates, operating temperature and major product. Of the various pyrolysis technologies available, fast pyrolysis seems to havethe highest potential to be explored and developed. Pyrolysis conversion process is defined as thermal degradation of biomass without complete combustion that is in the absence of air or with very limited amount of oxidizing agents. From the process, three main products formed, the char (solid), pyrolytic oil (liquid) and gaseous fuel. The oil palm shell char could be used to make activated carbon for water treatment and gas adsorbent materials.

2.8 Principles of Pyrolysis

Fast pyrolysis is a high temperature process in which biomass is rapidly heated in the absence of oxygen. In fast pyrolysis, biomass decomposes very quickly to generate mostly vapours and aerosols and some charcoal and gas. After cooling and condensation, a dark brown homogenous mobile liquid is formed which has a heating value about half that of conventional fuel oil. A high yield of liquid is obtained with most biomass feeds low in ash. The features of a fast pyrolysis process for producing liquids are very high heating rates and very high heat transfer rates atthe biomass particle reaction interface usually require a finely ground biomass feed of typically less than 3 mm as biomass generally has a low thermal conductivity, carefully controlled pyrolysis reaction temperature of around 500^{o}C tomaximise the liquid yield for most biomass, short hot vapour residence times of typically less than 2s to minimise secondary reactions, rapid removal of product char to minimise cracking of vapours and rapid cooling of the pyrolysis vapours to give the bio-oil product.

As fast pyrolysis for liquids occurs in a few seconds or less, heat and mass transfer processes and phase transition phenomena and chemical reaction kinetics play an important roles. The critical issue is to bring the reacting biomass particles to the optimum process temperature and minimise their exposure to the lower temperatures that favour formation of charcoal. One way this objective can be achieved is by using small particles, for example in the fluidised bed processes that are described later. Another possibility is to transfer heat very fast only to the particle surface that contacts the heat source which is used in ablative processes that are described later.

The main product, bio-oil, is obtained in yields of up to 75 wt.% on a dry-feed basis, together with by-product char and gas which can be used within the process to provide the process heat requirements so there are no waste streams other than flue gas and ash. Liquid yield depends on biomass type, temperature, hot vapour residence time, char separation and biomass ash content. A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimise the water in theproduct liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, fast pyrolysis, rapid and efficient separation of solids (char) and collection of the liquid product (bio-oil).

2.9 Fast Pyrolysis Reactors

At the heart of a fast pyrolysis process is the reactor.There has been considerable growth and expansion of activities over the last few years with more innovation in the types of reactor explored by academic institutions. It is disappointing to see so much re-invention and poor appreciation of the underlying fundamental requirements of fast pyrolysis as well as a reluctance to carry out basic reviews of past research publications. There are increasing activities on fixed bed and related systems that are unlikely to give high liquid yields but are likely to give phase separated liquids. Phase separated liquid products may be desirable in some applications where fractionation is required, but it would seem preferable to control such separation rather than rely on poor design and process control.

2.9.1 Bubbling fluid beds

Bubbling fluid beds have the advantages of a well understoodtechnology that is simple in construction and operation, good temperature control and very efficient heat transfer tobiomass particles arising from the high solids density. Figure 2.5 shows a typical configuration using electrostatic precipitators for coalescence and collection of what are referred to as aerosols. These are incompletely depolymerised lignin fragments which seem to exist as a liquid with a substantial molecular weight. Evidence of their liquid basis is found in the accumulation of liquid in the ESP which runs down the plates to accumulate in the bio-oil product. Demisters for agglomeration or coalescence of the aerosols have been used but published experience suggest that this is less effective.

Heating for bubbling fluid bed can be achieved in a variety of waysand scaling is well understood. However, heat transfer to bed at large scales of operation has to be considered carefullybecause of the scale-up limitations of different methods of heat transfer. Fluid-bed pyrolysers give good and consistent performance with high liquid yields of typically 70e75 wt.% from wood on a dry-feed basis. Small biomass particle sizes of less than 2-3mmare needed to achieve high biomass heating rates, and the rate of particle heating is usually the ratelimiting step.

Vapour and solid residence time is controlled bythe fluidising gas flow rate and is higher for char than forvapours. As char acts as an effective vapour cracking catalystat fast pyrolysis reaction temperatures, rapid and effective char separation is important. This is usually achieved by ejection and entrainment followed by separation in one or more cyclones so careful design of sand and biomass or char hydrodynamics is important. The high level of inert gases arising from the high permanent gas flows required for fluidisation result in very low partial pressures for the condensable vapours and thus care is needed to design and operate efficient heat exchange and liquid collection systems. In addition the large inert gas flowrates result in relatively large equipment thus increasing cost.

The byproduct char is typically about 15 wt.% of the products but about 25% of the energy of the biomass feed. It can be used within the process to provide the process heat requirements by combustion or it can be separated and exported, in which case an alternative fuel is required. Depending on the reactor configuration and gas velocities, a large part of the char will be of a comparable size and shape as the biomass fed. The fresh char is pyrophoric where it spontaneously combusts when exposed to air so careful handling and storage is required. This property deteriorates with time due to oxidation of active sites on the char surface.

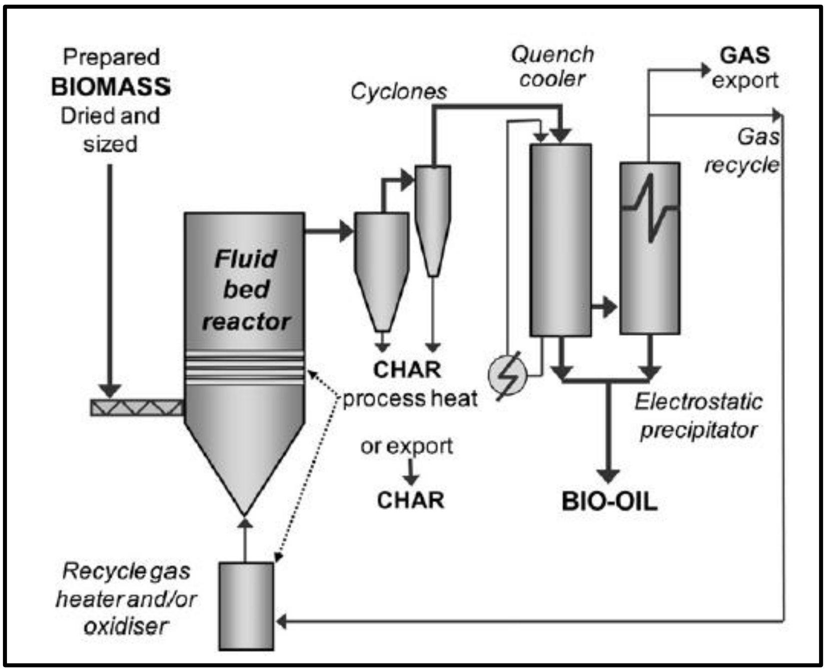


Figure 2.5: Bubbling fluid bed reactor with electrostatic precipitator

(A.V Bridgwater,2011)

2.9.2 Circulating fluid beds and transported beds

Circulating fluid bed (CFB) and transported bed reactorsystems have many of the features of bubbling beds described above, except that the residence time of the char is almost the same as for vapours and gas, and the char is more attrited due to the higher gas velocities. This can lead to higher char contents in the collected bio-oil unless more extensive char removal is included. A typical layout is shown in Figure2.6 An added advantage is that CFBs are potentially suitable for larger throughputs even though the hydrodynamics are more complex as this technology is widely used at very high throughputs in the petroleum and petrochemical industry.

Heat supply is usually from recirculation ofheated sand from a secondary char combustor, which can be either a bubbling or circulating fluid bed. In this respect theprocess is similar to a twin fluid-bed gasifier except that the reactor (pyrolyser) temperature is much lower and the closely integrated char combustion in a second reactor requires careful control to ensure that the temperature, heat flux andsolids flow match the process and feed requirements. Heattransfer is a mixture of conduction and convection in the riser.One of the unproven areas is scale up and heat transfer at highthroughputs.

All the char is burned in the secondary reactorto re-heat the circulating sand, so there is no char available for export unless an alternative heating source is used. If separated the char would be a fine powder.

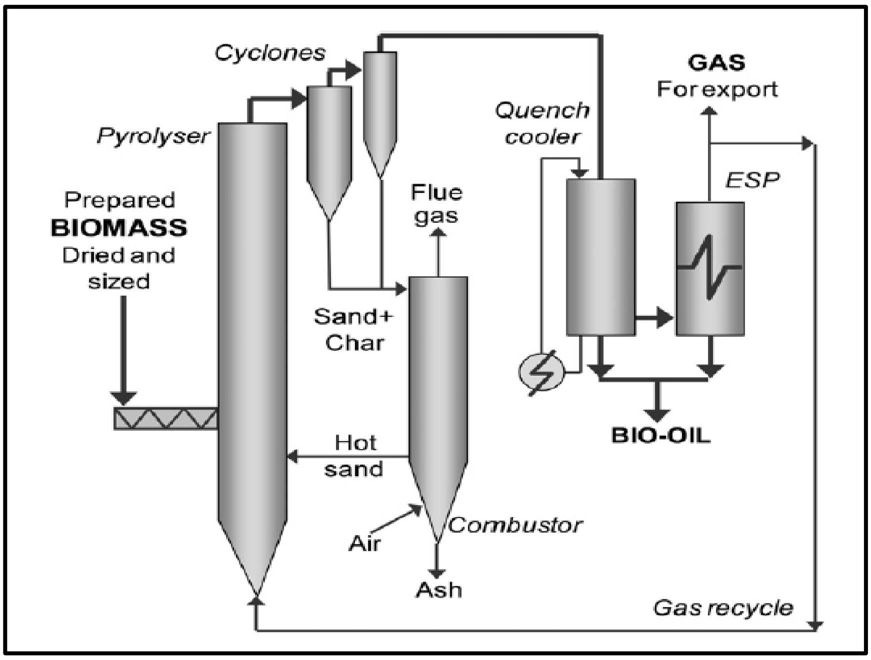


Figure 2.6: Circulating fluid bed reactor

(A.V Bridgwater,2011)

2.9.3 Rotating cone

The rotating cone reactor, invented at the University ofTwente (Prins W *et al*,. 1997) and developed by BTG (Wagenaar BM *et al*,. 2001), is a relatively recent development and effectively operates as a transported bed reactor, but with transport effected by centrifugal forces in a rotating cone rather than gas. A 250 kg/h unit is now operational, and a scaled up version of 50 t/d was commissioned in Malaysia in mid 2005. A 120 t/d plant is at an advanced planning stage (Muggen G, 2010).Figure 2.7 show s an early prototype on the left and its role in an integrated fast pyrolysis process on the right. Aswith CFB and transported beds all the char is burned so is not a byproduct, although the char could in principle be separated and recovered if analternative heating source is provided.

