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Construction and Performance Test of a Batch Pyrolyser for Plastic Waste

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ABSTRACT

In our daily life, plastic plays an important role and its use is increasing day by day resulting to a huge amount of wastes. Due to their non-biodegradable nature, they are posing a major problem to the environment. Recycling of waste plastics is a means of reducing it, but recently pyrolysis becomes a good option to manage these wastes. Moreover, pyrolysis is a relatively clean and less toxic method compared to incineration. Plastics are petroleum-based material, so it is possible to convert them into fuels by breaking their long molecular chain into small chains. This fuel could be used as alternative fuel to reduce the fossil fuel crisis in future. During pyrolysis, plastics are heated inside a reactor in absence of air and the final product of pyrolysis depends on the temperature, heating rate, etc. Most of the researchers, working on pyrolysis of plastic waste, are using electricity as the means of heating. But we know, electricity is the finished form of energy, so using electricity for pyrolysis is not a wise decision from an energy point of view. In this study, a batch type pyrolysis reactor was developed to extract liquid oil from plastic waste. Heating was done by using low-grade biomass fuel. The performance of the reactor was tested for different types of plastics like polythene, saline bottle, saline bag, etc. Properties such as density, calorific value, flash point, and boiling point were measured for the liquid oil obtained and they were within the range of 603-704 kg/m^3, 36-44 MJ/kg, 62-78°C, 234-276°C respectively which identifies its characteristics as alternative fuel.

Keywords: Waste plastic, Pyrolysis, Batch reactor, Low-grade energy, Pyrolytic oil

1. Introduction

Today plastic plays an important role in our daily life. The use of plastics is increasing day by day due to their low cost, variability in use, high durability and water barrier properties. After use the plastics are thrown to the environment as waste. Thus, most urban areas are littered with a large volume of plastic materials. Due to their non-biodegradable nature, they impose a major problem to the natural environment. So, a proper waste management system is necessary for these wastes. Recycling of waste plastics is a means of reducing it, but other disposing methods e.g., incineration sometimes costly. Pyrolysis is a good option to manage these waste plastics and save the environment. It is the process of chemical breakdown of a substance at an elevated temperature in an oxygen-free environment. Moreover, pyrolysis is a relatively clean and less toxic method compared to incineration.

Wood pyrolysis was possibly the first chemical process performed by humans. It is believed to have been practiced by the ancient Chinese. The pyrolysis method was used in amazon rainforest a thousand years back. The local people started fires and when the fuel was hot enough, they covered it with earth to deprive the fire of oxygen. The high temperature would continue to break down the fuel and char was produced instead of ash in the absence of oxygen. The char was used for the enrichment and stabilization of poor rainforest soils with nutrients [1]. Wood carbonization was the main pyrolysis process until the late 1800s and supplied the increasing quantities of charcoal needed for iron ore smelting [2]. In recent times, pyrolysis process is used for production of char, gas and bio-oil from plastic waste which can be used as alternative fuel. The different types of plastics used are Polyethylene terephthalate (PET), High-density polyethylene (HDPE), Low-density polyethylene (LDPE), Polyvinyl chloride (PVC), Polypropylene (PP) and Polystyrene (PS) [3].

Pyrolysis process can be thermal or catalytic. The three main products generated during pyrolysis include gas, oil, and char. Temperature is one of the most important operating parameters in pyrolysis because it controls the polymer chain's cracking reaction. It is possible to optimize for one or more of the three pyrolysis by adjusting the temperature and duration. When the gases produced by pyrolysis are cooled to room temperature, the heavier gases are condensed into liquids called pyrolytic oil. The liquid oil produced can be used in different applications such as boilers, furnaces and diesel engines. The lighter gases that remain gases at room temperature, are known as “syngas”. Slow pyrolysis, for example, produces more char at lower temperatures, while fast pyrolysis produces more liquid oil at a relatively higher temperature.

