OIL PALM BIOMASS CONVERSION TO BIO-OIL THROUGH DIRECT FIRED PYRORYSIS PROCESS

AHMAD ZULKHAIRI BIN MUHAMAD

UNIVERSITI MALAYSIA PAHANG

CHAPTER 1

INTRODUCTION

1.1 Introduction

Biomass is organic materials from plants and animals. The term 'biomass' can be applied to any fuel type derived from recently living tissue. Biomass contains stored energy from the sun that is absorbed through photosynthesis process. The transfer process of the chemical energy to the animals and people occur when they eat the plant. Biomass is a renewable energy source due to the continuous grows of trees and crops, bringing to the existent of waste. Wood, crops, manure, and some garbage are the example of biomass fuels (USEIA, 2009).

Biomass is actually the most common and readily-available source of renewable energy in the world. Biomass is simple, cost effective and environmental friendly. The next ten years, there will be active development of efficient systems to convert Biomass into electricity and encourage the development of a fast growth new global bio-power industry. And it is expected by 2050, biomass will covered 50% of the world's primary energy needs (Business Insights, 2004).

Biomass is the only sustainable source of organic carbon and has been recognized as an attractive feedstock for fuels and chemicals production. Due to the price rise of crude oil in recent years and the concern of greenhouse gas emissions attract the attention to the bio-oil production. Biofuels offer number of advantages over the fossil fuels in terms of availability of renewable sources, presenting of CO_2 cycle in combustion; environmental friendly and biodegradable and sustainable. In particular, biodiesel produce from palm oil provides a high-quality supplementary fuel for blending with fossil fuels in order to meet the growing energy demand in the developed countries, especially those under the European Union. Intensive use of biomass as a renewable energy source could reduce dependency on fossil fuels and could provide significant advantage in terms of carbon dioxide emissions and less greenhouse effect. Biofuels are competitive economically once the fossil fuel price increases in the few years to come (Thiam *et al*. 2008).

1.2 Fast Pyrolysis Process of Biomass

A promising method to transform solid biomass into bio-oil is fast pyrolysis. Fast pyrolysis is a thermal decomposition process that occurs at moderate temperature in which the biomass is rapidly heated in the absence of oxygen to produce a mixture of condensable liquids, gasses and char. This method is able to convert up to 70 mass% of the biomass into a crude bio-oil, which can be transported to centralized refineries for the production of transportation fuels and chemicals. Bio–oil derived from this process is a high density oxygenated liquid that can be used as a replacement for liquid fossil fuels in certain application and can be burned in diesel engines, turbines or boilers (Abdullah *et. al*. 2007).

The fast pyrolysis process promises high yields of liquid with minimum of gas and char production if this process is carefully controlled. Compared to other thermal conversion processes, this process is also perceived to offer more logistical and hence economic advantages. This is because the liquid produce from this process can be stored until it required or readily transported to where it can be most effectively utilized, and the high density of this liquids (around 1.2 kg/litre) (Abdullah *et. al.* 2007).

A fast pyrolysis process includes drying the feed to typically reduce the moisture to 10% in order to minimize the water in the product liquid oil, size reduction of the feed (to around 2 mm in the case of fluid bed reactors), to give sufficiently small particles in ensuring rapid reaction, pyrolysis reaction, separation of solids (char), and collection of the liquid product (bio-oil). To produce liquid, there are few parameters that are really critical in this process **(**Bridgwater, 2004);

1. Very high heating and heat transfer rates at the reaction interface, which usually requires a finely ground biomass feed.
2. Carefully controlled pyrolysis reaction temperature of around 500 ºC and vapor phase temperature of 400-450 ºC,
3. Short vapor residence times of typically less than 2 seconds·
4. Rapid cooling of the pyrolysis vapors to give the bio-oil product.

1.3 Availability of Oil Palm Biomass in Malaysia

In 2006, Malaysia is the second largest palm oil production in the world covered about 43% of the total world supply. The total production is growing from year to year resulted the increase of 3.4% productive oil palm plantation to 4.3 million hectares in 2007. This increase is stimulated by the growing of global demand. As long as the increasing of production result the growth of residue amount (Shuit *et al.* 2009). One hectare of oil palm plantation generates about 21.625 tonnes per year of biomass residues and overall estimation about 73.74 million tons per year. The residues produce annually are shown in Table 1.1.

