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Utilization plastic waste using pyrolysis fixed bed

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Abstract. This investigative research aims to convert urban non-organic waste fuels such as plastic waste into energy using fixed bed pyrolysis technology. Pyrolysis fixed bed (PFB) is one of the most efficient technologies for converting various types of undegradable solid waste into thermal energy and liquid fuels with high efficiency. The study was conducted on a lab-scale PFB reactor with dimensions of 15 cm and 55 cm in diameter and bed height respectively. The reactor is equipped with a cooling and decomposition system to accommodate liquid and gas products. Reactor temperature variations using an external heater were tested and quartz sands were selected as a bed material to improve the temperature function of the PFB reactor so as the maximum quality and quantity of liquid product were obtained. The fuel properties of the derived oil were tested including their physical properties, calorific value, elemental measurement (CHNOS) analysis. The results of the study showed that the increase in temperature resulted in an increased pyrolysis performance which was indicated by the increased volume and liquid caloric value.

1. Introduction

Urban wastes such as plastic debris have become a common problem in the big cities over the world due to the massive increase of plastic usage in daily life as it is versatile, lightweight, flexible, moisture resistant, strong and considered cheap (Guern C.L.,2018). Plastic is a polymeric compound with a very large molecular shape, in the chemical sense, includes synthetic or semi-synthetic polymerization products which are formed from organic condensation or the addition of polymers and can also consist of other substances to improve their performance or economic value.

Some plastic wastes cannot be recycled so that the solution comes to a conventional method by transporting them to the landfill disposal which is not suitable to be called a waste problem-solving. In its development, waste management using landfill and open-dump methods is not appropriate because not only requiring a large site area but also raising various adverse impacts on the environment and community (Salem-Al S.M., *et.al*. 2017). In addition, the wastes such as plastic, tire, and other materials cannot be easily decomposed over time (non-biodegradable waste), so they have a strong impact on increasing the volume of landfill area.

One of advanced technology is by using a thermo-chemical process such as pyrolysis technic converting solid plastic waste into liquid fuel in the absence of oxygen or with a limited supply that does not permit reduction process to an appreciable extent (Basu, 2010). Pyrolysis is one of the alternatives for processing solid plastic waste which is considered quite prospective to be developed because it has several advantages in its delivery with a high conversion ratio and energy content. The low temperature of the pyrolysis in the range of 300-650^{o}C makes it flexible to choice, while gasification and combustion occur at between 800-1000^{o}C (Basu, 2013).

Research on the characteristics of the gas fraction resulting from the pyrolysis process has been performed by many investigators (Islam NM. and Beg M.R.A., 2004, Moinodim KAM., *et.al*., 2012, Papuga *et.al*., 2016, Miandad et.al., 2016). Therefore, in this study, the decomposition characteristics of plastic at pyrolysis temperature were conducted to obtain liquid yield as an alternative fuel. The study was carried out in a bench scale fixed bed pyrolyzer using quart sand as catalyst bed material in the variation of reactor temperature of 300 to 600^{o}C. The research is carried out using plastic polypropylene

(PP) pellet with the aim to get an optimal content and quantity of liquid products. The liquid yield is measured and analyzed by the calorimetric test, and the reactor PFB efficiency is determined based on fuel conversion attained from the proposed investigations.

2. Materials and Methods

2.1. Materials

The sample materials used in the study of fixed bed pyrolysis are in the form of granular polypropylene plastic (PP) pellet as shown in Figure 1.

Figure 1. A sample of plastic pellet

In the initial process, the calorific value of plastic PP was determined using the Parr 6200 Calorimeter for fuel based on ASTM D5865, standard test method for the coal and coke. The following are the results of the measurement as seen in Table 1 with two times repetitions.

Table 1. The calorific value of plastic PP (as received)

No.	Sample	Mass(gr)	LHV (cal/gr)	LHVaverage (cal/gr)
1.	Plastic 1	1.01606	10205.242	10184.394
2.	Plastic 2	1.01938	10163.547	

2.2. Experimental setup and methods

Figure 2 shows the detail part of the PFB reactor while Figure 4 shows the schematic diagram of the pilot PFB conversion system of plastic waste into liquid oil and char. The FB reactor is 15 cm, 55 cm, 400 cm^3 of diameter, high and bed volume respectively.

