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# Design and Fabrication of Bench-Scale Flash Pyrolysis Reactor for Bio-Fuel Production

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The purpose of this paper is to present the construction and testing of a bench-scale flash pyrolysis reactor for bio fuel production from local biomasses such as empty fruit bunches (EFB) and rice husk. The reactor is intended for a mobile application where it can be brought into the fields. The design is based on ablative reactor technology so that larger feed size can be processed. The moving rotor is equipped with helical strips to create optimum centrifugal and mechanical force inside the system. In order to provide a sustainable heat source, the resulting syngas is burned and recycled back into the reactor. This reactor will operate with reactor temperature ranges from 450 to 600 °C, 300 - 1,000 °C/s heating rates and 5 - 20 g/min biomass processing capacity. This study can provide an important basis in designing a mobile fast pyrolysis reactor for Malaysia's biomass which in general consists of higher cellulose content

## 1. Introduction

Fast pyrolysis is one of the most promising thermal conversion processes to transform biomass into a more convenience fuel source. During the process, biomass is thermally decomposed without an oxidizing agent to produce liquid oil, solid charcoal, and gases. Compared to other pyrolysis processes, fast pyrolysis has few advantages such as maximum liquid fuel production, can be easily operated, cheap and has a short cycle time. The resulting liquid fuel or bio-oil has lower heating value of 15-20 MJ/kg, about half of conventional fuel oil (Bridgewater and Peacocke, 2000). Mohan et al. (2006) reported that flash pyrolysis reactor designs are commonly based on fluidized bed, entrained flow, ablative vortex, and rotating cone technology.

Most fast pyrolysis reactors are currently operated using fluidized bed flow design, because scaling up and product maximization are relatively easier (Bridgewater et al., 1999). However this technology has several drawbacks such as low bio-oil quality and requires high volume of carrier gas (Ellens, 2009). Low bio-oil quality is characterized by several parameters such as high water content, high viscosity and high amount of contaminant present in the oil. While most of these properties are inherited from parent materials, reactor design does affect the end products characteristics. Circulating fluidized bed for example will produce greater amount of char in bio-oil due to high abrasion between biomass and fluidizing medium such as sand (Bridgewater et al., 1999).

Commercial fluidized bed fast pyrolysis reactor has by far being designed to make use of local biomass within 25 km radius (Raffelt et al, 2006). Since it is a centralized plant, feedstock from further locations have to be transported from its origin which gives rise to handling cost that can be up to 5 times the cost of biomass itself (Bech, 2008); in this case, wheat straw. This scenario is also true in Malaysia. Palm oil industry for example spans over hundreds of acres wide. Only fresh fruit bunches are carried back to processing plant while other waste such as fronds and trunks are left to decompose. Malaysian

government had targeted to generate more revenues from agricultural industries by balancing between the amounts of biomass left in the field versus that utilized for high-end product (National Biomass Strategy 2020, 2011)
Bridgewater et al. (1999) has provided a good comparison summary for all types of reactor technology. Each has its own advantages and disadvantages, and the criteria of selection are usually based on purposes and applications. Ablative reactor generally has higher design complexity and difficult to be scaled up because it involves many moving parts, but really suitable for a mobile usage. The reactor can be used for a large feed size and requires low volume of carrier gas. Bech et al. (2008) has outlined the important criteria in selecting the best reactor design for mobile application in Table 1. This type of reactor can eliminate the biomass handling cost hence reducing the cost of bio-fuel production by transporting condensed energy density fuel instead of bulky biomass to processing plant.
The objective of this paper is to present the construction and testing works of bench-scale flash pyrolysis reactor known as MyPyros. This machine is intended for the production of high quality and solids-free bio-oil from Malaysia's biomasses such as empty fruit bunches (EFB) and rice husk. The particle size of feedstock is set to be <3.0 mm to optimize bio oil production and reduce char formations. The reactor will also be tested against different type of locally available feedstock to check its suitability against wide range of biomasses, from hard wood to soft wood. This work is a preliminary step in creating a compact mobile flash pyrolysis reactor which can be carried into agricultural fields by attaching to an existing harvesting units used by the industry.