Table 1.1: Types of Biomass and Quantity Produced (Sumathi *et al.* 2007)

No. Type of biomass Quantity	**annum (MnT)**
Empty fruit bunch (EFB)	15.8
Fronds	12.9
Mesocarp fiber (MF)	9.6
Trunk	8.2
Shell	4.7

The treatment of the palm oil residue will cause a lot of money to be spent and the effects to the environment. The residue of palm oil are proved experimentally have multifunction purpose to generate the useful product. So, the converted of this residue should become the priority as long as to make money from it and also to safe our environment. The commitment of the worldwide to the reduction of greenhouse effect makes the utilization of the palm oil/palm oil product become popular for energy production and petrochemical replacement. If there is no any drastic change in cost component of palm oil, it can be assumed that palm oil will become competitively produced to meet the growing world market demand (Sarmidi *et al.* 2009).

1.4 Problem Statement

Generally, it is accepted worldwide that climate change is currently the most pressing global environmental problem facing the humanity. Utilization of fossil fuel as a source of energy for heat, electricity and transportation fuel has been identified as the primary cause of global warming. Thus, in order to reduce emission of greenhouse gases and to promote greater energy efficiency, substitution of fossil fuel with renewable energy should be part solution of the climate change (Shuit *et al.* 2009).

In Malaysia, energy demand shows the rapid increase from year to year. The increases of demand reduce the sources of fossil fuels cause the price to be increased (.Abdullah et al., 2009). In Malaysia, reserves of fossil fuels just can cover 30-40 years to come. However, Malaysia as a country with a significant amount of agricultural activities, biomass can be a very promising alternative source of renewable energy. As the world largest producer and exporter of palm oil in the world, Malaysia's palm oil industry leaves behind huge amount of biomass from its plantation and milling activity. These large values of biomass surely need a lot of money for treatment. The availability of new technology are really required to convert this sustainable source of palm oil into various types of value added products that will generate money and also save the cost of treatment (Shuit *et al*. 2009).

A fast pyrolysis process will produce bio-oil, chars and gas. The efficiency of this process is depending to the percentage of bio-oil production. The effects of temperature and air damper setting of gas burner are really important in influencing the high production of bio-oil through direct fired pyrolysis process. The best selection of parameters and condition ensures the rapid heating of each part of the sample that will be bringing to the high yield of bio-oil at the end of this process (Abdullah *et al.* 2008).

A lot of recent pyrolysis studies worldwide used the pyrolysis reactor that using electric as the main heating source. Daan Assink (2007) studied Empty Fruit Bunches (EFB) and Palm Kernel Shells (PKS) Fast Fired Pyrolysis Process, by using electricity as the heating source and obtaining the maximum yield of bio-oil from the process about 42% gained from the highest heating rate at 100^{O}C/min. The highest conversion of bio-oil is about 35% for the process temperature at 500 ^{O}C (Sukiran, 2008). Kim *et al.* 2010 studied the influence of operation parameters on the bio-oil yield for fast pyrolysis process of Palm Kernel Shells (PKS) using an electric-heater fluidized bed reactor to pyrolyze the sample. From this study, the highest yield of bio-oil (49.3%) is gained at temperature of 490 ^{O}C. All of this researches used electric as the heating source since the energy conversion of heat by electric will only have 40% of efficiency which is not efficient (A.H Jafar, 2008). Besides that, the sources for electric are very costly and limited to access at certain area. So, the search for a system that is used direct heated reactor with is compatible with the current system available is really essential in saving the energy and cost.

1.5 Objectives of the Research

The objective of this research is to study the effect of oil production from the different parameters, reaction temperature and air damper setting of fast pyrolysis process of Empty Fruit Bunches (EFB) and Palm Kernel Shells (PKS). Since most of the recent pyrolysis studies were using electric heated system, this research will use a gas-fired pyyrolysis system that is portable, saving energy and cheaper. So, this research is aimed to make the comparison in term of conversion of bio-oil to determine the new alternative system that is portable, energy saving and cheaper that is having a compatible performance with the electric heated system.

1.6 Scope of Works

In this research, the scopes of this research are stated as follows:

1. Fabricate the Gas Fired Pyrolysis system.

2. Study the effects of different palm oil biomass samples, Empty Fruit Bunches (EFB) and Palm Kernel Shells (PKS) to the bio-oil yields.

3. Analyze the optimum production of bio-oil will from the best parameter of pyrolysis condition.

1.7 Rationale and Significance

During this research, we will convert palm oil biomass into a very useful product, bio-oil. The significance of this research is to analyze the best setting of a few parameters for the highest gain of bio-oil from gas-fired Pyrolysis process of Empty Fruit Bunches (EFB) and Palm Kernel Shells (PKS). This parameters, process temperature and air damper setting are strongly influencing the conversion of bio-oil and also the characteristics of bio-oil itself. The best conversion of EFB and PKS will reduce the cost of treatment and generate money from the biomass beside to keep the environment clean. Empty Fruit Bunches (EFB) and Palm Kernel Shells (PKS) from palm oil residue will be used as the raw material for the production of bio-oil because the sustainable sources available in Malaysia.