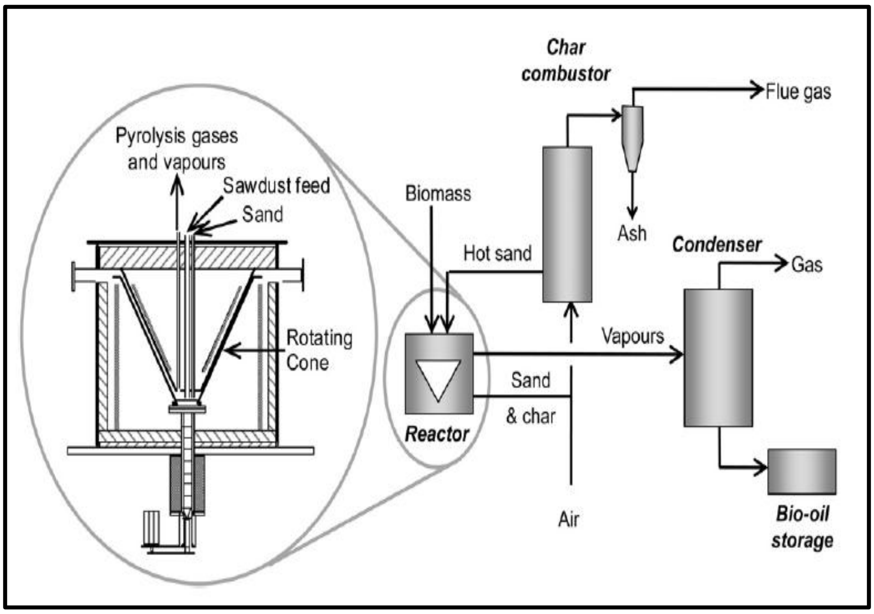


Figure 2.7: Rotating cone pyrolysis reactor and integrated process

(A.V Bridgwater,2011)

2.9.4 Ablative pyrolysis

Ablative pyrolysis is substantially different in conceptcompared with other methods of fast pyrolysis. In all the other methods, the rate of reaction is limited by the rate of heat transfer through the biomass particles, which is why small particles are required. The mode of reaction in ablative pyrolysis is like melting butter in a frying pandthe rate of melting can be significantly enhanced by pressing the butter down and moving it over the heated pan surface. In ablative“melt” wood that is in contact with it under pressure. As the wood is moved away, the molten layer then vaporises to a product very similar to that derived from fluid bed systems.The pyrolysis front thus moves unidirectionally through the biomass particle. As the wood is mechanically moved away, the residual oil film both provides lubrication for successive biomass particles and also rapidly evaporates to give pyrolysis vapours for collection in the same way as other processes. There is an element of cracking on the hot surface from the char that is also deposited. The rate of reaction is strongly influenced by pressure of the wood onto the heated surface, the relative velocity of the wood, the heat exchange surface; and the reactor surface temperature.

As reaction rates are not limited by heat transfer through the biomass particles, larger particles can be used and in principle there is no upper limit to the size that can be processed. The process, in fact, is limited by the rate of heat supplyto the reactor rather than the rate of heat absorption by thepyrolysing biomass, as in other reactors. There is no requirementfor inert gas, so the processing equipment is smaller and the reaction system is thus more intensive. In addition the absence of fluidising gas substantially increases the partial pressure of the condensable vapours leading to more efficient collection and smaller equipment. However, the process is surface-area-controlled so scaling is less effective and the reactor is mechanically driven, and is thus more complex.The char is a fine powder which can be separated by cyclones and hot vapour filters as for fluid bed reaction systems.

2.10 Others Reaction Systems

2.10.1 Entrained flow

Entrained flow fast pyrolysis is, inprinciple, a simple technology, but most developments have not been so successful because of the poor heat transfer between a hot gas and a solid particle. High gas flows are required to effect sufficient heat transfer, which requires large plant sizes and entails difficult liquid collection from the low vapour partial pressure. Liquid yields have usually been lower than fluid bed and CFB systems at 50-55 wt.% as in Georgia Tech Research Institute (Kovac RJ *et al*., 1989) and Egemin (Maniatis K *et al.,* 1997) but neither is now operational. There is some basic research in this area in China.

2.10.2 Vacuum pyrolysis

Vacuum pyrolysis, as developed inCanada by the University of Laval and Pyrovac, is arguably not a true fast pyrolysis as the heat transfer rate to and through the solid biomass is much slower than in the previously described reactors although the vapour residence time is comparable. The basic technology was developed at the University of Laval using a multiple hearth furnace butwas upscaled to a purposedesigned heated horizontal moving bed (Yang J *et al.*, 2001). The process operated at 450^{o}C and 100 kPa. Liquid yields of 35-50% on dry feed were typically obtained with higher char yields than fast pyrolysis systems. The process was complex and costly because the high vacuum necessitates the use of very large vessels and piping. The advantages of the process are that it can process larger particles than most fast pyrolysis reactors, there is less char in the liquid product because of the lower gas velocities, and no carrier gas is needed. The process has not operated for some years and no activities are currently knownusing vacuum pyrolysis.

2.10.3 Screw and augur kilns

There have been a number ofdevelopments that mechanically move biomass through a hot reactor rather than using fluids. These include screw and augur reactors. Heating can be with recycled hot sand as at the Bioliq plant at KIT (FZK until 2009) (Raffelt K *et al.*, 2006), with heat carriers such as steel or ceramic balls, or external heating. The nature of mechanically driven reactors is that very short residence times comparable to fluid and circulating fluid beds are difficult to achieve, and hot vapour residence times can range from 5 to 30 s depending on the design and size of reactor. Examples include screw reactors and more recently the Lurgi LR reactor at Karlsruhe Institute of Technology (KIT) (Henrich E *et al.*, 2009) and the Bio-oil International reactors which have been studied at Mississippi State University (Ingram L *et al.*, 2008).

Screw reactors are particularly suitable for feed materials that are difficult to handle or feed, or are heterogeneous. The liquid product yield tends to be somewhat lower than fluid beds and is often phase separated due to the longer residence times and contact with byproduct char. Also the char yields arehigher. KIT has promoted and tested the concept of producing a slurry of the char with the liquid to maximise liquid yield in terms of energy efficiency (Henrich E *et al.,* 2009), but this would requires an alternative energy source to provide heat for the process.

2.10.4 Fixed bed fast pyrolysis

There have been claims offast pyrolysis in fixed beds but it is difficult to envisage a fixed bed pyrolysis process that satisfies the basic requirements of fast pyrolysis which can be constructed at anything above laboratory or bench scale.

2.10.5 Microwave pyrolysis

Some basic research has beencarried out on microwave driven pyrolysis. Microwave heating is fundamentally difference from all other pyrolysis techniques as the biomass particles are heated from within and not by external heat transfer from a high temperature heat source. Microwave heating requires a material with a high dielectric constant or loss factor, of which water is a good example. So in microwave pyrolysis, water is rapidly driven off then the particle heats up to start forming char. It is notclear that this can be considered fast pyrolysis. This is electricallyconductive and eddy currents are created that providevery rapid heating. Therefore control of a microwave system is quite challenging. A further problem to be considered is that penetration of microwaves is limited to typically 1-2 cm, so the design of a microwave reactor presents interesting scale up challenges.

One of the potentially valuable aspects of microwave pyrolysis is that due to the absence of thermal gradients, an environment is created for studying some of the fundamentals of fast pyrolysis. This offers possibilities to examine the effect of the thermal gradient in a pyrolysing particle and the secondary reactions that occur both within and without the biomass particle.

2.10.6 Hydropyrolysis

In an effort to reduce the oxygencontent of the bio-oil product within a single step process, some attention has returned to the concept of integrating pyrolysis and hydrocracking in which hydrogen is added to the pyrolysis reactor. GTI is starting a new hydropyrolysis and hydroconversion programme to make gasoline and diesel inearly 2010 [38] and a new patent has been applied for that includes hydrogen in the pyrolysis reactor with claims of producing hydrocarbons, alcohols and other oxygenates [39]. The concept has some contradictory requirements e high pressure in pyrolysis increases char yields e.g. Antal [40] and reduces liquid yields while high pressures are required to provide effective hydrogenation.

2.11 Distinct Characteristics of Biomass Fuels

In comparison to fossil fuels, biomass fuels have relatively low heating values. This can be explained by two of their distinct characteristics that are high moisture and high oxygen contents (Jenkins BM et al., 1998, Demirbas, 2007).