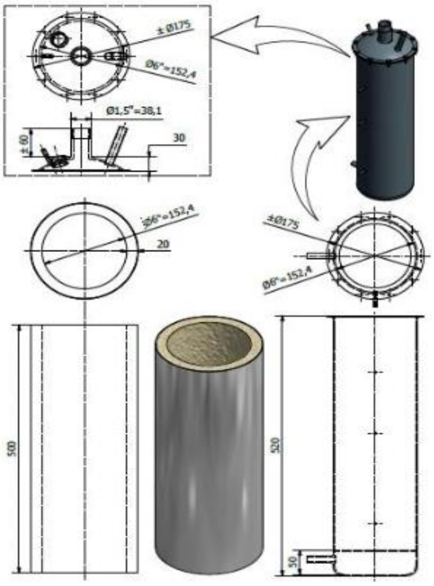

Figure 2. Detail part and dimension of a PFB apparatus

For the heating purpose, an electrical source heater was used. The heater supplied the heat to the pyrolysis reactor and when the desired temperature attained, PP particles were fed into the reactor from the reactor feeder. The reactor temperature was varied using thermostat control from the box panel. The condense vapor product and the gases passed through the condenser and then collected at the oil condensate tank, while the uncondensed products in the form of gases coming from same liquid oil pipe were collected in the gas container or directly exhausted from the reactor. Bed material as a catalyst of quartz sand was employed in this study as it can be stood at high-temperature o 1400°C.

The FB reactor is made of stainless steel and covered with a loop of an electric heater, which allows a maximum temperature of 800°C. The reactor was equipped with a K-type thermocouple inside to monitor the temperature when heated by an external furnace. The experiments in this study were designed at the temperature variation of 300 (I), 400 (II), 500°C (III) and 600°C (IV), while nitrogen gas was inserted to sterilize the reactor from oxygen.

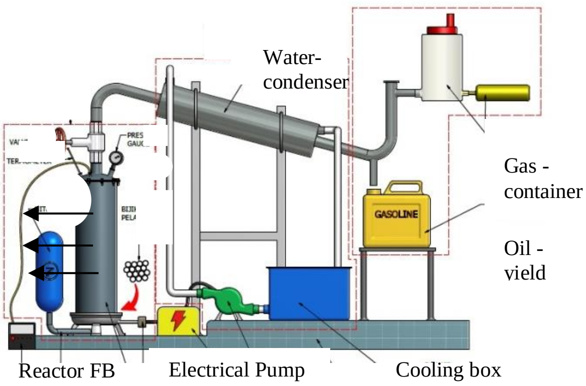

Figure 3. Schematic of fixed bed pyrolysis

In all of the experiments, 1000 gr of PP plastic feedstock was used in the form of pellets with an average diameter of 0.4 cm. The heating chamber of the pyrolysis reactor was heated at a rate of 5°C per min to achieve the set temperature.

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3. Result and Discussion

3.1. Effect of temperature on liquid oil yield

Experiments were carried out at three different temperatures (300, 400, 500 and 600°C) to investigate the effect of temperature on the yield and quality of produced liquid oil. After the determination of optimum temperature, experiments were carried out at similar reaction times of 120 min to investigate the effect on the feedstock decomposition solely based on temperature differences. The purpose of using different temperature was to find the optimum temperature at the same reaction time for pyrolysis of PP pellet so that the effect of the reaction time on the composition and quality of liquid oil and the production of char were predicted.

3.2. Temperature PFB profile

Figure 4 shows the characteristic temperature profile along the reactor representing the operation work on the temperature set at 400°C. This study uses 3 thermocouples (T1, T2, and T3) to determine the temperature profile in the reactor. Thermocouples installed on the reactor wall are connected to the data logger which is then recorded in the laptop. The total time needed for the variation II pyrolysis process is 168 mins, based on the details of 48 mins for heating the reactor and 120 mins for the pyrolysis process. Compared to variation I, the time needed for the variation II processes is longer than variation I because the time used to heat the reactor is longer. The position of the T1 thermocouple point is just above the bed material (10 cm), T2 (30 cm) and T3 (45 cm) which are measured from the bottom of the bed. It can be seen from Figure 4 where T1 is the experimental benchmark which when it reaches steady 400°C conditions, PP plastic pellet fuel starts to be employed into the reactor. T2 and T3 temperatures are lower than T1 because heat from the external heater is made more focused near quartz sand bed material.

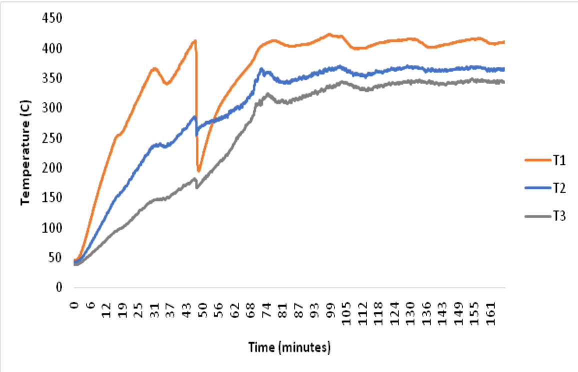

Figure 4. Temperature profile along 3 different positions along vertical bed reactor

3.3. Liquid yield

The gas formed in the PFB process naturally flows upward through a cooling pipe that has been designed to be submerged in a larger pipe containing cold water. The cold water condenser is made in circulating arrangement with the help of a pump located in the bottom of the test rig. After the gas is cooled, the denser of the gas melts and drips on the first tap (oil condensate), while for the lighter gas moves further up through the final tap (gas container/exit). The results of the liquid yield are then measured as can be seen in Figure 4.