*Table 1: Requirements and constraints for an in situ pyrolyzer (Bech et al., 2008)*

| Specification | Value |
|---|---|
| Weight/volume specific capacity | As high as possible |
| Acceptable particle feed size | As high as possible |
| Bio-oil yields | As high as possible |
| Maximum weight | As low as possible |
| Heat-up time | As low as possible |
| Source of thermal energy | Pyrolysis gas |
| Time between service | > 250 h |
| Capacity | > 10 t/h |
| Mechanical power demand | < 112 kW |
| Length | < 12.0 m |
| Width | < 3.3 m |
| Height | < 4.0 m |

## 2. Design and fabrication

### 2.1 Design principle

Reactor is the heart of a fast pyrolysis system. Among the critical features that help to increase bio-oil production are high heating rate (300-1,000 °C/s), optimum reaction temperature (425-600 °C) and short residence time (< 2 s). In ablative reactor technology, heat is transferred from a hot reactor wall to 'melt' the biomass that is in contact with it under pressure. The process is limited by rate of heat supply instead of rate of heat absorbed by biomass particles, which is why larger feed size can be used. Large contact surface area and high pressure will increase the rate of thermal degradation. Bech et al. (2008) sets the dimension of his reactor as L = 2D, where L is the horizontal length of the reactor and D is the diameter.
MyPyros utilizes both centrifugal and mechanical/shear force to aid heat transfer rate. Centrifugal force generated by swirling of inner rotor will press biomass to the hot wall of reactor while shear force will help to increase the heat transfer rate by compressingparticles of larger size. The inner rotor is designed in helical strips so as to maximize both forces and minimize the rate of wear and tear. In order to produce particle-free vapours, efficient char separating units are needed. Ellens (2009) stated that low carrier gas prohibits the use of a properly sized cyclone. He initially worked with a 3-L catch pot, but increased the size to 7-L for a longer vapour residence time, where bio-oil yield decreases slightly but char yields increases. The resulting bio-oil also contains fewer particles. Bech et al. (2008) also reported a low bio-oil yield when vapours come into contact with deposited char particles.
Product recovery is another important step in maximizing bio-oil production. The most common problem occuring at the condensation unit was blockage at the entrance. Bio-oil is composed of a very complex mixture of oxygenated hydrocarbons (Ibrahim, 2012) with molecular weights ranging from 100-1200 g/mol (Czernik et al., 1994). Gooty (2013) and Bech et al. (2008) utilizes fractional condensation train to optimize product recovery. Bio-oil in first condenser is more viscous and contains less water content, and is known

as the ‘oil fraction’. Bio-oil in the following unit is called ‘water fraction’. The whole pyrolysis system must be adequately heated during purging process to prevent premature condensation which usually occurs below 400 °C (Ellens, 2009).

**2.2 Reactor design**

Both reactor designs are developed based on a pioneering work by Bech et al. (2008). Among the most notable issue in the design is a pulse flow of biomass across reactor surface caused by accumulation at the entrance. This leads to a low bio oil production because not all particles come into direct contact with the heated reactor wall. It was alleviated by adding a helical guide ring along the reactor length to impede accumulation and slow down the transverse speed. In order to avoid this problem, the spinning rotor of MyPyros is equipped with helical strips. The flow behaviour of this rotor is analogous to that of screw propeller, and creates not only centrifugal force due to its high speed (< 2,800 rpm) but also forward thrust.

**2.2.1 MyPyros V1**

The first design version of MyPyros is shown in Figure 1.

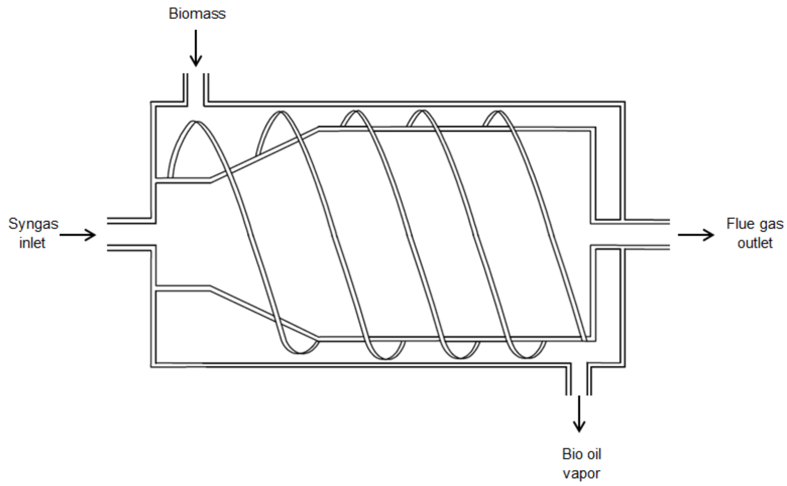


*Figure 1: Cross-sectional view of MyPyros V1. Note that the gap for first helical strip to reactor wall is bigger (6 mm) than the rest (3 mm)*

The main features of MyPyros V1 are helical strips and addition of recycle syngas loop. The gap between strips at the entrance and reactor wall are engineered to be slightly bigger to reduce collision during biomass feed which leads to accumulation at inlet as reported by Bech et al. (2008). The gas can be burned to supply a sustainable heat input into the system which helps in reducing the cost of production. In general only 10-20 % of syngas is produced. The amount of gas production may vary throughout the process and is measured by a gas flow meter. Butane can be used as an alternative heat source while collecting enough syngas for combustion. The recycled gas flow rate related to gas residence time throughout the system is controlled by a gas flow valve. The set-up can use gas residence time in the range of 0.5-5 s. The recycle syngas is an open loop and the resulting flue gas will be treated before being released into the air.