The high moisture content is one of the most significantly disadvantageous features of using biomass as a fuel. Although the combustion reactions are exothermic, the evaporation of water is endothermic. To maintain a self-supporting combustion process, the moisture content (on wet basis) of biomass fuels cannot be higher than 65% (Jenkins BM et al., 1998). In addition, the heating value of the fuel is negatively correlated with the relative amount of water even when the moisture content is within the maximum acceptable limit (Jenkins BM et al., 1998, Demirbas, 2007, Quaak P *et al.*, 1999).

Figure 2.8 exhibits the negative linear relationship between the moisture content and the heating value. As the moisture content increases, both the higher heating value (HHV) and lower heating value (LHV) decrease. HHV and LHV are used to describe the heat production of a unit quantity of fuel during its complete combustion. In determining the HHV and LHV values of a fuel, the liquid and vapour phases of water are selected as the reference states, respectively. As HHV incorporates the heat of the condensation of water vapour during the combustion, it is not surprising to observe that the curve of the HHV is always above that of the LHV (Quaak P *et al.,* 1999, Engineering Tool Book, 2009).

Another important feature of biomass fuel is its elevated oxygen content. Typically, the oxygen content of biomass is as high as 35 wt.%, approximately ten times higher than that of a high-rank coal, which is below 4 wt.% (Demirbas, 2007).Fouling and corrosion of the combustor are typical issues associated with biomass combustion. These are considered to be detrimental because of the resulting reduction in heat transfer in the combustor. Fouling is commonly associated with the presence of alkali metals and some other elements (such as silicon, sulphur, chlorine, calcium and iron) in the biomass ash. With a series of complex chemical reactions, these elements are deposited in the forms of chlorides, silicates or sulphates on the wall of the combustor or the surface of the heat transfer elements. Generally, herbaceous biomass, such as straws and grass with comparatively higher contents of alkali, sulphur, chlorine and etchas a higher potential for the occurrence of ash deposition and corrosion in comparison to woody biomass.

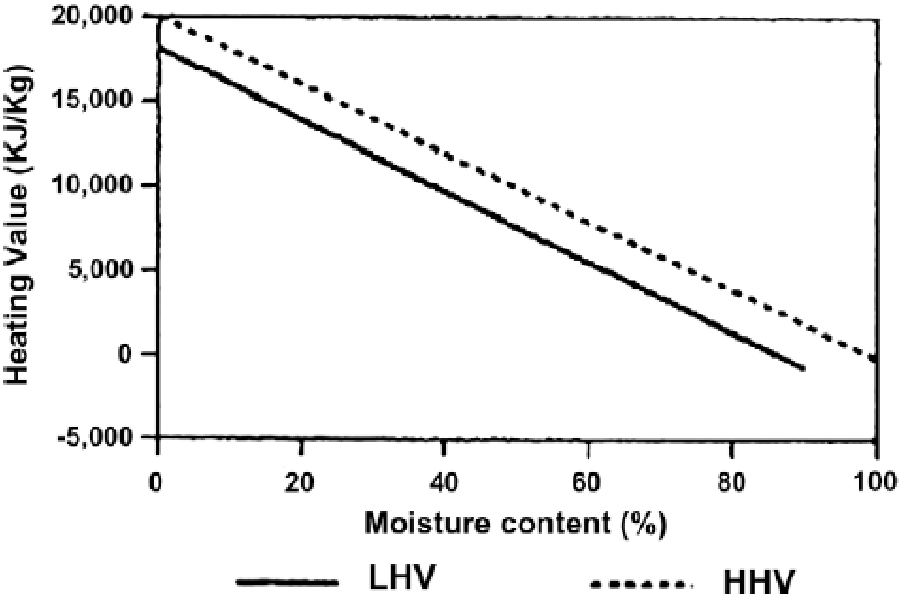


Figure 2.8: Relationship between heating value and moisture content of biomass fuel (Quaak P et al., 1999)

2.12 Applications of Bio-oil

Bio-oil can substitute for fuel oil or deise in many static applications including boilers, furnaces, engines and turbines for electricity generation. Liquids products from pyrolysis process can be used for combustion, power generation and chemicals constituents.The most significant changes since then are:

- An appreciation of the potential for fast pyrolysis to be a pre-treatment method i.e. for bio-oil to be an effective energy carrier.
- Greater interest in bio-oil as a precursor for second-generation biofuels for transport.
- Greater awareness of the potential for fast pyrolysis and biooilto offer more versatile processes routes to a wider rangeof products and contribute to biorefinery conceptdevelopment.

- Considerably greater interest in upgrading bio-oil sufficientlyfor it to be used for heat, power and other applicationswith greater confidence by users.

Figure 2.9 summarises the possibilities for applications for biooiland the main developments are expanded below.

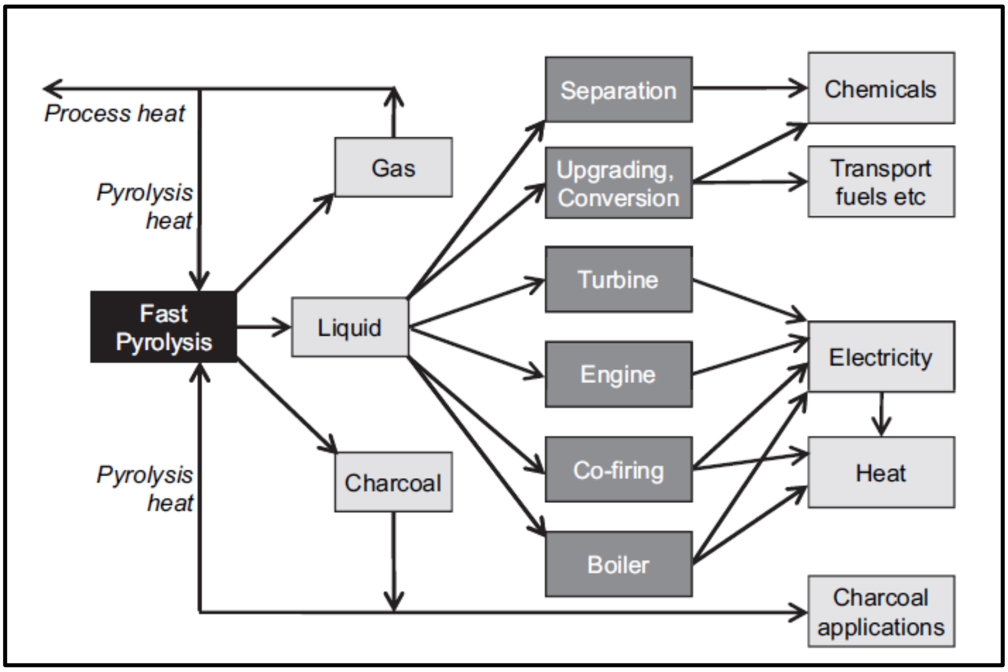


Figure 2.9 : Applications for pyrolysis products

(A.V Bridgwater, 2010)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This direct fired heating system using R40 GS Riello gas burner where it give direct heating to the reactor chamber. Liquefied Petroleum Gas (LPG) were used as the source of the heating for the system applicable for thermo chemical processes such as pyroplysis and gasification. Gas burner used to heat reactor in chamber to the required temperature for pyrolysis process which is approximately at 435^{o}C for obtaining an acceptable yields of liquid at least 50% with low reaction times (A.V Bridgwater, 1999).

3.2 Start-Up Procedure

Several procedure must be taken before run the experiment to make sure that the experiment run smoothly. All the equipments for the system should be placed in the correct position such as the liquefied petroleum gas (LPG) tank was connected to the system and the thermocouple termometer was connected to all the thermocouples at the system. Before experiment, the safety aspect is the most important priority. The experiment must be done with wearing the Personal Protection Equipments such as safety boots, google and gloves to avoid any accident happen. Before running the experiment, firstly the relief valve need to be opened to release all the gas that might contain inside the pipeline. Next, all the valves that connect the LPG tank and the gas burner must be closed so that there is no gas flow before the experiment start. The bolts and nuts tighness at every parts of the system especially at the reactor to make sure that the experiemnt was done in good condition. Besides, the condenser also need to be checked by flowing the cooling water to make sure that the water flow through the condenser without any problems. All the procedure must be taken before the experiment start to prevent from any accident.

3.3 Run the Experiment

After all the start-up procedures were done, the experiment can be done. To run the experiment, all the circuit of the system sould be fully connected. The system can be divided into three major parts that are gas burner, furnace and condenser. All this part must be completely connected before the experiment started.

3.4 Air-Fuel Setting Experiment

To start the air-fuel ration experiment, the gas hose was plugged to the LPG tank and the hose valve is open so that the gas in LPG tank can flow into the pipeline of the system. The thermocouple thermometer was connected to the themperature probe at the furnace. Then, the air ratio and fuel ratio was setting up at the gas burner. The air is setting at 2.5 and fuel ratio at 19mbar. The setting of the air being set at the air damper where it is shown in Figure 3.1. Before switch on the gas burner, the valve at the piping area was opened to allow the gas flow to the gas burner. The gas hose adjuster was opened to control the gas flow from the LPG tank to the gas burner. The gas hose adjuster was opened untill the pressure at the pressure gauge reach 400mbar. When the gas supplied to the gas burner, the burner was switched on. After the gas burner produces the fire, the furnace door was quickly closes. Then the temperature for each thermocouple was recorded for each one minutes. After the experiment was done, all the plugs were switched off and all the steps was repeated for other air-fuel setting.The setting of air-fuel ratio are given below.

