Design and Fabrication of Fluidized Bed Pyrolysis System

Nur A. Fadhilah, Muhammad N. Islam, and Roslynna Rosli
Universiti Teknologi Brunei, Bandar Seri Begawan, Brunei Darussalam
Email: amalfadhilah.narawi@gmail.com, {mohammad.gafur, roslynna.rosli}@utb.edu.bn

Abstract— **A fluidized bed pyrolysis system has been designed and fabricated for practical demonstration of the fluidization of biomass solid waste particles at optimal performance for bio-fuel production. The bed of this reactor was sand particles of average size 300µm and a density of 1.46g/cm3. Nitrogen gas was used as fluidizing fluid to maintain an inert atmosphere in the reactor. The major components of the system are: fluidized bed reactor, heating cylinder, cyclone, condenser and liquid collector. All the components have been successfully assembled for future experimental use. The height of the sand bed was 6.24 cm on a distributor with a mesh of 125 µm. According to hydrodynamic test, the minimum flow rate for the fluidization of the sand particles was 15 l/min; whereas, it was close to the theoretical value of 15.7 l/min when the optimum fluidization was expected.**

Index Terms—**fluidized bed reactor, fast pyrolysis, biomass solid waste, bio-oil**

I. Introduction

Energy White Paper has reported that hydrocarbon production has contributed to higher levels of carbon dioxide emissions, and that the consequences of severe drought, major floods and heat waves. This presents a particular challenge for small island developing states like Brunei Darussalam [1]. In addition, the fossil fuel reserves gradually deplete and rate of energy consumption increasing significantly day by day. Although oil and gas sector will likely remain at the forefront of economic growth in Brunei Darussalam, the country did prioritized sector diversification and development of renewable energy projects in recent years. Among current growth in the field of renewable energy, the utilization of biomass for the production of bio-energy and bio-fuels are a promising option to replace some fossil sources of energy in environmentally friendly ways [2]. Hence, this contributes to reduce net greenhouse gas emissions and increase economic development in the country [3].

One of the challenges involves in utilization of biomass for energy applications is to make use thermochemical conversion technologies to convert raw biomass sources into more energy intermediates [2]. Fast pyrolysis offers a convenient way to thermally decompose biomass macromolecules into bio-char, bio-oil and syngas in the absence of oxygen [4]. It is where biomass solid waste can be used without further pre-treatment and short residence time at a moderate temperature around 500℃ [5]. One of the common reactors used for fast pyrolysis is fluidized bed reactor, which consists of a fluid-solid mixture that exhibit fluid like properties. It is known for good heat transfer capability, better control of pyrolysis reaction and vapor residence time, large surface area contact between fluid and solid per unit volume, excellent thermal transport inside the system and high relative velocity between the fluid and solid phase. In addition, fluidized bed distributor are self cleaning, and require little or no maintenance [6-8].

The generic features of the fluidized bed pyrolysis system have been illustrated in research literature [2-5,9-12]. A Fluidized bed pyrolysis system was designed and fabricated in Civil and Mechanical Engineering Laboratory of Universiti Teknologi Brunei (UTB), for the study of characteristic flow through a bed of solid particles which is sand particles using nitrogen gas as fluid. Moreover, to determine the suitable flow rate of nitrogen gas in the fluidization process to happen. The system was equipped with fluidized bed reactor, including the filter distributor, a char separation system composed of the cyclone, heating cylinder with insulation, condenser and liquid collector for bio-oil collection in the future use.

II. Design and Fabrication

In the fluidized bed pyrolysis system, there are five main components, including fluidized bed reactor, heating cylinder, cyclone, condenser and liquid collector. The material used was specifically stainless steel Type 409 as it can withstand high temperature and also corrosion resistant.

A. Fluidized Bed Reactor

It is where the thermal decomposition of feedstock taking place at selected temperature. The fluidized bed reactor consist of three main parts including the feeder, updraft reactor and gas preheating chamber as shown by Fig. 1. Updraft reactor was selected due to the simplicity in fabrication at which the feedstock move in from the top through feeder and move downward to the reactor bed. The feeder is fully covered to avoid any oxygen entering the reactor. A cylindrical reactor was considered with

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internal diameter of 7 cm and vapor residence time of 5 s when the nitrogen flow rate set to 16 l/min. The reactor volume and length were designed to 1316 cm3 and 36 cm respectively, so that sufficient amount of feedstock could be taken into it. At the lower part of the reactor was fitted with a distributor by mesh of 125 µm at the base and the bed was filled with sand particles. The gas preheating chamber is attached at the bottom of reactor bed, it is where the fluidizing gas, which is nitrogen gas preheated around 100 ℃ to 200 ℃ before entering to the reactor..