**2.2.2 MyPyros V2**

The second design version of MyPyros is shown in Figure 2. This is an upgraded version on the former. MyPyros V2 can increase the rate of heat transfer and biomass conversion by increasing the amount of mechanical force imposed on the feedstock. In V1, the clearance between helical strips and reactor wall is maintained at 3mm. The wavy reactor wall of V2 will vary the clearance from 2.0-3.0 mm. Coefficient of expansion for the reactor wall and rotor must be taken into account to avoid both from touching which can cause serious wear and tear problem. The rest of features from V1 such as syngas recycle loop and bigger wall to helical strips clearance, are maintained in V2.

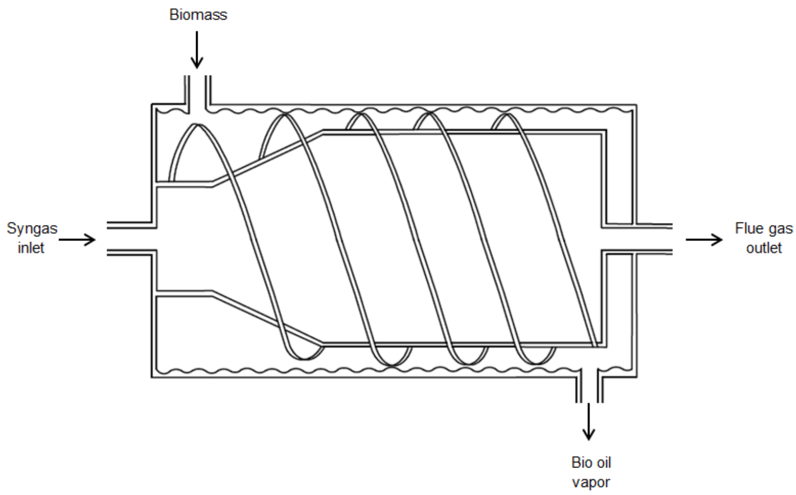


*Figure 2: Cross-sectional view of MyPyros V2. Note the wavy reactor wall and the gap for first helical strip is bigger (6 mm) than the rest (3 mm)*

Table 2 summarize the novelties of MyPyros designs against existing fast pyrolysis ablative reactor.

*Table 2: Comparison between MyPyros V1, V2 and WO 2006/117006 (Bech et al., 2008)*

| Features | WO 2006/117006 | MyPyros V1 | MyPyros V2 |
|---|---|---|---|
| Reactor dimension | L=2D | L=2D | L=2D |
| Rotor | 3 horizontal flight | Helical strips | Helical strips |
| Reactor wall | Welded with 1x4 mm guide ring | Flat surface | Wavy surface |
| Wall clearance | 2.2 mm | 3.0 mm | 2.0-3.0 mm |

**2.3 Operational principle**

The design layout of MyPyros fast pyrolysis reactor system fabricated in Universiti Teknologi Malaysia (UTM) is shown in Figure 3. This system operates under a batch mode at atmospheric pressure. A specific amount of biomass is placed inside the hopper mounted on a screw feeder. The screw feeder will supply a constant rate of feedstock into a horizontally oriented ablative reactor with processing capability of 5-20 g/min. The speed is controlled by a motor. The rotation of reactor rotor with helical-shape blades presses biomass particles on the hot surface of the reactor wall and drives the solid particles forward. Char is separated from the resulting gas via char separator and char cyclone. Both units and major piping lines will be kept at temperatures of 420 – 500 °C to avoid premature condensation, char blockage and further cracking of the vapor. The rotor speed is expected to be less than 2,800 rpm.

Heat is provided by three heating elements wrapped along the length of the reactor to maintain temperatures of 420 – 600 °C. Heat sensor is placed outside of the reactor in two locations to monitor temperature readings. Temperature drop up to 100 °C can occur (Bech et al., 2008) at the inlet which can affect the reactor performance. Vapor is condensed in singular coupled bio-oil condensation train (inner and outer cooling system) that will be kept at 40 - 50 °C by a chiller. Produced syngas will first be collected until it can be burned and supplied continuously into the reactor system to provide an alternative heating source. Nitrogen line is added into the system for purging purposes at the start-up of the pyrolysis process. This system is designed as a closed loop. Pressure build up might occur in case of blockage and a release valve is needed to maintain the pressure.