Table 3.1 : Air-Fuel Ratio Setting of the Experiment

Fuel Ratio (mbar)	Air Ratio
16	7.5
19	2.5
19	7.5

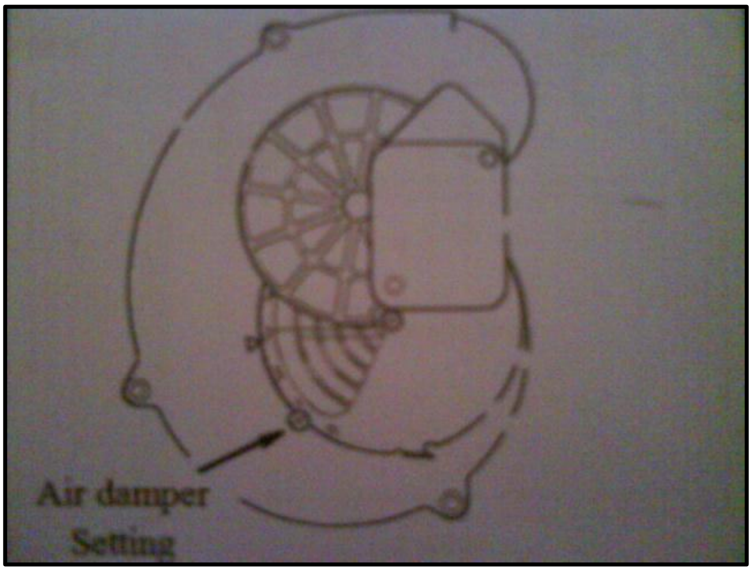


Figure 3.1: Air Damper Setting

3.5 Liquid Production Experiment

3.5.1 Feedstock and Sample Preparation

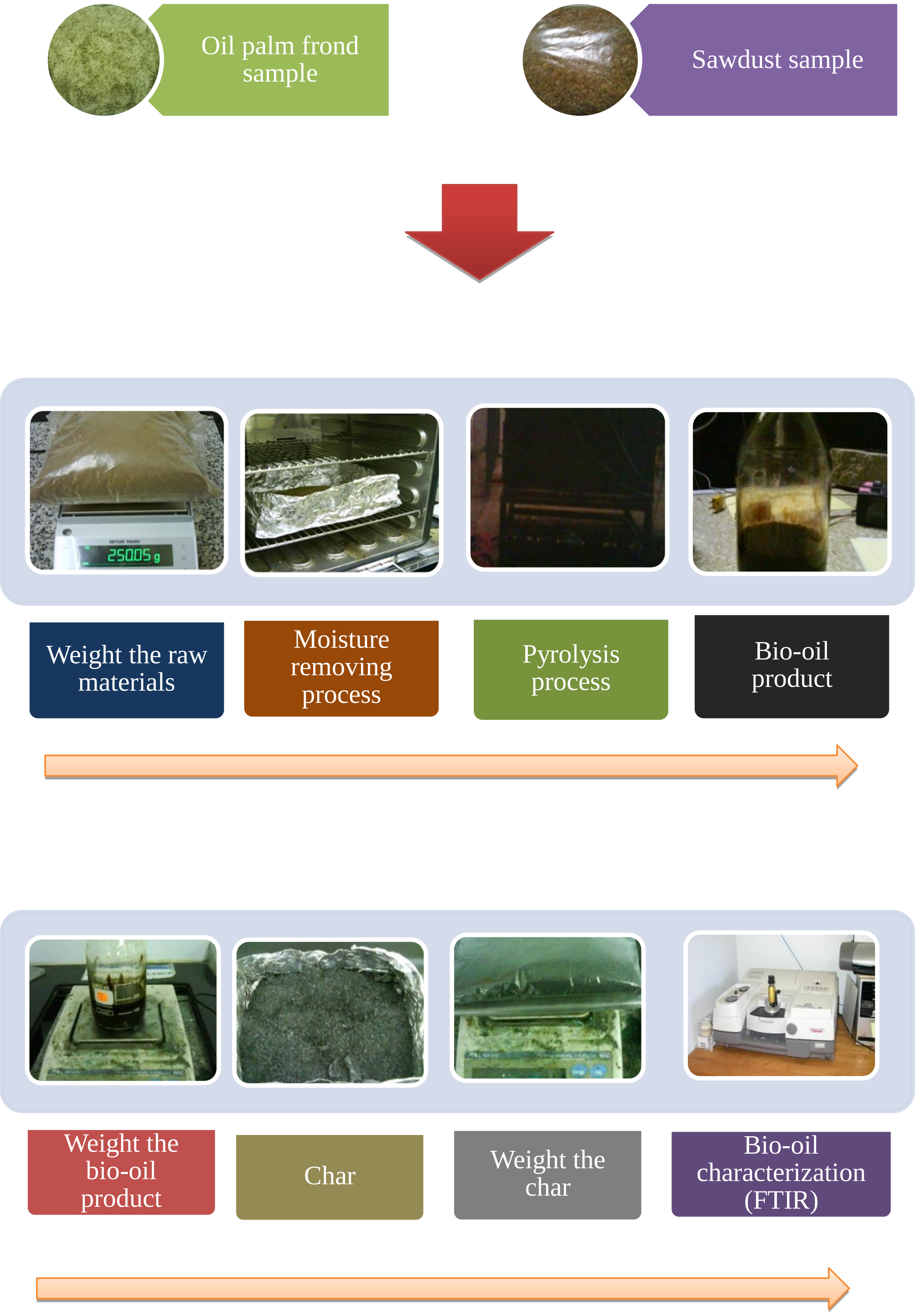
The sawdust and oil palm fronds sample was obtained from the local industries, near area of Pahang, Malaysia. Sample received were relatively wet and contain more than 10 wt% moisture. The oil palm fronds were received in fronds condition shows in Figure 3.2. Therefore the oil palm fronds were grinded first to make it into smaller size (Figure 3.3). The samples were dried in the oven at 70^{o}C for 24 hours to removed the water content in the samples (Figure 3.4). After the water content removed, the sample presumed dried in the oven to prevent growth of fugus or microorganism before it being use for the experiment.

Figure 3.2: Oil palm fronds sample

Figure 3.3: Oil palm fronds sample after grinded

Figure 3.4: Sample in the oven

3.5.2 Schematic Diagram for the Experiment



3.5.3 Experimantal Procedure

The reactor is the heart of a fast pyrolysis process (Brigwater AV *et al,*. 2001). The gas fired pyrolysis system has been selected for this study as it is relatively easy to contruct and operate . To investigate the effect of temperature, fast pyrolysis experiments were carried out at the temperature of range 400^{o}C to 600^{o}C in 100^{o}C increments.

The pyrolysis experiments were performed by charging 500g of sawdust into carbon steel reactor with length of 91.5 cm and an internal diameter of 11.5 cm. The reactor was heated externally by a gas burner , with the temperature being controlled by a K-type thermocouple placed inside the reactor and furnace. The experiment were carried out to investigate the effect of temperature on the pyrolysis yields with a constant particles size of $1.7 < dp < 2$ mm, air ratio 2 and fule rati 19mbar. The temperature were maintained at 400^{o}C, 500^{o}C and 600^{o}C. At the end of the experiment, the condensable products (liquid) were collected from the condenser. After that, the solid char was removed from the inside reactor and weighed. The experiemnt were repeated by using the palm oil frond samples. But for palm oil samples, the weight of the sample is 250g this is because of the consideration of the space in the reactor.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Experimental Result

From the experiment that has been done in this research, firstly for the air and fuel setting, tha data was collected and shown in the of temperature versus time in the appendix. There are three tables of results with difference air and fuel setting of gas burner. By studying the result of experiments, the idea of heay distribution in pyrolysis system designed was gain and several graphs of heat distribution were plotted. Next, the result for the products of pyrolysis process was calculated and graph of product yield versus temperature was plotted. From this experiment, the best temperature to produce bio-oil was obtain. The bio-oil then being analysis and the result of the analysis was discuss in this chapter.

4.2 Air and Fuel Setting

4.2.1 The Best Air and Fuel Setting

By comparing the data from the air and fuel setting experiment, the best setting was selected. The best air and fuel setting for better heat distribution is at setting of 2.5 air and 19mbar fuel. This setting give the shortest time taken for the heat to distribute inside the reactor and reach the pyrolysis temperature. The setting at 2.5 of air and 19mbar of fuel takes only 20 minutes to reach the temperature of 400°C. The other setting takes more then 40 minutes to reach the temperature. Therefore, the setting of 2.5 of air and 19mbar of fuel is the best setting for this pyrolysis system. Below shows the graph of this best air and fuel setting.

The graph in Figure 4.1 shows the pattern of temperature distribution in the pyrolysis system at setting of 2.5 air and 19mbar fuel. All the probes shows that all the point in the system having an increment in the temperature. The probes T1 nad T3 having slow increment compare to T2 due to the position of the probes on the system. The probe T2 located near to the burner and expose more to the flame from the burner. For the probe T4, it is the probe that located inside the reactor. Therefore the temperature detacted by the probe need more time to increase. Based on the graph above, the reactor takes about 20 minutes to reach the pyrolysis temperature which is at 400°C. The heat from the burner need some time to distribute into the reactor.