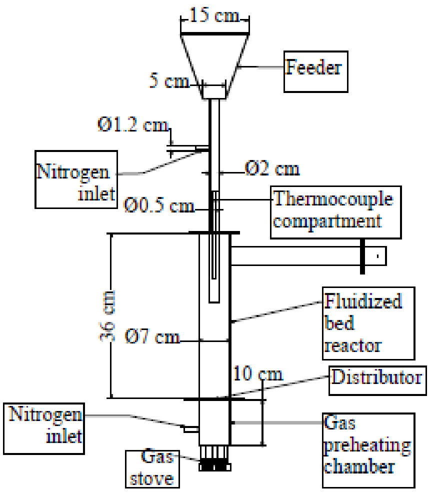

Figure 1. Dimensional view of fluidized bed reactor.

B. Heating Cylinder

The cylindrical tank is put around the reactor and it consists of two layers. First layer is surrounded by insulation known as asbestos in order to reduce heat loss to the surroundings. Then, the second layer in between the reactor is the place where to put the biomass, which is in this study coarse sawdust are used. The hybrid heating is the method applied in this study. It is the combination of biomass heating and gas heating. Biomass heating is where biomass is used as the source of heat energy to be supplied to the reactor and gas heating is where the Liquefied petroleum Gas (LPG) provide assistance to overcome the inconsistent heating problems. In addition, there is a semi hemisphere hole pass through the both layers of the tank to place the LPG heating torch and air blower for temperature control purposes. The dimensional view of the heating cylinder shown in Fig. 2.

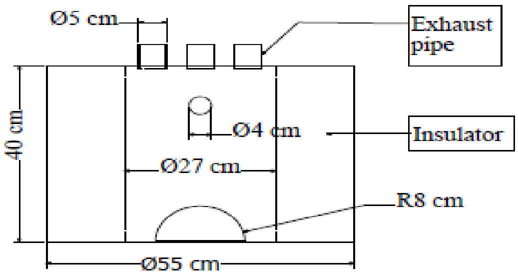

Figure 2. Dimensional view of heating cylinder.

C. Cyclone

Cyclone is where the hot vapor from the reactor enter and act as separators which provide a method of removing particulate matter, especially bio-char from the vapor at low cost and low maintenance. Conventional cyclone with tangential inlet structure is selected as shown by Fig. 3 due to simplicity in design and high char collection efficiency. It has a body diameter of 7cm with both lengths of the body and cone of 14 cm. The design of the cyclone was based on the standard cyclone dimension according to Lapple dimension (1940) [13]. .

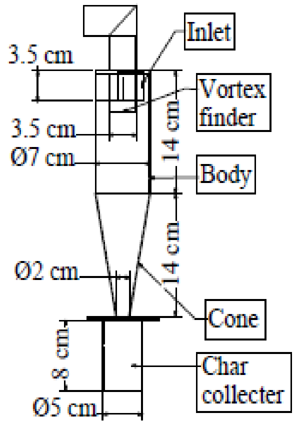

Figure 3. Dimensional view of cyclone.

D. Condenser

A condenser is simply a heat exchanger, a device that transfers heat from one fluid to the others. Parallel double pipe heat exchanger is selected due to ease in construction and cleaning purposes. According to Park et al. [14] parallel flow pipe with vertical design of heat condenser allows the vapor to fall along with gravity [15]. A water cooled, counter flow condenser used to cool down the hot vapor. Hence the rapid cooling of the hot vapor promote high conversion into product yield. The internal diameter and length of the condenser was 3.5 cm and 50 cm respectively. The outer shell diameter of the condenser was 6.5 cm. The dimensional view of condenser shown in Fig. 4..

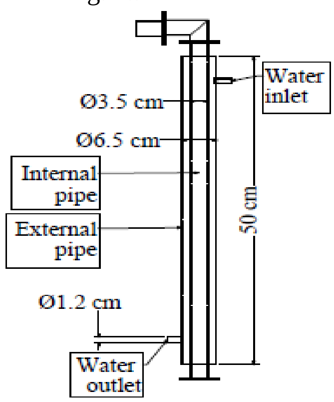

Figure 4. Dimensional view of condenser.

E. Condenser

It is where the bio-oil and non-condensable vapor, which is syngas, flow from the condenser. There are two cylindrical liquid collector as shown by Fig. 5 are arranged in series. Whereas, the first collector is to gather the bio-oil product. Then the other collector is where the syngas is passed through to the surrounding. The design of the liquid collector was made to accommodate up to 0.5652 litre..

