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Performance Test of a Batch Pyrolyser and Characterization of Liquid Fuel from Food Packaging Plastic Wastes

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ABSTRACT

Global generation of different types of food packaging plastic wastes which have negative environmental impacts are considerable and posing challenges for effective waste management. They impose environmental threats by blocking drains and thereby forming breeding places for mosquitos. It contributes significantly to the pollution, endangering life through consumption and entanglement. Energy recovery from plastic wastes are a useful choice as conventional energy supplies are decreasing at an alarming rate. Pyrolysis is an effective way for reducing pollution as well as recovering energy from waste plastic. Pyrolysis holds immense promise for the sustainable disposal and resource recovery from organic and inorganic materials like food packaging wastes. Medium temperature and moderate heating rate convert the non-biodegradable wastes into condensable and non-condensable vapour which was then condensed into pyrolytic liquid. As electricity is the final form of energy, so using electricity to produce a medium quality fuel by pyrolysis is not a wise decision. Also, in rural areas electricity may not be available. In this study, heating was done by using low-grade biomass fuel in a furnace. For temperature control, a small electric fan was mounted to control the combustion and thereby the temperature. The ideal temperature range to extract oil from this process was found to be 380 – 420°C. At this temperature, the average yields with 1 × 1 cm, 1.5 × 1.5 cm, and 2 × 2 cm samples of packaging waste were 73.91%, 67.92%, and 62.42%, respectively. The property analysis of the pyrolytic oil showed that they are comparable to diesel or heavy fuel oil. This liquid yield offers the potential production of liquid fuels, petro-chemicals, and other value-added products.

Keywords: Plastic waste, Pyrolysis, Low-grade fuel, Batch reactor.

1. Introduction

Food packaging plastics are diversified in size, color and type and are mostly thrown away here and there. Due to regulations preventing water contamination and labor-intensive isolation of various plastics before recycling and recycling of plastic is challenging and expensive. Since they are made of diverse resin compounds and have varying degrees of transparency and color, segregation of various plastic materials is crucial. Additionally, the market value of colored or pigmented polymers is reduced. It takes an ample amount of energy to recycle plastic. Energy recovery methods from plastic garbage are a useful choice because energy supplies are being depleted at an alarming rate. Pyrolysis is an effective technique for recovering energy from waste plastics in order to convert mass to energy [1].

In the process of biomass pyrolysis, it is broken down by heat in the absence of oxygen to produce charcoal, liquid, and gaseous byproducts. A low temperature, higher heating rate, and brief gas residence time would be necessary to increase the output of liquid products produced by biomass pyrolysis. Low temperature, low heating rate processes are preferred for high char formation. A high temperature and slow heating rate would be ideal if the goal is to increase the amount of fuel gas produced by pyrolysis. The pyrolysis process conducted with a slow heating rate is commonly known as conventional pyrolysis. In this situation, a substantial quantity of pyrolysis products is produced in solid, liquid, and gaseous forms. The initial stage of biomass degradation, referred to as pre-pyrolysis, occurs within the temperature range of 395- 475°C. During this phase, internal changes occurs that include the elimination of water, breaking of chemical bonds, emergence of free radicals, and formation of carbonyl, carboxyl, and hydro-peroxide groups. Second phase, representing the primary solid degradation process, progresses rapidly and contributes to the formation of pyrolysis products. Finally, in the third stage, the char undergoes slow decomposition, resulting in the formation of a residual solid material that is rich in carbon [2]. The pyrolysis of plastic waste is very similar to biomass pyrolysis.

In conventional pyrolysis, the heating of the materials is accomplished by using an electric source which is relatively expensive. Most of the previous researchers conducted their pyrolysis experiments using electrical heating which increases the overall expense. Also, the experiment could not be possible to conduct in those areas where there is no electricity. Besides if there is any shortage of electricity the experiment will be stopped immediately. Moreover, when energy extraction is considered through pyrolysis, using a high grade energy (electricity) is not a wise decision to obtain a relatively low grade energy (pyrolytic oil).

In the present study, low-grade fuels like rice-husk briquettes were used as fuel. A special furnace was developed having a more or less steady flow of heat and a convenient means for addition of fuel to the furnace. The types of plastic taken into consideration, the operating

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temperature, residence time and addition of other materials to promote decomposition are the key factors affecting the yield from pyrolysis.

The pyrolysis product from each form of plastic also depends on the temperature maintained during pyrolysis and the amount of time needed for decomposition to give the liquid and gaseous fuel because the plastics accessible from recycling sources come in a variety of types. The primary goal of this experiment is to extract more liquid fuel.