From 1000 gr of polypropylene (PP) plastic that was inserted into the fixed bed reactor, the liquid yield was produced as much as 0.9 liters at variation I while 0.99, 1.08 and 1.06 liters for variation II-IV respectively. Figure 5 below shows an increase in liquid yield accompanied by increasing temperature at the reactor. This implies that the higher the reactor working temperature, the higher the number of PP plastic converted into a liquid. However when the operation temperature of 600°C, the liquid yield was found slightly decreased.

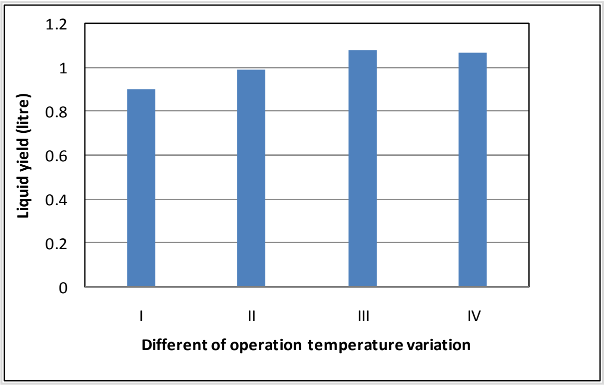

Figure 5. The liquid yield of pyrolysis fixed bed at different temperature operation

According to Basu (2010), in the process of slow pyrolysis tend to form charcoal in large quantities, whereas in the fast pyrolysis process there is a reduction in oxygen resulting in the possibility of forming more liquid hydrocarbons. The series of physical and chemical reactions take place slowly at temperatures below 350°C and runs faster at higher temperatures, this process is heat-absorbing (endothermic). Figure 5 also shows a slight drop of liquid yield when the temperature as high as 600°C. This may indicate more light gas was produced that not condense into the liquid with existing cooling water. Other work from different researchers (Islam et.al., 2010) also showed a decreased oil yield at higher temperature operation.

The purpose of the mass balance calculation is to find out the amount of mass in and out. For the mass out includes the liquid mass and charcoal. Mass balance calculations are separated based on variation I to IV. The following were the measurement of mass equilibrium of 680, 760, 800 and 790 gr for variations I to IV respectively. The remaining mass was considered a loss. Losses rather than the calculation above were gas that comes out of a fixed bed device and was not converted to liquid. For losses in variations, I-IV were as many as 200, 180, 160 and 164 gr respectively.

3.4. Oil yield calorific value

The oil yield produced from pyrolysis fixed bed of PP pellet was then tested to measure their calorific value for a different variation of temperature. The most important factor during pyrolysis is the temperature, with an increase in temperature the polymer is cracked and more light condensed liquid is produced with higher calorific content as shown in Table 2. Taking account in comparison of the initial calorific value of PP pellet from Table 1, the average increased of 2.58% was achieved.

Table 2. Calorific value of oil yield at different variation temperature

Variation	Oil yield	Mass (gr)	LHV (cal/gr)
I	Yield @300°C	0.81027	10205.165
II	Yield @400°C	0.83483	10341.970
III	Yield @500°C	0.88930	10411.661
IV	Yield @600°C	0.88930	10856.661

3.5. Pyrolysis efficiency

The efficiency calculation aims to determine the performance of fixed bed pyrolysis using PP plastic as fuel. The efficiency in this calculation uses the value of Low Heating Value (LHV) since evaporation generated from the heat of condensation of water vapor from the combustion results is not counted.

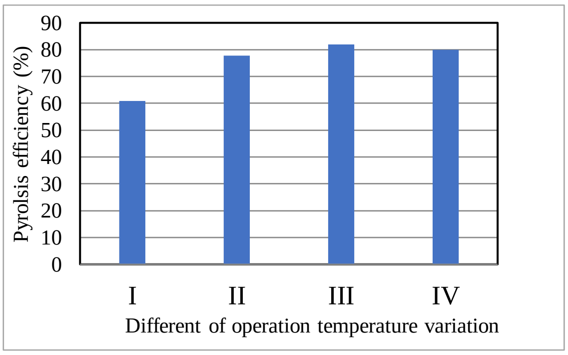

Figure 6. Pyrolysis efficiency of PP fixed bed at different temperature operation

The efficiency at an operating temperature of 500°C results in higher performance than that at operating temperatures of 300°C and 400°C. This shows that the greater the working temperature, the greater the thermal energy to break the PP plastic carbon chain in the reactor so that more carbon molecules (C) and hydrogen (H) are converted into liquid fuel capable of high calorific value. However, at a temperature of 600°C, there is a slight decrease in liquid production, as explained earlier.