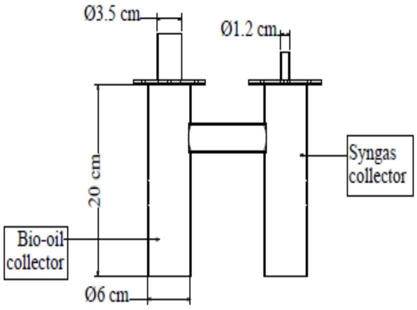

Figure 5. Dimensional view of liquid collector.

III. Construction of the Bed

A. Sand Bed Calculation

The density and particle size of the sand was determined according to standard procedure [16], and it was found to be 1.46 g/cm3 and 300 µm respectively. Choosing the mass of the sand to be 200g for fluidized bed reactor of 7 cm diameter and sand void fraction of 0.43 [17]. According to Suleiman et al. [7] the height of sand bed was determined by following equation:

$$\varepsilon = 1 - \frac{m_s}{\rho_s \times \left(\frac{\pi d^2 h}{4} \right)}. \quad (1)$$

where ε is the sand void fraction, m_s is the mass of the sand, ρs is the density of the sand, d is the diameter of fluidized bed reactor and h is the height of the sand bed as shown below:

$$\varepsilon = 1 - \frac{200}{1.46 \times \left(\frac{\pi (7)^2 h}{4} \right)} = 0.43$$

$$h = 6.24\, cm.$$

Actual fluidization happens in a velocity known as fluidization velocity, the point at which the drag force on an individual particle is about to exceed the gravitational force exerted on it [18]. Whereas in this case, the fluidization velocity is sufficient enough to suspend the sand particles from the bed, however; not large enough to carry the sand particles out of the fluidized bed reactor. Fluidized velocity was calculated and it is given by:

$$V_f = \frac{(\rho_s - \rho_f) \times g \times s^2 \times \varepsilon^3}{150 \times \mu \times (1 - \varepsilon)}. \quad (2)$$

where V_f is the fluidized velocity of the sand, ρ_s is the density of the sand, ρ_f is the density of nitrogen gas [19], g is the earth gravitational accelerations, s is the size of sand particles, ε is the sand void fraction and μ is the absolute viscosity of nitrogen gas [20] as shown below:

$$V_f = \frac{(1460 - 1.250) \times 9.81 \times (300 \times 10^{-6})^2 \times 0.43^3}{150 \times (1.76 \times 10^{-5}) \times (1 - 0.43)}$$

$$V_f = 0.068\, ms^{-1}.$$

The nitrogen gas will flow upward through the distributor which cause the sand particle on the filter to fluidized. Hence the flow of nitrogen gas needs to be controlled properly to ensure it just enough to keep the sand particles in suspension. Theoretically, as shown in (3), flow rate of nitrogen gas was determined by multiplying the area of the fluidized bed reactor and fluidization velocity:

$$Q = \frac{\pi d^2}{4} \times V_f. \quad (3)$$

where Q is the flow rate of nitrogen gas, d is the diameter of the fluidized bed reactor, V_f is the fluidized velocity of the sand as shown below:

$$Q = \frac{\pi (7)^2}{4} \times 0.0680 = 15.7\, l / \min.$$

B. Hydrodynamic Test

The test was done to investigate the motion of fluids and forces acting on solid bodies immersed in the fluid as well as motion relative to them [21]. It was done by putting the sand particle on the distributor in a plastic bottle as shown in from Fig. 6. Then let the nitrogen gas flow by opening the gas pressure regulator through the hole at the bottom of the plastic bottle. From the observation, it was determined that the sand particles start to fluidize at a flow rate of 15 l/min and above.

Figure 6. Hydrodynamic test assembly.