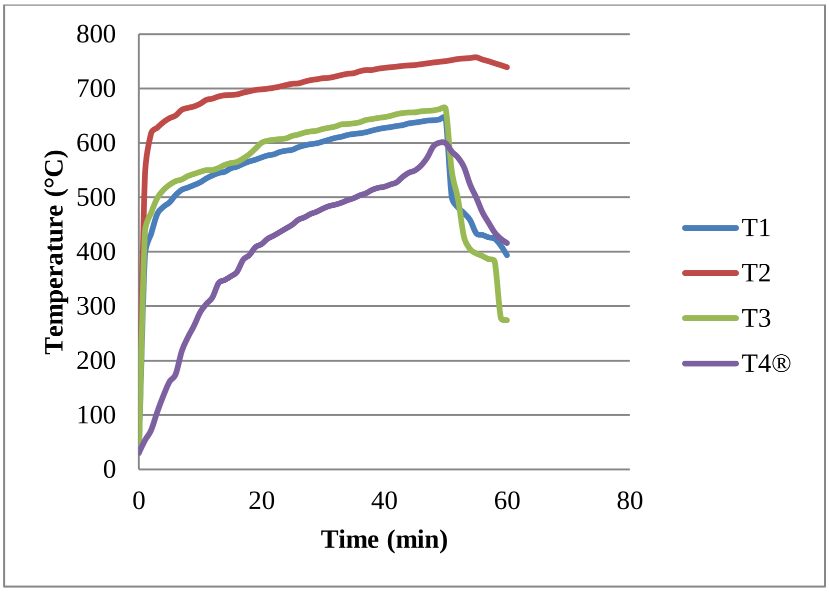


Figure 4.1: Graph of Temperature Distribution at 2.5 of Air and 19mbar of Fuel Setting

After 50 minutes running the experiment, the temperature of the all probes were decreasing.This situation happen because of the condition of the gas supply system which is from Liquified Petroleum Gas tank. This problem will be discuss in the end of this chapter.

4.2.2 The Temperature of Reactor (T4)

Based on the three differences air and fuel setting, the differences of the temperature distribution inside the reactor was investigated. Graph of temperature versus time for the temperature inside the reactor for each setting was ploted. From Figure 4.2, the graph shows that the temperature of the reactor increase in directly proportional to the time. The temperature increase slowly at 5 minutes early. This is due to the barrier of the wall of the reactor where the heat from the inside of the furnace need to passes through the wall before entering the inside of the reactor. However, after 50 minutes of experiment, the temperature of the reactor become steady. The heat in the furnace is circulating steadily and heat is fully transfered from furnace to the reactor.

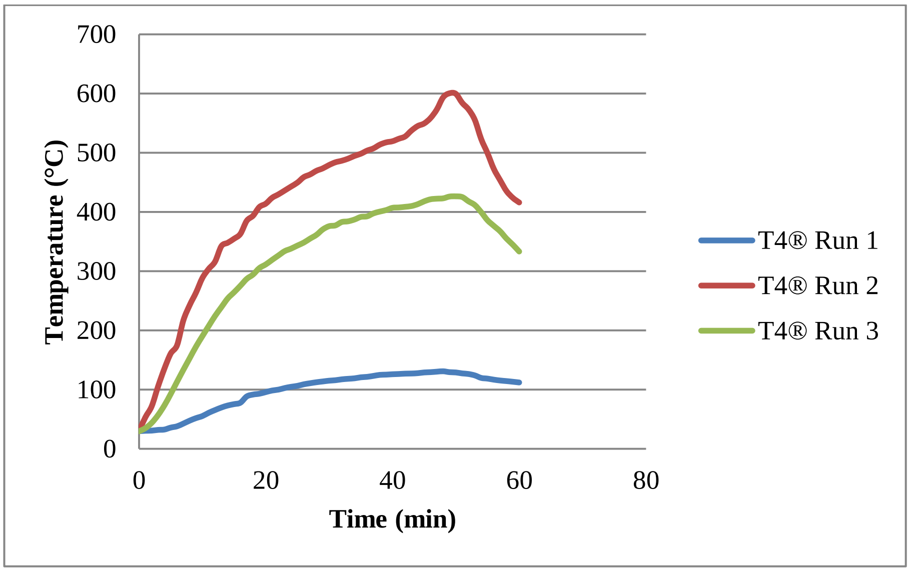


Figure 4.2: Graph of Temperature Distribution inside the Reactor

By comparing all graphs from the experiments, the best graph for temperature of reactor is setting 2 where the setting is 2.5 of air and 19 mbar of fuel. For the early stage of the experiment, the temperature of the reactor increase drastically. This is due the effects of the flame length of the burner. At this setting, the flame length is longer than other setting which it produced higher heat transfer to the reactor. Therefore, 2.5 of air and 19 mbar of fuel setting gives the higher temperature at shortest time taken. With the increasing of time, the temperature of the reactor will increase until it reaches steady temperatureThe amount of heat produce in this setting give the best temperature distribution which is it can produced the pyrolysis temperature in the shortest time taken. The maximum temperature that produced by this setting is 600°C where it is range of pyrolysis temperature that is from 400°C to 600°C. Therefore, it is clear that setting for run 2 give the temperature that required in the ptrolysis process.

4.2.3 Sweating of Liquified Petroleum Gas (LPG) Tank

During the experiment, it was observe that the temperature of the all probes was decreasing after 50 minutes. This is due to the supply of the gas to the gas burner.

The two main forms of LPG are commercial butane and commercial propane. LPG may be liquefied by moderately increasing the pressure or by reducing the temperature. Because of LPG has a high coefficient of expansion in its liquid phase, the tanks are never completely filled with liquid, tanks are filled to approximately 85% of their water capacity and the remaining space being taken up with vapor often referred to as the vapor space to facilitate expansion without allowing the liquid to become 100% full.

As LPG gas is drawn from the tank, the vapour pressure in the tank falls and the liquid boils, producing more vapour and restoring the pressure. To maintain boiling, the liquid absorbs heat from itself, from the metal alls of the tank in contact with the liquid known as the wetted surface area and from the air surrounding the tank. The available gas 'off take', therefore, is dependent upon the surface area of the tank, the quantity of liquid within the tank and the temperature. The low temperature of the liquid where excess off takewas happen may be indicated as 'sweating' which the water vapour in air condenses on the wetted surface area of the tank and if the off take is large enough 'frosting' where the condensed water vapour freezes on the walls of the tank. The freezes of the tank was shown in the Figure 4.3 below.

Figure 4.3: Sweating of LPG Tank

4.3 The Effect of Reaction Temperature on the Bio-oil Products

4.3.1 Effect on sawdust

Figure 4.4 shows the effect of reaction temperature on the yields and the results indicate that as the temperature were moved from 400°C to 500°C the bio-oil yield increased from 36.2wt% to 38.7wt%. The bio-oil yeilds were increased about 2.5wt% with a ration 100°C. It was the optimum condition for production of bio-oil with temperature maintained at 500°C. On the other hand, at 600°C the bio-oil yeilds were decreased to 33.8wt%. The reason why the bio-oil product decreased at pyrolysis temperature of 600°C was the decreases of the organic and specific products and secondary cracking of volatiles at temperatures above 500°C. The cracking has led to more resulting in higher gas production which is also observer at other biomass wastes in the literatures (Jung S-H et al.,2008, Luo Wang & Liao Cen, 2004).

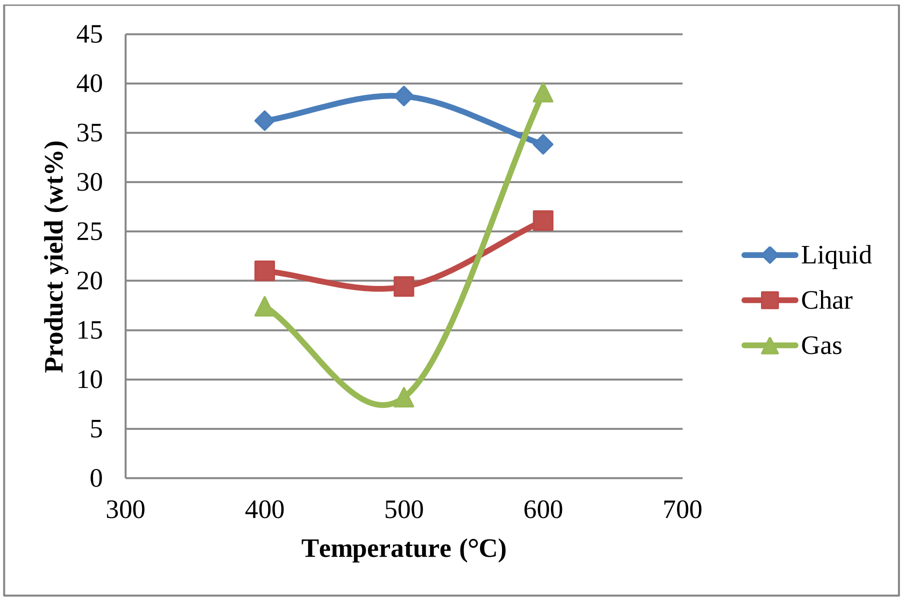


Figure 4.4: Effect of temperature on sawdust yield products

4.3.2 Effect on oil palm fronds

Figure 4.5 shows the effect of reaction temperature on the yields and the results indicate that as the temperature were moved from 400°C to 500°C the bio-oil yield increased from 33.5wt% to 50.5wt%. The bio-oil yeilds were sharp increased about 17wt% with a ration 100°C. It was the optimum condition for production of bio-oil with temperature maintained at 500°C. On the other hand, at 600°C the bio-oil yeilds were decreased to 7.8wt%. The reason why the bio-oil product decreased at pyrolysis temperature of 600°C was the decreases of the organic and specific products and secondary cracking of volatiles at temperatures above 500°C. The cracking has led to more resulting in higher gas production which is also observer at other biomass wastes in the literatures (Jung S-H et al.,2008, Luo Wang & Liao Cen, 2004).