2. Theoretical Aspect

As mentioned earlier, pyrolysis is the thermally breaking of biomass or plastic materials through heating in the absence of oxygen, leading to the creation of solid charcoal, liquid oil, and gaseous fuels. The primary aim of studying biomass pyrolysis is to recover a biofuel with a low to moderate calorific value [3]. Thus, pyrolysis involves the degradation of biomass through heating in an oxygen-free environment.

The process involves breaking down the large and complex polymers into smaller and simpler ones through heat. The process occurs briefly at moderate to high temperatures and pressures, in the absence of oxygen. Researchers have recommended pyrolysis of inorganic materials like plastics because it has the potential to generate significant quantities of liquid oil, often reaching up to 80% by weight, typically at temperatures around 500°C. By adjusting the process parameters, it is possible to customize the outcomes to meet specific requirements, making pyrolysis a versatile method. The moderate-quality liquid oil produced through pyrolysis could be used for various purposes without the need for additional treatment or special handling. Furthermore, the energy requirements of the pyrolysis plant could be partially met by utilizing the gaseous fuel produced as a byproduct.

Hemicelluloses normally break down at temperatures ranging from 197℃-257℃, followed by cellulose in the temperature span of 237℃-347℃ and lignin, which undergoes pyrolysis at temperatures between 277℃-497℃. If the objective is to maximize the production of liquid products during pyrolysis, it necessitates a process characterized by low temperature but higher heating rate, and a brief residence time for gases. Conversely, for enhanced char production, selecting a process featuring low temperatures and a slow heating rate would be preferred. Different operating circumstances might be encountered throughout the pyrolysis process, which can serve as the foundation for classification [4]. Among other factors, they can be differentiated by the amount of time the pyrolyzed material must remain in the reactor, the size of the feedstock particles, the temperature of the pyrolysis process, and the process heat rate.

There have been numerous published research papers on the topic of plastic waste disposal using the pyrolysis process. Most of them used electric heater to produce high temperature. R. Miandad et al. [5] conducted a study to assess how different types of plastic waste influenced both the quantity and quality of the liquid oil produced through the pyrolysis process. They conducted the pyrolysis process under optimized conditions, maintaining a temperature of 450°C and a retention time of 75 minutes. Among the plastic wastes investigated, polystyrene (PS) demonstrated the highest liquid oil production of 80.8%, while also exhibiting the lowest levels of gas production (13%) and lower char formation (6.2%) when compared to the other plastic materials.

Ayhan Demirbas et al. [6] described the recovery of gasoline-range hydrocarbons by pyrolysis of municipal plastic wastes. This paper describes non-catalytic pyrolysis of plastic waste materials. Three types of waste plastics were used in that study: polystyrene (PS), polyethylene (PE) and polypropylene (PP). The heating was carried out from 250℃-752℃ in a nitrogen stream. Al-Salem et al. [7] reviewed the effectiveness of thermal and catalytic pyrolysis for transforming plastic solid waste into chemicals and fuels. Up to 80% of the liquids produced by thermal pyrolysis are enhanced by the use of catalysts such as zeolites, which also improve the quality of gasoline-range hydrocarbons. Yields are maximized at pyrolysis temperatures between 400°C and 600°C. M. S. Hossain and ANMM. Rahman [8] described the process of catalytic pyrolysis of tyre wastes for liquid oil production. Key factors affecting yield include pyrolysis temperature, catalyst-to-tyre (CT) ratio, and operating conditions. Optimal oil yields were found at 450ºC, with 42.0% (wt) without a catalyst and 36.67% (wt) with a catalyst.

3. Design and Construction

The main features for the pyrolysis system used in this research is to use low grade fuel and also to control the heating rate as much as possible. To control the heating rate with biomass fuel, a small fan was included in the furnace. Although it might not be as efficient as with electrical heating. The various components of the pyrolysis system are briefly described below:

3.1 Reactor

This is the main component of the pyrolysis reactor. For good heat transfer characteristics and corrosion resistance, stainless steel was selected for designing the reactor. The melting point of steel is around 1350℃. Also, earlier experience with aluminum was not successful, it was burnt out. Considering the average bulk density of plastic material (0.40g/cc) the reactor was designed. The reactor was sized to accommodate a feeding capacity of 1 kg waste plastic, considering factors such as the desired residence time for effective pyrolysis. Diameter of the reactor chosen was 21.5 cm. There was a cover in the upper side which was made of same material. The cover plate was connected with the reactor chamber with nuts and bolts. For making airtight silicon gasket was used. A thermocouple was installed inside the reactor chamber to observe the instantaneous temperature inside the reactor. A photographic view of the reactor is shown in Fig. 1. The reactor was housed inside the furnace.