Besides that, this conversion of bio-oil from this research will be compared with the recent study that was using electric-heated system. A direct fired reactor gained the heat from the gas burner and the distribution of heat is influenced by the wall design of the furnace. This kind of reactor is able to save energy and cost beside is accessible at certain area without the electric coverage and saving energy, cost and time. So, this comparison will able to initiate the development of the new fast pyrolysis technology that will reduce the cost of energy consumption and enhance the operation at the larger scale.

Empty Fruit Bunches (EFB), is a rich fibrous material with a clean, biodegradable and compatible characteristic that is produced in large quantity as the residue from palm oil processes. Palm Kernel Shell (PKS) is a shell that surrounds kernel of palm fruit and produce as the residue after extraction of palm oil process. A fibrous material with low moisture content compared to other biomass residue.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Biomass

Today, fossil fuels cover 86% of the world energy consumption and almost 100% of the energy needed in the transportation sector. Environmental pollution and diminishing supply of fossil fuels are the key factors leading to search for the alternative sources of energy. Thus, the renewable energy sources, in conjunction with other clean energy sources, appear to be the best and necessary substitution alternative. There are many other sources of renewable energy such as solar, wind, and geothermal. But biomass seems to have been receiving a lot of attention lately because it not only provides an effective option for the provision of energy services from a technical point of view but is also based on sustainable resources that can be utilized all around the globe (Tau *et al.* 2007).

The term biomass refers to plant materials and animal wastes used for energy, especially tree and grass crops, forestry, agricultural and urban wastes. Biomass is a renewable energy source because it contains energy that comes from the suns. Through photosynthesis process, sun's energy is captured by chlorophyll in plants and converted carbon dioxide from the air and water from the ground into carbohydrates, complex compounds composed of carbon, hydrogen and oxygen. When these carbohydrates are burned, they turned back into carbon dioxide and water and the sun's energy content is released. In this way, biomass functions as a sort of natural battery for storing solar energy (de la Garza, 2007).

Biomass currently represents approximately 14% of world's final energy consumption. About 25% of the usage is in industrialised countries, where a significant level of investment in environmental protection has been made to meet emissions standards, especially air emissions. The other 75% of primary energy use of biomass is in heat production for developing country household energy needs and in process heat production for biomass-based industries through the use of their generated residues **(**Parikka, 2003).

2.2 Biomass in Malaysia

Modern bio-energy has gained increased attention in the past decade. Not only does bio-energy provide an effective option for the provision of services from the technical point of view, but also based on sustainable resources that can be utilized all around the globe (Silveira, 2005).

In addition, to mitigate climatic change caused by greenhouse gas emissions, the developed world is working to substitute fossil fuels with renewable energy sources. To stabilize the atmospheric concentration of CO_2, global emissions must be reduced by at least 60% from the current levels. Approximately 80% of the total emissions come from use of fossil fuels, mostly from industrialized nations and the remaining 20% is believed to come from deforestation, mostly from tropical nations. Furthermore, there are indications that forestland could contribute more to global CO_2 stabilization through sustained production chains of fuel for biomass energy systems to replace fossil fuels (Parikka, 2004).

Energy demand in Malaysia indicates a rapid increase for a few years to come and to be expected to reach almost 100 Mtoe (million tonne of oil equivalent) in 2030. However, these are depleting energy resources and increasing demand has made it necessary for the Government to embark on alternative energy sources. Malaysia as a country that has a significant amount of agricultural activities, biomass can be a very promising alternative source of renewable energy (Shuit *et al.* 2009).

But, it is rather surprising the use of renewable energy supply in Malaysia is still very low. In 2005, 93% energy consumption of Malaysia is still depended heavily on fossil fuels (natural gas, coal, diesel and oil) and only 0.5% of energy came from renewable sources such as biomass (excluding hydropower). If this trend continued on, Malaysia would suffer from lack of energy security as Malaysia fossil fuel reserves is predicted to last only for another 30–40 years. Beyond that, Malaysia will become a net importer of fossil fuel, mainly oil and gas (Shuit *et al.* 2009).

However, Malaysia is taking pro-active steps in strategizing the development of bio-fuel in the country (Abdullah *et al.* 2009). In fact, the government of Malaysia has embarked on this ideology by drafting the 5th fuel policy that states. ‘‘To supplement the conventional energy supply, new sources such as renewable energy will be encouraged and biomass such as oil palm, wood waste as well as rice husk will be used on the wider basis” (Shuit *et al.* 2009).