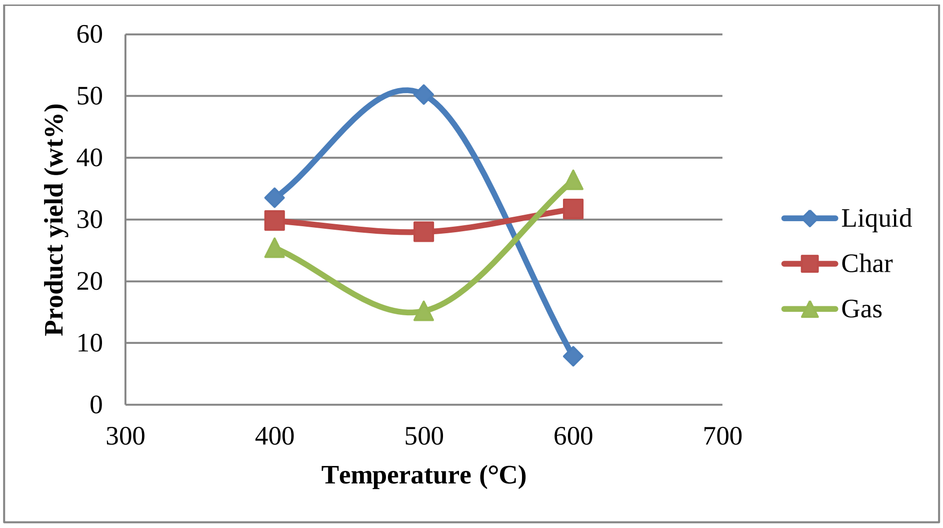


Figure 4.5: Effect of temperature on palm oil frond yield products

4.4 Chemical Characterization of Bio-oil

4.4.1 FT-IR Analysis for Bio-oil from Sawdust

The FT-IR spectra of the pyrolytic liquids obtained under different pyrolytic condition are given in the Figure 4.6, Figure 4.7 and Figure 4.8. Characteristic vibration modes of aliphatics were observed at 2850 cm^{-1} and 3000 cm^{-1}(C-H stretching). The pyrolytic liquids obtained at various pyrolysis temperatures comprise mainly aliphatic fraction fractions as also abserves by H NMR result shown in Table 4.1 (A.Sinag *et al*,.2010) which represent the aliphatic characters of the pyrolytic liquids. The broad peaks around at 3200 cm^{-1} and 3600 cm^{-1} which is the O-H stretching vibration of the bio-oil indicate the presence of phenols and alcohols. For all pyrolytic liquids, the absorption band at around 1475 cm^{-1} and 1600 cm^{-1}show the C=C stretching vibration present the present of aromatic and conjugate olefinic. The peaks 1669.72 cm^{-1} in the case of pyrolytic liquids obtained at 500°C and peaks between 1600 cm^{-1} and 1680 cm^{-1} for pyrolytic liquids obtained at 600°C can attributed to the C=C stretching vibration whic is indicate the presence of alkenes group.

Increasing experimental temperature leads to a decrease in the intensity of the peaks between 1114 cm^{-1} and 1700 cm^{-1} which is the C-O, C=O and C-H stretching vibration of the pyrolytic liquids where it indicate the present of aliphatic and aromatic groups. This can be explained by the decarboxylation and the dehydration resulting the loss of hydrogen and oxygen atoms (A.Sinag *et al*,.2010). The functional group compositional analysis for pyrolytic liquids was shown in Table 4.2.

Table 4.1: Composition of the pyrolytic liquids according to the H NMR Results (vol%)

	400^oC	500^oC	600^oC	700^oC
Aromatic	15	14	15	12
Olefins	16	17	15	15
Etheric	13	12	13	12
Aliphatics	55	56	56	59

Source: A.Sinag et al,.2010

Table 4.2: FT-IR functional group composition of pyrolysis liquid from sawdust

Frequency range (cm^{-1})	Groups	Class of compounds
3000-2800	C-H stretching	Alkanes
1675-1600	C=C stretching	Aldehydes, carboxylic acids, ketones
1500-14500	C-H bending	Alkanes
3600-3200	O-H stretching	Alcohol, phenols

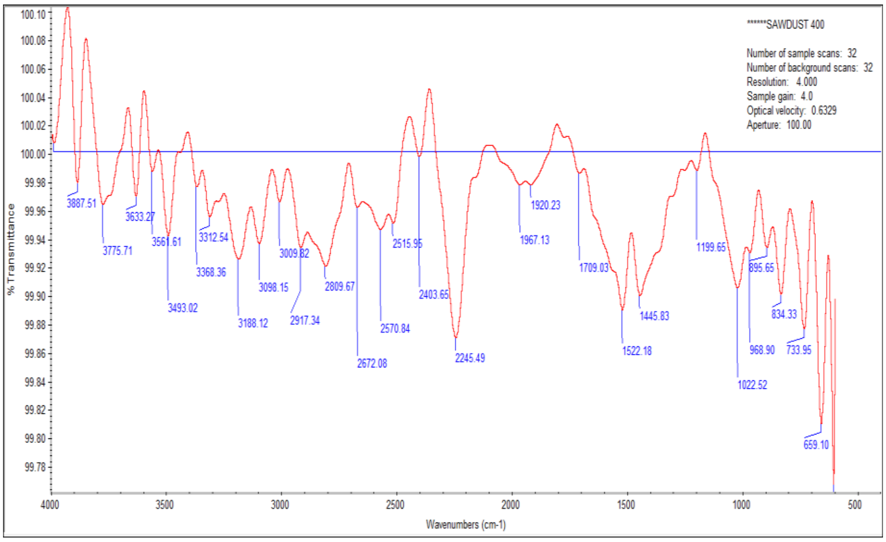


Figure 4.6: FT-IR Spectrum of Pyrolytic Liquids obtain from sawdust at 400^oC

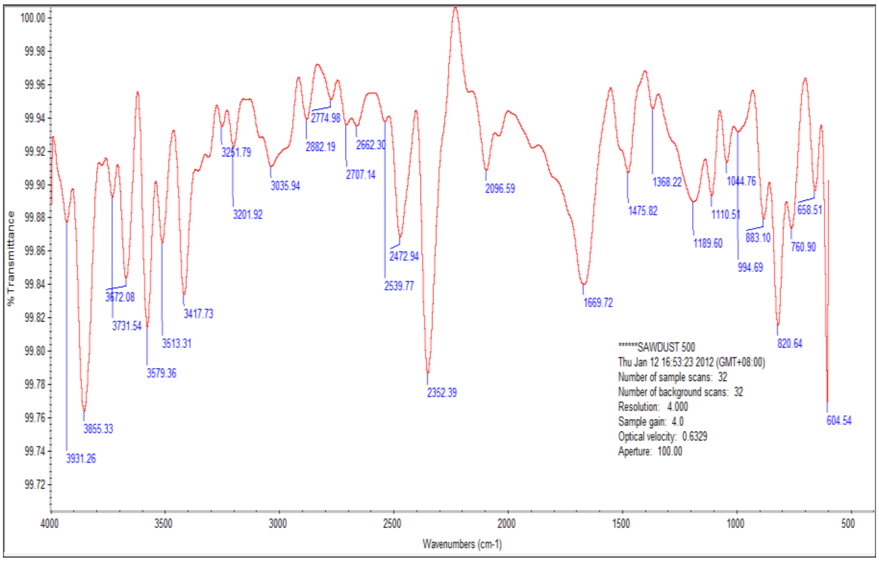


Figure 4.7: FT-IR Spectrum of Pyrolytic Liquids obtain from sawdust at 500^{o}C

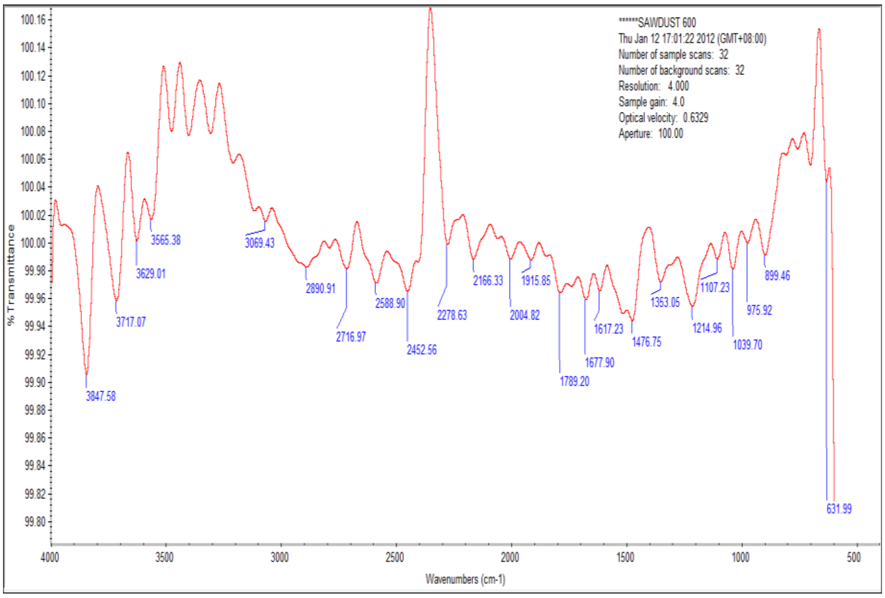


Figure 4.8: FT-IR Spectrum of Pyrolytic Liquids obtain from sawdust at 600^{o}C

4.4.2 FT-IR Analysis for Bio-oil from Oil Palm Fronds

The Fourier Transform Infrared Spectroscopic (FT-IR) spectra of the bio-oil were given in Figure 4.9, Figure 4.10 and Figure 4.11, representing functional group compositional analysis of bio-oil obtained from oil palm fronds for different reaction temperature. It is possible that the organics phase contains a small amount of oil palm, as the organics in the organic phase have a significantly higher hydrogen to carbon ratio than is the case for wood derived slow pyrolysis tars (EU Contract, 2001). The absorption frequency spectra representing the functional group composition of the pyrolysis liquid is shown in Table 4.3. The O-H streching vibration between 3200cm^{-1} and 3400cm^{-1} of the bio-oils indicate the presence of phenols and alcohols. The C-H streching vibrations between 2800cm^{-1} and 3000cm^{-1}, C-H deformation vibrations between 1350cm^{-1} and 1450cm^{-1} indicate the presence of alkane groups. The C=O streching vibrations between 1680cm^{-1} and 1750cm^{-1} are compatible with the presence of ketones, quinones, aldehyde groups and etc. The absorbance peak between 1500cm^{-1} and 1645cm^{-1} represent C=C streching vibrations indicative of alkenes. Furthermore, mono, polycyclic and substituted aromatic groups are indicated are by the absorption peaks between 690-900 and 1350-1450 cm^{-1}. Finally, the absorption peaks between 650 cm^{-1} and 900 cm^{-1} indicate the presence of single, polycyclic or substituted aromatic groups.