3.6. Fuel conversion rate (FCR)

The rate of conversion of plastic PP fuel into liquid and gas in the pyrolysis process can be calculated using the following equation based on variation I to IV:

$$FCR=\frac{mass\ of\ initial\ PP\text{-}mass\ of\ char}{timeofoperational}\left({}^{kg}\!/\!{}_{s}\right)$$

From the mass measurement and LHV of each PP condition, the maximum of PP plastic conversion was attained at the highest operating temperature of 600°C. Although not all of PP was converted to liquid for the reason of cooling equipment, high temperature allows having high solid cracking of PP into gas/liquid. The complete calculations of FCR for variation I to IV are done as below:

- FCRI= $\frac{1-0,12}{7200}\left({}^{kg}\!/\!{}_{s}\right)$ = 0,000122 $\left({}^{kg}\!/\!{}_{s}\right)$
- FCRII= $\frac{1-0,06}{7200}\left({}^{kg}\!/\!{}_{s}\right)$ = 0,000130 $\left({}^{kg}\!/\!{}_{s}\right)$
- FCRIII= $\frac{1-0,04}{7200}\left({}^{kg}\!/\!{}_{s}\right)$ =0,000133 $\left({}^{kg}\!/\!{}_{s}\right)$
- FCRIV= $\frac{1-0,03}{7200}\left({}^{kg}\!/\!{}_{s}\right)$ =0,000146 $\left({}^{kg}\!/\!{}_{s}\right)$

It is easy to understand as the higher the temperature so the rate of the fuel conversion into liquid/gas is more rapid.

3.7. Yield oil performance

As seen in Figure 7, the liquid yield from the pyrolysis process at 300°C produces a rather dark and cloudy color. Liquid began to trickle in the 70th mins of the total testing time of 120 mins. At temperatures of 400°C, the liquid is rather bright yellowing, not too cloudy. Liquid starts trickling in the

30th min from the total testing time of 120 mins. While at a temperature of 500ºC and 600ºC liquid it is bright yellow and clear. Liquid began to trickle in the 10th min of the total testing time of 120 mins. The Brightness of liquid results at high temperatures due to the small amount of charcoal (black powder) in the liquid. This also indicates that at the higher temperature, the higher amount of yield oil is achieved.

@300ºC dark residue cloudy	@400ºC chocolate small residue rather cloudy	@500ºC, 600ºC yellow no residue bright

Figure 7. Performance of yield liquid at different temperature operation

3.8. Charcoal yield

In this fixed bed pyrolysis research using PP plastic as fuel besides producing liquid also produces charcoal in the reactor as seen in Figure 8. Charcoal is removed from the reactor and weighed in units of mass (gr). The yield of charcoal in the variation I is 120 gram. Charcoal produced in the variation I was hard and dense. This was because plastic PP that was not converted into gas makes it blend with quartz sand.

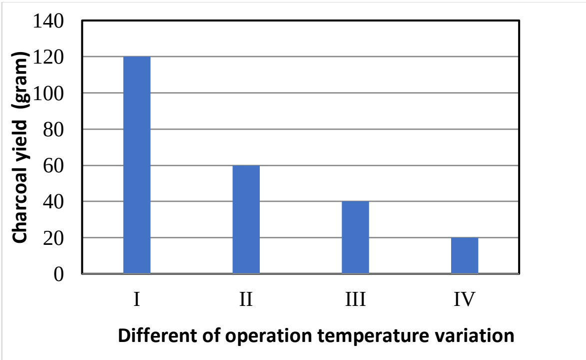

Figure 8. The charcoal yield of PP fixed bed at different temperature operation

In addition, tar was hardened and eventually turned to a solid state when exposed to the room temperature (Sharuddin SDA. *et all*, 2017). In the variation II charcoal was produced as much 60 gram which was different from those of variation I. The charcoal was seen as sand-like. This is indicated by the color of dark quartz sand indicating the presence of charcoal. For variation III and IV, the amount of charcoal produced was 40 and only 20 gram respectively. The observations show that the color of sand/charcoal is brighter in color. This is because the charcoal mass produced is less than the other variations.

4. Conclusion

The study has shown that the fixed bed pyrolysis technology could be used in utilizing the PP plastic pellet into liquid fuel. There is an increased 2.58% of calorific value from PP solid to oil yield using the PFB reactor. Increase in temperature for variation I to IV results in an increase in the FCR and calorific value. The efficiency at an operating temperature of 500°C results in higher performance than that at operating temperatures of 300°C 400°C and 600ºC based on the oil yield. In general, the study showed that the increase in temperature resulted in an increased pyrolysis performance which was indicated by the increased volume and liquid caloric value.

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