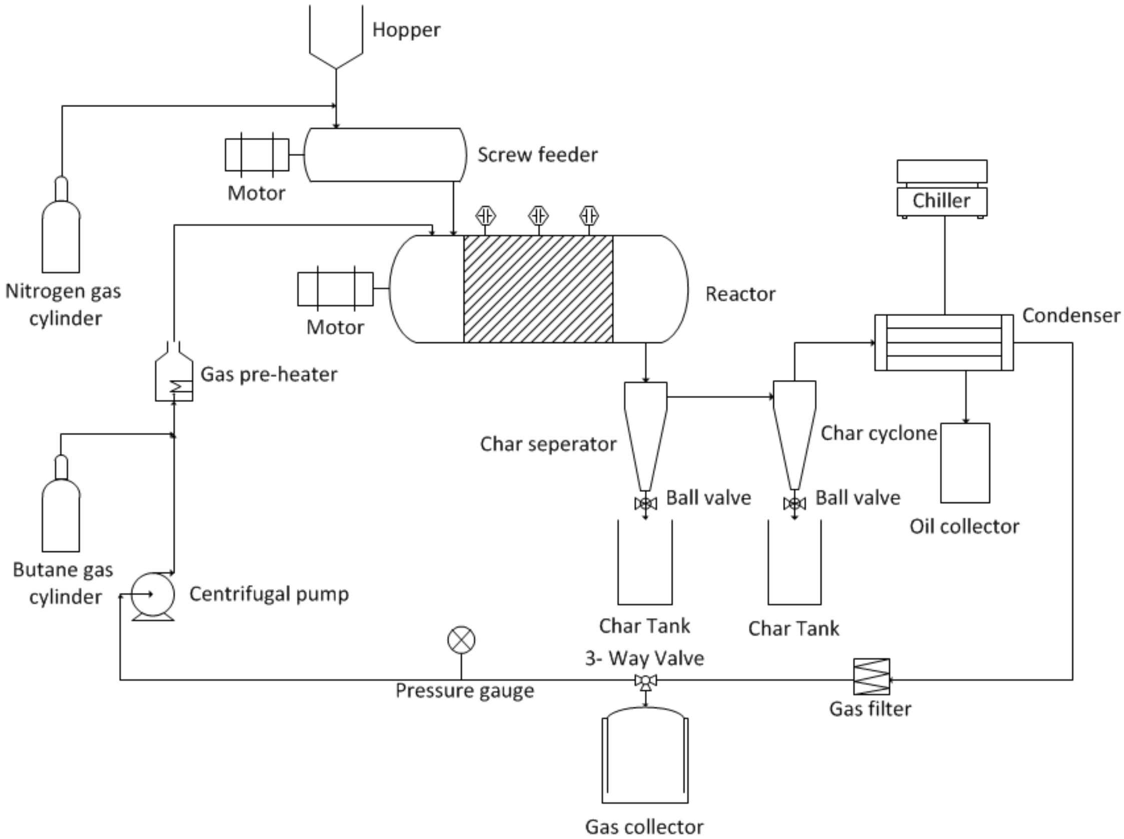


*Figure 3: Design layout for MyPyros fast pyrolysis reactor system*

## 3. Fabrication Limitation

The reactor will operate at high temperature of approximately 600 °C. It can only be made out of stainless steel which comes in standard size of straight profile. In order to create a wavy stainless steel pipe, a special mould will need to be made, and it can be very costly and time consuming. As such, MyPyros V1 will be fabricated first and then tested its suitability and efficiency for bio-oil production. For future development, a semi circle ring will be welded onto the reactor wall to imitate the wavy profile of MyPyros V2. The helical strips will need to be trimmed a little bit to provide sufficient areas for the added features.

## 4. Conclusion

Ablative flash pyrolysis reactor is the most suitable technology for mobile application purposes. It can be used against large feed size (< 5 mm), does not require carrier media and can produce high quality of bio-oil. For commercialization purposes, it can be attached to a harvesting unit and can be carried into the field for in situ pyrolysis to reduce biomass handling cost. Fabrication limitation is one of the main challenges in developing a feasible and operable reactor. It is also difficult to predict the flow behaviour of biomass particles inside the reactor. Rice husk for example is very light and tend to leave the reactor faster than empty fruit bunches (EFB). This pioneering works will first focus on the efficiency of reactor design by conducting pyrolysis on EFB and rise husk waste. The results obtained will be compared with other findings for justification purposes. Other units such as char separator and condensation train shall be improved over time.

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