Table 4.3: FT-IR functional group composition of pyrolysis liquid from oil palm fronds

Frequency range (cm^{-1})	Group	Class of compound
3000-2800	C-H stretching	Alkanes
1750-1625	C=O stretching	Aldehydes, carboxylic acids, ketones
1675-1600	C=C stretching	Alkenes
1500-1450	C-H bending	Alkanes
1300-1000	C-O stretching O-H bending	Alcohol Phenols
900-650		Aromatic compounds

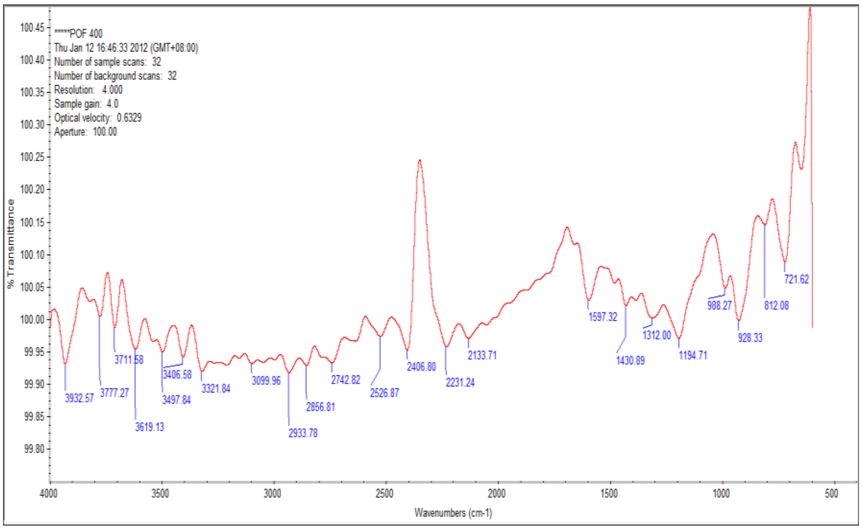


Figure 4.9: FT-IR Spectrum of Pyrolytic Liquids obtain from oil palm fronds at 400°C

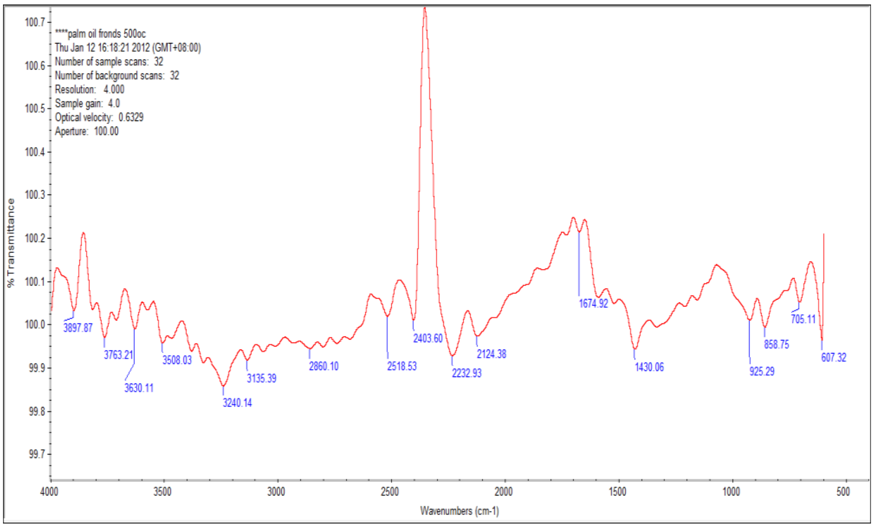


Figure 4.10: FT-IR Spectrum of Pyrolytic Liquids obtain from oil palm fronds at 500°C

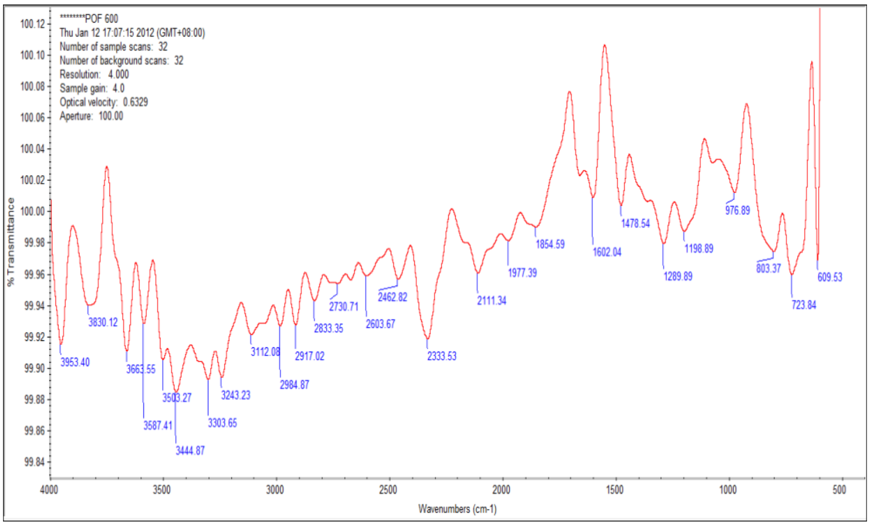


Figure 4.11: FT-IR Spectrum of Pyrolytic Liquids obtain from oil palm fronds at 600^{o}C

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, the heat distribution is very important in gas fired pyrolysis syetem. With good heat distribution, it will save energy consumption and giving better condition for the pyrolysis process. So this research, the best setting of air and fuel was obtained by selecting the setting that give the shortest time taken to increase the temperature of the reactor to 400^{o}C. Pyrolysis process can be obtain started at temperature of 400^{o}C. Therefore, from this research, the best setting obtain is at 2.5 of air and 19 mbar of fuel. The time taken to achieve 400^{o}c is only 20 minutes. From this setting, the pyrolysis process was run for future experiment that is to obtain the maximum yields of bio-oil frol biomass that are sawdust and oil palm fronds.

In comparision to the existing literature, this research comfims the shape of the yeild curves for sawdust and oil palm fronds by observing liquid, char and gas with the experiment done with temperature increments of 100^{o}C each. The data shows that the optimal pyrolysis temperature for the production of bio-oil from both biomass, sawdust and oil palm fronds was found to be at 500^{o}C. In the other hand, 600^{o}C is the best temperature to produce the char and gas products. For the production of the char and gas is differ from the existing literature. This may happen due to the problem at pyrolysis system or due to the effiency of the condenser.

Bio-oils are low-grade liquid fuels when compared with petroleum fuels. The poor fuel properties include the complex multiphase structures, hihg content of oxygen, water, solids and ash, low heating values, high viscosity and surface tension, chemical and therma instability, low pH values and poor ignition and combustion properties. In spite of these poor fuel properties, bio-oils also have some promising properties. They usually possess some lubricity and they are less toxic and more biodegradable fuels.

5.1 Recommendations

By doing this research, it was found that there are several things should be improve to find the better result of the reseacrh. Imrovements and applications will follow futher investigate the applicability and flexibility if the model in the design for gas fired pyrolysis system. For the recommendation, firstly, the experiment must be done at good weather condition. It is better to do the experiment in the day compared to night because the humidity in the night air may affect the heat distribution of the experiment. Beside that, the reactor should be change to the other material that has less wall thickness to increase the heat transfer in the system. Other than that, the pyrolysis experiment can be run by using other raw materials or combine two or more raw materials. Therefore, we can see the production of bio-oil when using different types of raw materials. Lastly, the bio-oil product should be analyzed using different analysis method so that the properties of the bio-oil can be determine. So, by considering the recommendation, this research can be more flexible with higher performance of system.

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APPENDICES

APPENDIX A

Tables of Results

Table 1: Setting of 7.5 of air and 16 mbar of fuel

TIME (MIN)	T1 (^oC)	T2 (^oC)	T3 (^oC)	T4® (^oC)
0	29.9	29.4	29.4	29.7
1	43.2	64.2	53.8	30.4
2	48.6	120.9	102.6	30.7
3	53.8	167.4	104.7	31.9
4	55.3	183.9	106.3	32.5
5	61.8	194.2	108.9	35.8
6	64.4	196.0	110.7	38.0
7	67.7	198.3	112.4	42.6
8	72.1	200.1	113.7	47.6
9	74.4	200.1	115.0	51.8
10	76.8	200.4	115.8	55.3
11	87.4	200.6	117.3	60.8
12	90.6	200.7	118.2	65.4
13	92.0	200.8	119.0	69.7
14	94.7	201.3	120.7	73.1
15	98.4	202.4	121.5	75.4
16	98.9	203.4	123.1	77.8
17	101.6	205.8	124.8	88.4
18	103.7	207.3	125.2	91.6
19	105.3	208.8	167.4	93.0
20	107.9	208.9	183.9	95.7
21	110.7	210.0	194.2	98.4