3.2 Furnace

The shell of the furnace was made of mild steel. The thermal conductivity of it is relatively lower than copper that helps to reduce the heat transfer to outside for maximum fuel economy. More over the inside of the furnace was line with fire clay and the outside of the furnace was insulated. For the combustion products to travel through the space between the reactor and furnace wall, there need to be some space. The installation of a chimney ensured a natural draft. The bottom

portion of the furnace was provided with two gates. One for getting rid of the ash left over after burning the biomass, and another for adding biomass fuel to the furnace. The following dimensions were chosen as per the amount of fuel burnt for a single test. The furnace serves as the combustion chamber where biomass briquettes were burned to generate heat. Air was utilized for the combustion process, allowing the fuel to burn efficiently. The grate was positioned at 15.25 cm below the bottom of the reactor, ensuring proper airflow and combustion within the furnace. The furnace was provided with a gate through which the biomass briquettes were placed above the grate. Additionally, that can be opened (if necessary) to facilitate the feeding of combustion air. Thus, the specialties of the furnace are low heat loss by using fireclay inside and insulation at the outside, the sufficient airflow for better combustion by using the fan, easy maintenance and handling of fuel and ash by using the gate and a draft system. Moreover, it uses biomass fuel instead of electricity. The photographic view of the furnace is shown in Fig. 2.

Fig. 1: Photographic View of the Reactor

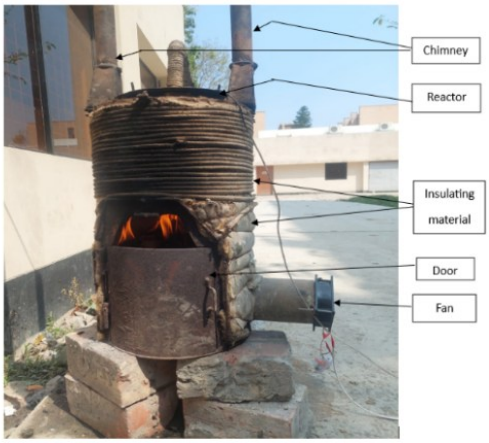

Fig. 2: Photographic view of the furnace

Based on the reactor size the dimensions of the furnace were selected as: Diameter of the furnace was 35.56 cm; Height of the furnace was 63.5 cm; So, the clearance on each side between the reactor and the furnace was 7.62 cm which is sufficient for flue gases to flow; Height of the chimney was 76.2 cm; and Diameter of the chimney was 5.10 cm.

3.3 Condenser

The condenser is that component where the condensable vapor evolved from pyrolysis reaction condenses and converted into liquid known as pyrolytic oil. The design of the spiral condenser allows for a large surface area within a compact space, facilitating rapid cooling of the hot vapors. As the vapors flow through the tube, they come into contact with cool tubes that were ensured cold by circulating water around the outside of the tube. Heat from the vapors is transferred to the cold circulating water, causing the vapors to condense into liquid. The liquid is then collected and could be further processed or stored for various applications. Meanwhile, the cold water becomes relatively hot by absorbing heat from the vapors. The heated water then circulated by flowing water from a tap or by putting some ice into the coolant to obtain better performance of the spiral condenser. The length of the condenser tube was 270 cm. The diameter of the pipe was 1.27 cm. The photographic view of the condenser is shown in Fig. 3.

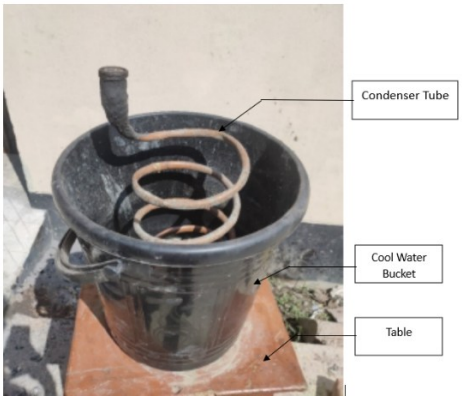

Fig. 3: Photographic View of the Condenser

3.4 CAD Model of the Pyrolyser

The CAD model of the pyrolysis system was designed in SOLIDWORKS 2018, taking into account both general and mechanical aspects. A fan was added to the furnace as mentioned earlier which was essential for controlling the temperature of the reactor by circulating the air inside the furnace. The overall CAD model of the pyrolysis system is shown in Fig. 4.