Moreover, Malaysian palm oil industry has grown tremendously over the last 4 decades and since then; it has maintained its position as the leading world's country in the production of palm oil (Nasrin *et al.* 2008). Currently, Malaysia is the largest producer and exporter of palm oil, producing about 47% of the total world supply. The total mature areas of palm oil plantation represent 56% of total agricultural land and 11.75% of the country's total land area. With the projected growth in the cultivation of palm oil, the destination of the huge amount of residues raises concerns. The amount of residues produced from palm oil plantation is much larger in comparison with other types of biomass produced in Malaysia. It is estimated that oil palm plantation generates 73.74 million tonnes of biomass annually with the estimation of one hectare of oil palm plantation generates about 21.625 tonnes per year of biomass residues. With the huge amount of biomass generated annually, Malaysia has the potential to utilize the biomass efficiently and effectively to other value added products (Tau *et al*. 2007).

Sustainability of oil palm biomass creates the carbon balance for palm oil biomass utilization. Note that combustion of palm oil biomass does not contribute to net amount of carbon in the atmosphere as carbon is absorbed during plant growth. In addition, utilization of palm oil biomass could also ensure social sustainability by creating job employment opportunities for rural areas in a developing country like Malaysia because the high operator requirement for the cultivation of energy crops compared to another renewable energy (Shuit *et al*. 2009).

The crucial role of energy in achieving Malaysia's development aspirations has long been recognized, particularly in the country's five-year plans. This development, of major significance to the country's economy, has been followed by the formulation of several important policies developed over the last four decades focused on ensuring a secure, reliable and cost-effective supply of energy, aimed at enhancing the competitiveness and resilience of the economy (UNDP, 2007). Table 2.1 shows the policies or plans introduced by Malaysian government to enhance more secure, reliable and cost-effective supply of energy over the last four decades.

Table 2.1: Policy/Plan introduced by Malaysian government for the last four decades (UNDP, Malaysia, 2007)

Policy/ Plan	**Broad Objectives**
1975 National petroleum policy	Introduced to ensure optimal use of petroleum resources, regulation of ownership and management of the industry, and economic, social, and environmental safeguards in the exploitation of this valuable resource
1979 National energy policy	Formulated to achieve supply, utilization and environmental objectives.
1980 National depletion policy	Introduced to guard against over exploitation of oil and gas
1981 Four diversification policy	Fuel emphasis given to fuel diversification, designed to avoid dependence on oil; aimed at placing increased emphasis on gas, hydro and coal
2000 Renewable, as the fifth fuel policy	Energy introduced in recognition of the potential of biomass biogas and other renewable energy resources
2006 National Biofuel Policy	Designed to pave the way for extensive development of the biofuels industry
Seventh Malaysia Plan 1996-2001, Eighth Malaysia Plan, 2001-2005 and Ninth Malaysia Plan 2006-2010	Emphasis on energy efficiency and on generation from renewable sources in an effort to reduce the rapid depletion of other fuel sources

2.3 Thermal conversion processes of biomass.

Generally, biomass conversion system consist of a few of conversion processes; thermo chemical, physical, liquefaction, and biochemical conversion. A variety of biomass resources can be used to convert to liquid, solid and gaseous fuels using these conversion processes. Thermo chemical biomass conversion does include a number of possible roots to produce from the initial bio renewable feedstock useful fuels and chemicals. Thermo chemical conversion processes consist three sub-categories: pyrolysis, gasification, and combustion process. Through this thermo chemical process, bio renewable feedstocks can be used as a solid fuel, or converted into liquid or gaseous forms for the production of electric power, heat, chemicals, or gaseous and liquid fuels. The summary of the alternatives of the biomass conversion processes is showed in Figure 2.1.