22	113.4	213.4	196.0	99.9
23	113.7	215.3	198.3	102.6
24	115.0	216.3	200.1	104.7
25	116.8	217.8	200.1	106.3
26	117.3	218.4	200.4	108.9
27	118.2	219.3	200.6	110.7
28	119.9	220.1	200.7	112.4
29	120.7	220.6	200.8	113.7
30	122.5	220.8	201.3	115.0
31	124.1	221.7	202.4	115.8
32	124.8	221.9	203.4	117.3
33	125.2	222.0	205.8	118.2
34	125.9	222.3	207.3	119.0
35	126.3	222.5	208.8	120.7
36	126.9	222.7	208.9	121.5
37	127.1	222.8	210.0	123.1
38	127.7	222.9	213.4	124.8
39	128.9	231.1	215.3	125.2
40	129.4	231.5	216.3	125.9
41	130.2	231.8	217.8	126.3
42	130.4	232.0	218.4	126.9
43	129.4	232.6	219.3	127.1
44	127.9	227.4	220.1	127.7
45	127.3	226.9	220.6	128.9
46	125.3	226.3	220.8	129.4
47	123.9	225.3	218.2	130.2
48	118.7	222.9	214.3	130.9
49	117.5	222.1	207.2	129.4
50	116.7	221.7	201.9	128.9
51	114.3	221.5	195.3	127.3
52	113.3	221.1	191.0	126.3
53	112.2	220.8	183.9	123.9

54	112.0	218.3	176.2	119.7
55	111.6	215.4	171.9	118.5
56	108.3	213.0	170.6	116.7
57	104.3	207.4	170.2	115.3
58	102.0	202.1	168.3	114.3
59	99.5	196.9	162.1	113.2
60	96.2	296.4	159.3	112.0

Table 2: Setting of 2.5 of air and 19 mbar of fuel

TIME (MIN)	T1 (^{o}C)	T2 (^{o}C)	T3 (^{o}C)	T4® (^{o}C)
0	30.2	33.6	29.5	30.1
1	393.4	540.1	435.7	53.2
2	432.5	617.3	471.0	71.9
3	469.0	627.8	498.2	105.2
4	482.3	638.0	513.2	135.2
5	490.6	645.3	522.9	160.9
6	504.1	650.3	529.6	174.8
7	513.7	660.7	532.8	216.9
8	517.9	664.3	539.1	242.7
9	522.5	667.0	542.9	263.9
10	527.4	671.9	546.8	288.5
11	534.6	679.0	549.8	303.8
12	540.1	681.3	550.2	316.1
13	544.6	685.3	553.9	342.2
14	546.9	687.5	559.5	347.9
15	553.2	688.1	562.9	354.7
16	556.3	689.0	565.0	362.9
17	561.4	692.2	571.3	385.0

18	565.8	694.7	579.0	393.6
19	569.0	697.3	589.4	404.6
20	573.2	698.3	600.1	413.9
21	576.9	699.6	603.9	423.8
22	578.9	701.3	605.7	427.3
23	583.3	703.5	606.9	435.8
24	585.6	706.3	608.3	442.8
25	587.3	708.6	612.8	449.5
26	592.1	709.3	615.3	458.9
27	595.3	712.5	618.9	463.5
28	597.7	715.3	621.0	469.4
29	599.2	716.9	622.3	471.5
30	602.4	718.9	625.6	475.9
31	605.8	719.6	627.8	478.4
32	609.1	721.9	630.0	482.9
33	611.2	724.6	633.9	487.3
34	614.5	726.9	634.7	492.7
35	616.3	728.0	635.8	495.3
36	617.6	731..6	637.9	499.7
37	619.5	733.9	642.0	500.4
38	622.6	734.0	643.7	506.9
39	625.3	736.3	645.8	512.1
40	627.4	737.8	647.3	512.3
41	628.9	739.0	649.5	512.6
42	631.0	740.1	652.7	516.6
43	632.6	741.5	654.8	518.9
44	635.8	742.3	655.8	522.4
45	637.3	743.1	656.1	543.6
46	639.0	744.6	658.0	557.7
47	640.9	746.1	658.9	577.2
48	641.6	747.7	659.6	600.9
49	642.9	749.0	661.9	603.7

50	645.7	750.3	663.0	608.3
51	500.3	752.1	548.7	520.7
52	481.6	754.2	497.9	512.7
53	470.8	755.1	426.9	496.8
54	457.8	756.0	404.7	483.0
55	433.8	757.2	396.8	477.8
56	430.8	753.2	392.0	458.5
57	426.4	750.1	386.1	437.8
58	423.9	746.3	381.7	425.9
59	411.3	742.9	278.4	416.2
60	393.5	739.0	274.1	401.5

Table 2: Setting of 2.5 of air and 19 mbar of fuel

TIME (MIN)	T1 (^{o}C)	T2 (^{o}C)	T3 (^{o}C)	T4® (^{o}C)
0	11.8	29.7	29.7	29.5
1	202.7	350.0	224.3	34.8
2	327.1	400.0	239.2	43.8
3	379.3	475.7	253.9	56.9
4	404.1	489.7	264.3	73.2
5	419.3	500.2	275.3	92.6
6	431.9	509.1	286.9	113.2
7	438.2	513.7	294.3	133.4
8	445.3	520.3	305.2	153.1
9	450.8	523.7	311.3	172.7
10	456.2	527.9	319.0	190.3
11	460.3	533.1	326.4	207.4
12	465.3	533.4	333.8	224.3
13	467.0	536.7	338.0	239.2

14	473.0	539.3	343.2	253.9
15	476.9	541.9	348.2	264.3
16	480.1	545.6	354.9	275.3
17	483.2	547.9	361.2	286.9
18	486.3	551.9	370.4	294.3
19	490.7	552.2	379.3	305.2
20	492.5	553.3	404.1	311.3
21	495.0	557.8	419.3	319.0
22	499.7	560.6	431.9	326.4
23	502.4	563.7	438.2	333.8
24	504.6	565.8	445.3	338.0
25	507.2	567.3	450.8	343.2
26	509.0	567.7	456.2	348.2
27	510.7	568.0	460.3	354.9
28	511.1	568.0	465.3	361.2
29	511.1	570.0	467.0	370.4
30	512.0	571.0	473.0	375.9
31	513.1	572.0	476.9	377.2
32	519.2	578.2	480.1	382.9
33	523.8	583.3	483.2	384.1
34	529.2	584.4	486.3	387.1
35	533.9	588.5	490.7	391.5
36	536.8	592.3	492.5	392.5
37	539.4	596.3	495.0	397.5
38	539.8	599.5	499.7	400.5
39	543.0	600.3	500.2	403.1
40	544.9	602.7	509.1	406.9
41	547.3	603.7	513.7	407.5
42	550.3	606.4	520.3	408.6
43	552.9	607.4	523.7	409.9
44	555.2	611.3	527.9	413.1
45	556.9	613.5	533.1	417.8

46	558.4	615.1	533.4	421.3
47	561.0	615.5	536.7	422.3
48	561.8	616.8	539.3	422.9
49	564.5	618.9	540.7	425.9
50	565.2	619.5	541.0	426.3
51	564.3	620.2	540.9	425.1
52	560.1	619.4	540.5	417.9
53	554.2	618.5	540.2	411.6
54	553.9	617.2	539.7	399.6
55	551.8	615.0	539.6	385.9
56	549.0	614.8	539.1	376.4
57	548.7	614.5	538.9	367.2
58	548.4	614.0	538.6	354.9
59	547.9	613.8	538.4	344.6
60	547.5	613.2	538.1	333.1

Data from the Experiments

Pyrolysis with sawdust

Run 1

Temperature : 400°C

Mass of biomass + moisture: 500g

Mass of biomass after heated in the oven : 421.3g

Moisture : 68.7g

Moisture content : (68.7 / 500) × 100

: 13.57%

Mass of char : 105.9g

Char content : (105.9 / 500) × 100

: 21%

Bio oil produce : 180.88g

Bio-oil content : (180.88 / 500) × 100

: 36.18%

Run 2

Temperature : 500^{o}C

Mass of biomass + moisture: 500g

Mass of biomass after heated in the oven : 447.92g

Moisture : 52.08g

Moisture content : (52.08 / 500) × 100

: 10.42%

Mass of char : 96.7g

Char content : (96.7 / 500) × 100

: 19.35%

Bio oil produce : 193.38g

Bio-oil content : (193.38 / 500) × 100

: 38.68%

Run 3

Temperature : 600^{o}C

Mass of biomass + moisture: 500g

Mass of biomass after heated in the oven : 431.51g

Moisture : 68.49g

Moisture content : (68.49 / 500) × 100

: 25.32%

Mass of char : 130.3g

Char content : (130.3 / 500) × 100

: 26.06%

Bio oil produce : 169.16g

Bio-oil content : (169.16/ 500) × 100

: 33.83%

Pyrolysis with oil palm fronds

Run 1

Temperature : 400^oC

Mass of biomass + moisture: 250g

Mass of biomass after heated in the oven : 120g

Moisture : 130g

Moisture content : (130 / 250) × 100

: 52%

Mass of char : 74.45g

Char content : (74.45 / 250) × 100

: 29.78%

Bio oil produce : 83.74g

Bio-oil content : (83.74 / 250) × 100

: 33.49%

Run 2

Temperature : 500^oC

Mass of biomass + moisture: 250g

Mass of biomass after heated in the oven : 120g

Moisture : 130g

Moisture content : (130 / 250) × 100

: 52%

Mass of char : 70.12g

Char content : (70.12 / 250) × 100

: 28.04%

Bio oil produce : 125.5g

Bio-oil content : (125.2 / 250) × 100

: 50.2%

Run 3

Temperature : 600°C

Mass of biomass + moisture: 250g

Mass of biomass after heated in the oven : 120g

Moisture : 130g

Moisture content : (130 / 250) × 100

: 52%

Mass of char : 79.12g

Char content : Char content : (130.3 / 500) × 100

: 26.06%

Bio oil produce : 19.519g

Bio-oil content : (19.51 / 250) × 100

: 7.8%