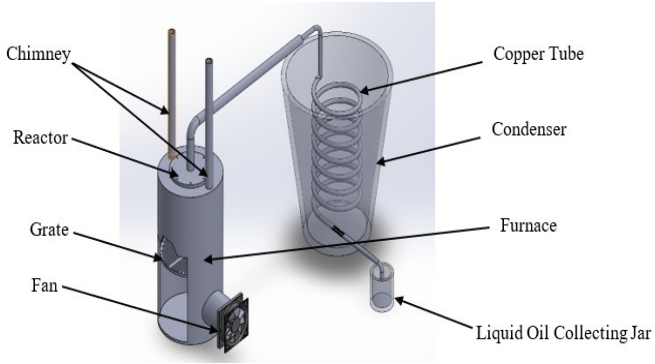

Fig. 4: Schematic Diagram of Pyrolysis System

3.5 Construction and Experimental Setup

The batch type pyrolysis reactor was constructed according the materials described before. Part of the construction was carried out at KUET workshop but some components were made by professional welders at Khulna city. After construction, the experimental setup was installed at the Heat Engine laboratory of Mechanical Engineering department. Food packaging plastic wastes were collected from different shops and roadside dustbins.

The waste materials were cut into small pieces of 2 ×2 cm, 1.5 ×1.5 cm and 1 ×1 cm. Then the samples were washed and

dried to remove the dirt and moisture. Following the pretreatment, 400g raw wastes were charged into the reactor through the top. After charging, the reactor cover was tightened with nuts and bolts. A thermocouple with display facility was also inserted inside the reactor through the top. To make the reactor leak-proof, silicon gasket was used. The reactor was then installed within the furnace which had two additional gates to manage the air flow and handle the ash. After being placed on the grate, the biomass fuel was ignited.

There was a small electric fan attached to the furnace to ensure the desirable temperature more or less uniform. This also helps uniform heat distribution, combustion efficiency and remove floating byproducts. This airflow improved energy efficiency, optimizing the pyrolysis process by preventing hotspots, ensuring complete material conversion, and reducing operational costs. A temperature range of 380-440℃ was maintained. The plastic begins to evaporate as a result of the rising temperature. The evolved vapor was allowed to pass through the condenser.

The condenser tube was immerged in water causing condensable gases to convert into liquid. A total of 9 (nine) sets of experiments were conducted with three different waste sizes. The experiments were conducted for three different sets of sample size: 2 ×2 cm, 1.5 ×1.5 cm and 1 ×1 cm. When pyrolysis was completed, the setup was cooled and the solid char was taken out and measured by opening the cover. The amount of pyrolytic oils and solid char was measured. The non-condensable gases were measured by difference. Fig. 5. Shows the photographic view of the experimental setup.

Fig. 5: Photographic view of Experimental Pyrolysis setup

4. Result and Data Table

The tests were carried out for different waste sizes. For different sizes, the amount of liquid, solid and non-condensable vapor produced during pyrolysis are shown in Table 1 to Table 3. The temperature range was recorded by temperature recorder between the first and last drop of pyrolytic liquid. The amount of gases were measured by difference after calculating the total mass of liquid and ash. The heating rate was calculated by dividing the temperature difference with average time required for liquid yield.

Table 1: Product yields during pyrolysis of packaging waste size: 2 × 2 cm

Sample No.	Mass (kg)	Liquid (%)	Gas (%)	Ash (%)	Heating rate (℃/min)	Temp. range (℃)
1	0.4	66.50	29.50	4.0	6.40	387 - 421
2	0.4	59.50	35.00	5.5	7.10	382 - 414
3	0.4	61.25	33.75	5.0	7.23	392 - 426
Avg.	0.4	62.42	32.75	4.83	6.91	

Table 2: Product yields during pyrolysis of packaging waste size: 1.5 ×1.5 cm

Sample No.	Mass (kg)	Liquid (%)	Gas (%)	Ash (%)	Heating rate (℃/min)	Temp. range (℃)
4	0.4	68.25	26.00	5.75	6.5	383 - 422
5	0.4	66.75	26.75	6.50	6.8	393 - 428
6	0.4	68.75	24.50	6.75	7.7	389 - 426
Avg.	0.4	67.92	25.75	6.33	7.00	

Table 3: Product yields during pyrolysis of packaging waste size: 1 ×1 cm

Sample No.	Mass (kg)	Liquid (%)	Gas (%)	Ash (%)	Heating rate (℃/min)	Temp. range (℃)
7	0.4	72.75	21.75	5.50	7.2	391 - 327
8	0.4	73.75	21.50	4.75	7.5	393 - 435
9	0.4	75.25	19.50	5.25	7.1	402 - 445
Avg.	0.4	73.91	20.92	5.17	7.27	

4.1 Properties of the Liquids

Different properties of pyrolytic oil obtained from food packaging plastic wastes were tested in the Heat Engine laboratory of Mechanical Engineering Department of KUET. The results are presented in Table 4 to Table 6.