IV. Experimental Setup

Proper assembly of the various components in the pyrolysis system was the important task needed to allow optimum performances as shown from Fig. 7. At first, the weight all the main components such reactor, cyclone, condenser and liquid collector before the test runs to determine the initial weight of the components. Screw and flange were used to join the components. The joints were sealed by liquid gasket that can withstand up to 600 ℃ to ensure no leakage to the atmosphere. Fluidized bed reactor was bolted inside the heating cylinder where the end flange is connected to the entry flange of the cyclone. Closing lid of the heating cylinder has a compartment for the thermocouple probe to be placed inside. Both feeder and gas preheating chamber are connected with nitrogen gas cylinder by a pipe. The flow rate of nitrogen gas was controlled and regulated using a nitrogen gas pressure regulator. End flange of cyclone is connected to entry flange of the condenser. Whereas, end of the condenser is connected to the entry of the liquid collector. Water is supplied to the condenser through the pipe. The end flange of the liquid collector is bolted with a lid with a smaller vent to allow the non-condensable gas to go out into the atmosphere. Coarse sawdust will be put around the heating cylinder and also the sand bed in the reactor before the test runs. While the LPG cylinder is connected to a gas stove and heating torch through hose pipes. In addition, ice bath is placed inside a large container that surround the liquid collector. After the tests and the unit has cooled down, disassemble the components from the liquid collectors to the reactor, and weigh the final weight of each component.

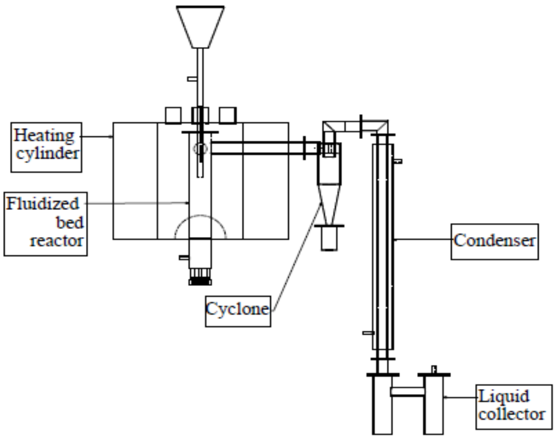

Figure 7. Dimensional view of design assembly.

V. Conclusion

The fluidized bed pyrolysis system was successfully designed and fabricated for practical demonstration of the fluidization of biomass solid waste. All the components have been successfully assembled for future experimental use. However, after all the components are installed, there are some modification that requires some changes such as feeder size and amount of flanges which will be done for future experimental study. In order for the sand particle to fluidized, the nitrogen gas flow rate need to be 15 l/min and above is based on hydrodynamic test. Moreover, according to the theoretical the optimum fluidization happens at 15.7 l/min. The height of sand bed was 6.24 cm and corresponding fluidization velocity was 0.068 ms-1. This study was found to be useful for designing the fast pyrolysis system for bio-oil production with variations of temperature and nitrogen gas flow rate.

Conflict of Interest

The authors declare no conflict of interest.

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Nur A. Fadhilah received her B.Sc. in Mechanical Engineering from Universiti Teknologi Brunei, Brunei Darussalam in 2017. Currently, she is pursuing her Ph.D. at the Department of Mechanical Engineering, Universiti Teknologi Brunei. Her main research interests are: thermodynamics, renewable energy, utilization of biomass solid wastes and co-pyrolysis. She is also a member of the IMechE, UK.

Muhammad N. Islam is a Senior Faculty Member at the Universiti Teknologi Brunei (UTB) of Brunei Darussalam. He completed his B.Sc. in Mechanical Engineering from Bangladesh University of Engineering and Technology (BUET) Dhaka. He completed his M. Eng. Sc. from Melbourne University, Australia in Mechanical Engineering. Then he completed his Ph.D. in Mechanical Engineering from Universiti Teknologi Malaysia (UTM), Malaysia. He was a Professor of Mechanical Engineering at Rajshahi University of Engineering and Technology (RUET) Bangladesh for 14 years. Currently, he is Assistant Professor and Examination officer in the Mechanical Engineering Programme Area, Faculty of Engineering, Universiti Teknologi Brunei. His research interests are in the area of pyrolysis of biomass solid waste and solar thermal system in the field of advanced thermodynamics and heat transfer. He has published around 80 articles in different internationally renowned journals and conference proceedings and book. He is a C Eng and a member of the IMechE, UK. He is also Fellows of BSME and IEB, Bangladesh.

Roslynna Rosli received her Ph.D. from Newcastle University, specializing in marine renewable where she conducted both the numerical and experimental hydrodynamic analysis of a novel tidal turbine, the Hydro-Spinna. This research was a direct outcome of her interest for a cleaner and sustainable future based on her prior Masters in Renewable Energy. Currently, she is Assistant Professor in the Mechanical Engineering Programme Area, Faculty of Engineering, Universiti Teknologi Brunei. She is also the Deputy Director of Tri-CEd, UTB's own unit overlooking the advanced continuing education where she is responsible for facilitating lifelong learning programmes offered by the university. Her research interests are in the researches and activities related to renewable energy as well as climate change mitigation and adaptation. She is also involved with the development of climate change strategies and activities in Brunei.