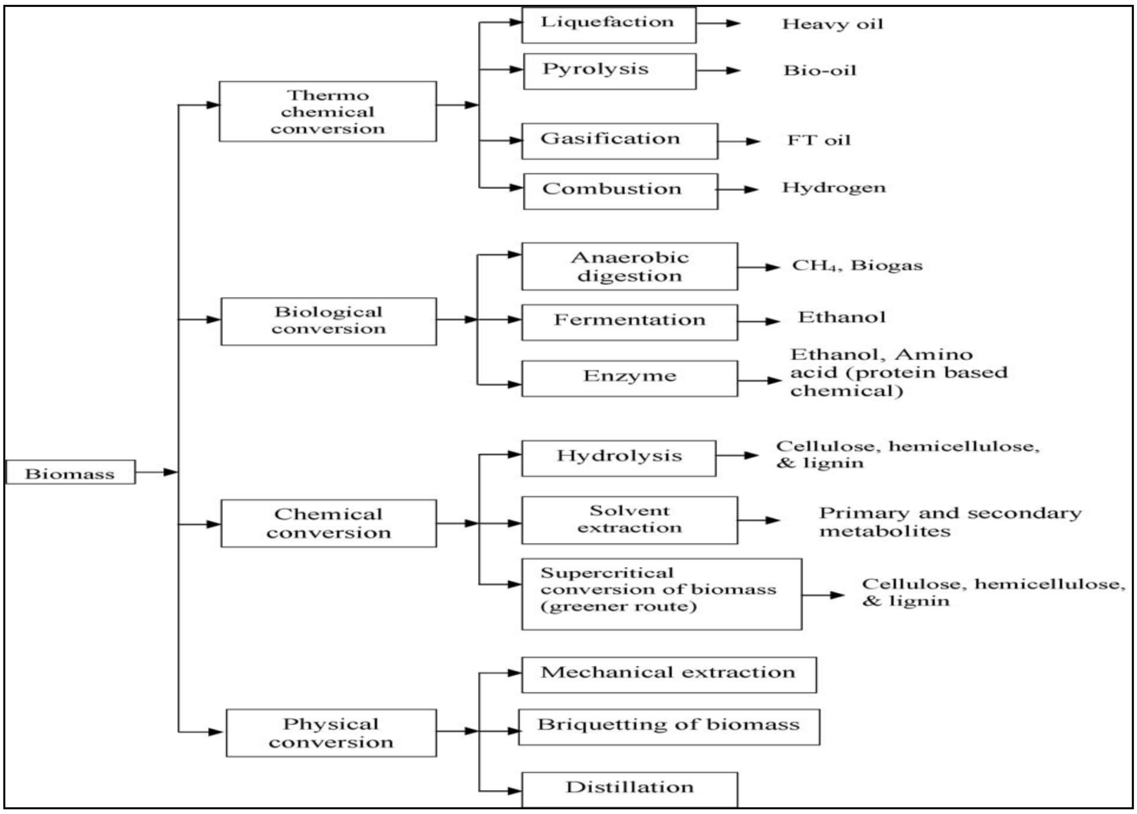

Figure 2.1: Biomass Conversion Processes (Naik *et al.* 2009)

2.3.1 Gasification Process

Gasification is an energy process producing a gas that can substitute fossil fuels in high efficiency power generation, heat and/or CHP applications, and can be used for the production of liquid fuels and chemicals via synthesis gas. Gasification is one of the effective energy conversion methods for the utilization of biomass. The resulting gas, known as producer gas, is a mixture of carbon monoxide, hydrogen and methane, together with carbon dioxide and nitrogen (Umeki *et al.* 2009).

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 combustible gas can be burnt to provide energy for cooking and space heating, or create electricity to power other equipment (Demirbas, 2009).

2.3.2 Combustion Process

Combustion is the chemical reaction between a fuel and oxygen which usually takes place in air and is more commonly known as burning. The products are carbon dioxide and water with the release of heat (Naik et. al, 2009). Direct combustion is the most common way of biomass transformation into heat or electric energy. Worldwide, in ninety percent of cases, energy is obtained from biomass through the combustion process, because of a relatively advanced knowledge of this technology, its relative simplicity, and commercial availability (Janasek, 2009).

One of the major barriers is the public concern of the release of solid and gaseous toxic matter into the environment from the combustion process. Toxic heavy metals cannot be destroyed during the combustion process and the toxic metal particles or vapors are generated as by-products when wastes containing these metals are burned. A significant fraction of volatile metal compounds (e.g. lead, mercury, cadmium and chromium) are emitted as vapors or fine particles. Non-volatile toxic metal compounds are also released with the ash and also require safe disposal. Thus, it is important to improve combustion processes, in which products that could be safely land filled or reused would be generated (Zheng *et al.* 1999).

2.3.3 Liquefaction Process

Thermo chemical liquefaction mainly aimed at obtaining low molecular weight liquid fuels from organic high molecular weight compounds by conversion of biomass in the liquid water at high temperature and high pressure in the presence of alkali catalyst with/without reducing gas. Liquefaction usually produces water insoluble oils of high viscosity and usually requires solvents, reducing gases such as CO or H_2 and/or catalysts to be present in addition to biomass (Naik *et al.* 2009).