Table 4: For samples of 2 ×2 cm food packaging wastes

Sample No.	Density (kg/m^3)	Calorific Value (MJ/kg)	Flash Point (℃)	Boiling Point (℃)
1	672.2	42.50	74	246
2	669.5	42.40	76	241
3	673.8	42.50	75	243
Diesel	820 - 850	42 – 46 [9]	61.5 (min)	180 - 360
Gasoline	700 - 800	44 – 46 [9]	− 45 to − 43	35 - 200

Table 5: For samples of 1.5 ×1.5 cm food packaging wastes

Sample No.	Density (kg/m^3)	Calorific Value (kJ/kg)	Flash Point (°C)	Boiling Point (°C)
1	645.1	42.67	81	249
2	641.3	42.59	84	253
3	645.9	42.68	82	250
Diesel	820 - 850	42 – 46 [9]	61.5 (min)	180 - 360
Gasoline	700- 800	44 – 46 [9]	− 45 to − 43	35 - 200

Table 6: For samples of 1 ×1 cm food packaging wastes

Sample No.	Density (kg/m^3)	Calorific Value (MJ/kg)	Flash Point (°C)	Boiling Point (°C)
1	638.3	42.79	78	251
2	635.2	42.67	76	247
3	640.5	42.79	80	251
Diesel	820- 850	42 – 46 [9]	61.5 (min)	180- 360
Gasoline	700- 800	44 – 46 [9]	− 45 to − 43	35- 200

5. Discussion

From Table 1 for sample size 2 × 2 cm, it is noted that the highest yield occurs at 400°C. The duration of pyrolysis reaction was around 50 minutes. The average value of the liquid yields was 62.42%. The heating rate was around 7°C/min. The uncondensed gas was flared to the atmosphere as fumes and by calculating the mass percentage of liquid and solid, it was more than 32%. The properties of pyrolysis oil from this sample size are presented in Table 4. From the table it was noticed that the density of pyrolytic oil was within the range of gasoline. The flash point and boiling points are within the range of diesel. The gross calorific value is also very close to gasoline fuel.

From Table 2 for the sample size 1.5 ×1.5 cm, it was noted that the average yield was 67.92% which was slightly higher than that of the sample size of 2 cm ×2 cm. Besides this the uncondensed gas percentages were also lower than the sample size 2 cm ×2 cm. The temperature ranges was between 383°C - 428°C. That gives better yield than the previous data in Table 1. From the Table 3 for the sample size 1 ×1 cm, it was noticed that the average yield for 1 ×1 cm size samples was 73.91% which was higher than the previous two sample sizes. Beside this the non-condensed gas percentages were also lower than the previous two samples. That gives better yield than the previous data in Table 1 and Table 2.

From Table 5 and Table 6 the properties for the sample of 1.5 ×1.5 cm and 1.0 × 1.0 cm food packaging wastes respectively, it was seen that the density was close to gasoline. The flash and boiling points were within the ranges of diesel fuel. The gross calorific value was also very close to gasoline fuel. So, from the above information it can be said that product yield increases as the sample size decreases. It is because when the sample size is smaller, the plastic samples melt quickly and vaporization starts at a lower temperature. For this condensation occurs earlier and most of the vapor turns into liquid. It was also noted that the heating rate and the temperature could not be controlled properly with the heat produced from biomass fuels. Hence the results were not obtained like other researchers. The oil obtained from pyrolysis process could be a solution for moderate heating applications.

6. Conclusion

The production of the pyrolytic oil from non-biodegradable plastic wastes was conducted by heating them in inert atmosphere in a fixed bed reactor and condensing volatile gases in the condenser. So,

- The optimum temperature for extracting oil from pyrolysis of food packaging waste was observed between 380°C - 420°C.
- For optimum temperature, the average yields were 73.91% for the sample of 1 ×1 cm, 67.92% for the sample of 1.5 ×1.5 cm, 62.42% for the sample of 2 ×2 cm plastic packaging wastes.
- The fuel properties for different sample sizes were determined and found that most of the properties are very similar to gasoline but calorific value is close to diesel fuel.

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