The advantage of this process is that it does not require drying process of feed stocks. Since most biomass usually has high moisture content, a drying process requires much heating energy due to the large latent heat of water vaporization. The process is attractive from the viewpoint of energy consumption and it is a promising method for the biomass conversion. Liquefaction process can be an effective method for converting woody biomass into oil or other types of fuels (Qian *et al.* 2005).

2.3.4 Pyrolysis process

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 H_2-rich gases under an oxygen absence condition (Yang, 2006). Pyrolysis is not only as an independent process leading to the production of energetically-dense products, but also as an intermediate step in a gasification and combustion process make pyrolysis is interesting (Koufopanos *et al.* 1992).

Conventional slow pyrolysis has been applied for thousands of years mainly for the production of charcoal. Lower process temperature and longer vapour residence times favour the production of char coal. High temperature and longer residence time increase the bio mass conversion to gas and moderate temperature and short vapour residence time are optimum for producing liquids (Bridgwater, 2004).

The yields and compositions of pyrolysis products are highly dependent on biomass species, chemical and structural composition of biomass material, process temperatures and heating rates. At present, fast or flash pyrolysis at high temperatures with very short residence times is the most preferred technology for production of bio-oil (Razuan, 2010). Table 2.2 shows the pyrolysis routes and their variant.

Table 2.2: Pyrolysis routes and their variants **(**Demirbas, 2009)

Method	Residence time	Temperature (K)	Heating rate	Products
Carbonation	Days	675	Very low	Charcoal
Conventional	5–30 min	875	Low	Char, oil, gas
Slow	20–200s	900	High	Oil, char, gas
Fast	0.5–5 s	925	Very high	Bio-oil
Flash-liquid	<1 s	<925	High	Bio-oil
Flash-gas	<1 s	<925	High	Chemicals, gas
Hydro-pyrolysis	<10 s	<775	High	Bio-oil
Methano-pyrolysis	<10 s	>975	High	Chemicals
Ultra pyrolysis	<0.5 s	1275	Very high	Chemicals, gas
Vacuum pyrolysis	2–30 s	675	Medium	Bio-oil

2.4 Fast Pyrolysis of biomass

Fast pyrolysis is a thermal decomposition process that occurs at moderate temperatures in which the biomass is rapidly heated in the absence of oxygen or air to produce a mixture of condensable liquids, gases and char (Abdullah et. al, 2008). This process is perceived to offer logistical and hence economic advantages over other thermal conversion processes because the liquid product can be stored until required or readily transported to where it can be most effectively utilized, and the liquid's density is also high (around 1.2 kg/litre) (Abdullah et. al, 2007).

The yields of end products of pyrolysis are dependent on several parameters including temperature, biomass species, particle size, heating rate and operating pressure but the most critical parameters are temperature and residence time (Yang, 2006). To obtain bio –oil yields of around 70%, and char and gas yields of around 15% each for woody feedstocks, required temperature around 500^{0}C together with short vapour residence times (Abdullah et. al, 2008). But, generally to produce liquid yield, essential parameters for fast pyrolysis includes;

a. very high heating and heat transfer rates at the reaction interface, which usually requires a finely ground biomass feed,
b. carefully controlled pyrolysis reaction temperature of around 500 ºC and vapour phase temperature of 400-450 ºC,
c. short vapour residence times of typically less than 2 seconds, and rapid cooling of the pyrolysis vapours to give the bio-oil product **(**Bridgwater, 2004).

Tsai *et al.* (2005) investigated the fast pyrolysis process of rice husk using a horizontally tubular reactor under different pyrolysis temperature, holding time, heating rate, sweep gas, flow rate, condensation temperature, and particle size to study the percentage of pyrolysis product yield and their chemical composition. The optimum bio-oil yield of 40% achieved at the pyroysis temperature of 500°C, heating rate of 200°C min^{-1}, holding time of 2 min, condensation temperature of -10°C and particle size of 0.50 mm. This study also found that the pyrolysis oils contain complex compound mostly composed of aromatic and carbonyl structures, resulting in low pH and low heating values.

Zheng (2008) investigated the pyrolysis oil that is produced from fast pyrolysis of maize stalk in fluidized bed reactor at a temperature range 420-580°C. From this study showed that the highest pyrolysis oil yield of 66 wt% was obtained at 500°C for maize stalk. The result also showed that pyrolysis oil from the maize stalk can be used directly without any upgrading as a fuel oil for combustion in a boiler or furnace.

Hyeon *et al.* (2009) studied the fast pyrolysis of waste furniture sawdust in a fluidized-bed reactor for different temperatures, flow rates of fluidizing agent and particle sizes. These researchers found that the highest yield of bio-oil can be obtained at 450°C with the particle size of 0.7mm and using the noncondensable product gas as the fluidizing medium compared by using nitrogen gas with the maximum percentage of bio-oil yield about 65%.

Kim *et al*. 2010 performed the Palm Kernel Shells (PKS) pyrolysis process in a bench-scale plant, with a throughput of up to 1 kg/h, consisting of a feeding system, a fluidized-bed reactor, a char-separation system, a quenching system and a gas-circulating system. The fluidized-bed reactor was heated indirectly with the electricity and Nitrogen became the fluidizing agent. The usage of Nitrogen will be replaced by recycled non-condensable gas produced from the reaction stage by stage. The char-separation system consisted of a cyclone and a hot filter designed to capture particles bigger than 10 and 2 µm, respectively. The quenching system was made up of a stainless condenser, two glass condensers and an electrostatic precipitator by which oil and aerosol were caught. The stainless condenser and glass condenser were cooled to 20 and 30^{o}C using water and ethanol, respectively. The maximum yield of bio-oil of 48.7% was obtained at reaction temperature of 490^{o}C. The schematic diagram of the pyrolysis system used by Kim *et al*. 2010 was showed in Figure 2.2.

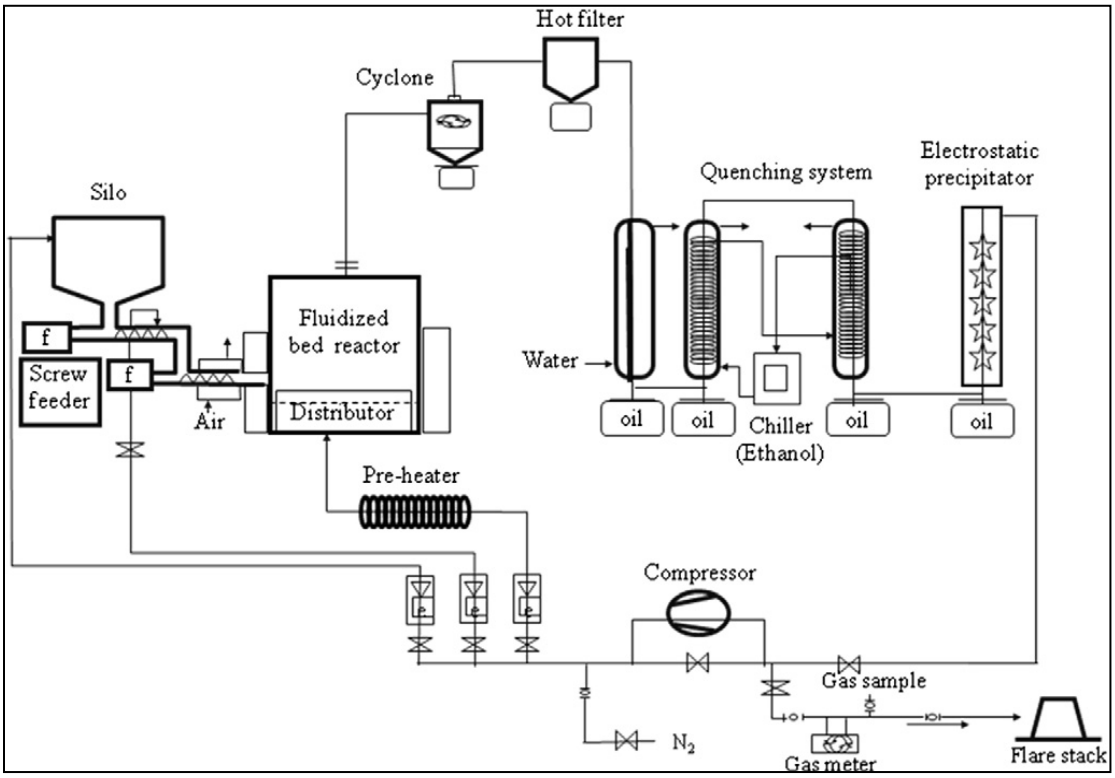

Figure 2.2: Pyrolysis System used by Kim *et al*. 2010

In the study by Li *et al.* 2007, 1g/min of PKS samples sized below 1mm were pyrolyzed in a bench-scale countercurrent fixed bed. The system consists essentially of quartz with a continuous feeding system, a gas cleaning section containing a cyclone solid collector and a quartz wool filter, a cooling system for the separation of water and condensable organic vapors (oil), and various gas measurement devices. The quartz tube reactor was heated by a furnace with four independently controlled electric resistance heaters. As a result, the maximum bio-oil product of 31% was obtained at 500^{o}C. The schematic diagram of the pyrolysis system used by Kim *et al*. 2010 was illustrated in Figure 2.3. There were a lot of researches of fast pyrolysis process around the globe that can be summarized in Table 2.3.

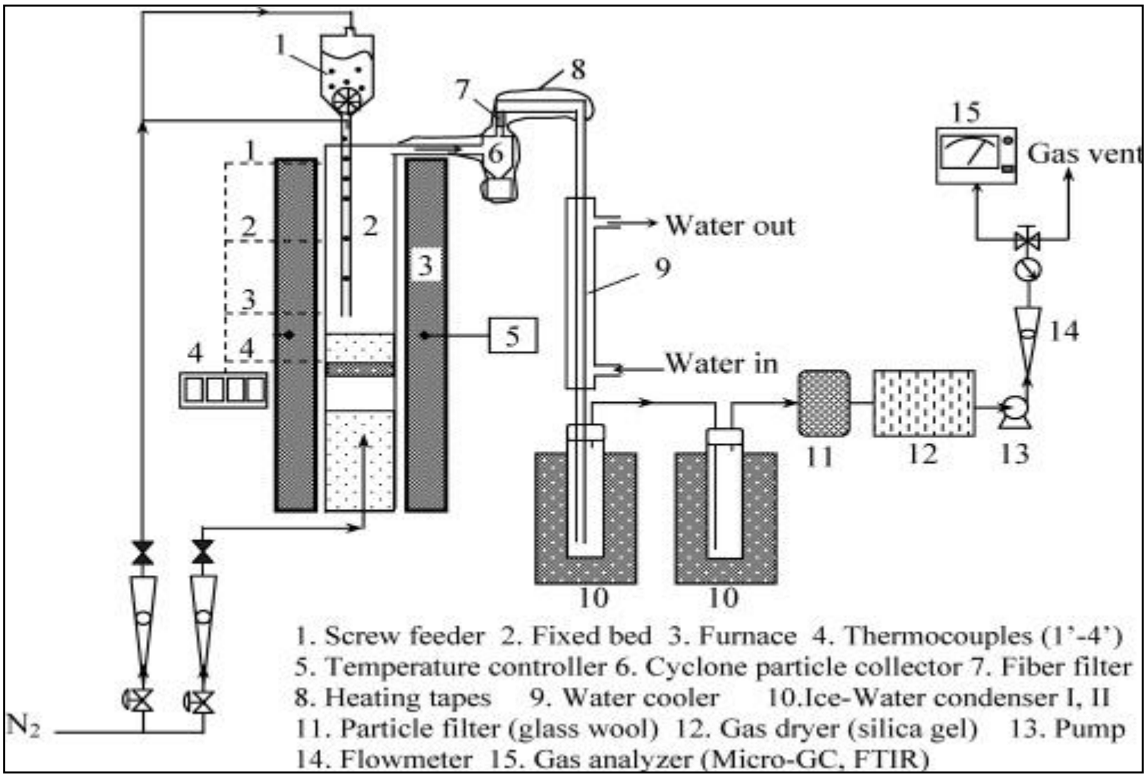

Figure 2.3: Pyrolysis System used by Li *et al.* 2007

Table 2.3: Summary of fast pyrolysis biomass researchers (Sukiran, 2008)

Type of feed (biomass)	**Type of pyrolysis**	**Reactor**	**Maximum bio-oil yield**	**Researcher**
Sunflower press cake	Fast pyrolysis	Tubular transport reactor	45.0%	Yorgun et al. (2001)
Rice husk	Fast pyrolysis	Induction heating rate furnace	40.0%	Tsai et al. (2005)
Rape seed	Fast pyrolysis	Well-swept fixed–bed tubular reactor	68.0%	Onay et al. (2001)
Soybean cake	Fast pyrolysis	Well-swept resistively fixed-bed reactor	42.8%	Uzun et al (2006)
Linseed	Fast pyrolysis	Tubular transport reactor	68.8%	Acikgoz et al. (2007)
Bark from Turkish red pine	Slow pyrolysis	Fixed-bed reactor	33.3%	Sensoz (2003)
Palm oil wastes	Fast pyrolysis	Countercurrent fixed bed reactor	~57.0%	Yang et al. (2006)
Rice straw, sugarcane baggase, coconut shell	Fast pyrolysis	Induction-heating reactor	40.0%	Tsai et al. (2006)
Palm Kernel Shells	Fast Pyrolysis	Fluidized Bed reactor	48.7%	Kim *et al.* (2010)
Palm Kernel Shells	Fast Pyrolysis	Countercurrent fixed bed reactor	31%	Li *et al.* (2007)