There are a number of research papers published based on plastic waste disposal by pyrolysis process. The product yield and quality depend upon the set up parameters as mentioned before. Some works carried out on plastic pyrolysis focuses on the generation of liquid fuel while some others are more concerned with the properties of the liquid fuel. Bagri and Williams [4] investigated the pyrolysis of LDPE at temperature of 500°C in a fixed-bed reactor with a heating rate of

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10°C/min. The experiment was lasted for 20 min and N_2 was used as fluidizing gas. They observed a yield of 95% (w/w) liquid and a negligible amount of char and gas. Liu et al. [5] investigated the pyrolysis of PS using fluidized bed reactor at temperature of 450–700ºC. The maximum liquid oil was found at 600ºC and it was 98.7% (w/w). Sakata et al. [6] have explored the PP pyrolysis at a temperature of 380ºC. They found liquid yield of 80.1% (w/w), 6.6% gaseous and 13.3% (w/w) solid residue left. Kaminsky et al. [7] worked on the pyrolysis of mixed plastic waste consisting of about 75% polyolefins (PE, PP) and 25% PS. The test was performed in a fluidized bed reactor at 730°C that produced finally 48.4% liquid oil.

Some researchers concentrate on producing char while a few concentrates on gaseous products. Çepelioğullar and Pütün [8] found gas created in pyrolysis of PET was 76.9% (w/w) and PVC was 87.7% (w/w) at 500°C. Jung et al. [9] observed that the char formation was increased from 2% to 4% (w/w) in PP pyrolysis and from 0.7% to 2% (w/w) in PE pyrolysis as the temperature was raised from 668℃ to 746℃.

Most of the works done by various researchers on pyrolysis of plastic materials used electrical heater as a means of heating source. The reason may be easy control of electrical heaters, means easy control of the heating process. But we know, electricity is the finished form of energy that could be utilized conveniently to a number of applications, so using electricity for pyrolysis to obtain liquid fuel is not a wise decision from an energy point of view. In this research, the attention was focused on producing liquid oil from plastic waste using low-grade energy. Low-grade energy like fire-wood or briquette was used instead of using high-grade energy like electricity or other types. Moreover, there are many areas where people are deprived of electricity. So, choosing low-grade energy could be a good decision.

2. Theoretical Aspect

Plastic waste produces many social and environmental issues, because it is chemically stable and is not easy to degrade within a short interval in natural conditions. Strong and durable covalent bonds in plastics also contribute to their resistance to natural degradation. Ingesting plastic waste in most rural areas often kills domestic animals. Littering plastic waste on land surfaces contributes to its burial in soil that can interfere with nutrient production and thus reduce soil fertility. Environmental and social issues caused by plastic waste include contamination of underground water, land-filling, lack of natural resources, sewage system blockage and negative health impacts. Degradation of plastic waste at landfill usually takes a long time. Plastic wastes are important components of solid waste after food and paper in towns and industries. Being lighter in weight, plastic waste is transported to flood water bodies by rivers, wind and humans. Plastic waste kills animals in the marine ecosystem by ingestion and entangling. There is also a rise in plastic demand in developing countries because of their low price and diversity in use and which eventually increases the amount of plastic waste. Some plastic waste is burned in the backyard or outdoors near homes. Burnt plastics using unregulated fire at low temperatures create black carbon smoke due to incomplete carbon backbone combustion in polymers. Toxic reactive compounds, as well as greenhouse gas emissions, are also released into the environment. When plastic waste is burned, such as polystyrene foam jars, food trays and many other styrene bases, styrene gas is released that can be easily absorbed by the skin and lungs. At high levels, styrene gas can damage the mucous membranes of the human body and eyes and the central nervous system can be damaged by very long exposure. PVC is also called hazardous plastic because burning of PVC releases organo-chlorides as well as dioxins. Even at low levels, dioxins are cancerous chemicals and highly toxic [3].

3. Design and Construction of Batch Type Reactor

The batch type pyrolysis reactor has three major components namely, the reactor, the furnace and the condenser. The major components of the batch type pyrolysis reactor were fabricated with aluminium and mild steel. In the design consideration, some parameters were assumed. As low-grade fuel was proposed to be used in this research as the heating material, so the furnace was designed that is capable of supplying heat to the reactor externally. Since low grade fuel like firewood or similar solid fuel will be used, the heating rate of the reactor will be relatively low compared to heating rate by electrical heater. To avoid the use of electricity, the design was made in such way that the temperature required for pyrolysis could be obtained by burning biomass fuel in the furnace. The reactor was designed for feeding about one kg of waste plastics. Accordingly, the design of grate system and chimney of the furnace was made. For condensing the vapour, a condenser was also designed. Fig. 1 shows the CAD model of the batch type pyrolysis reactor system (i.e., the reactor, the furnace with chimney and the condenser system).

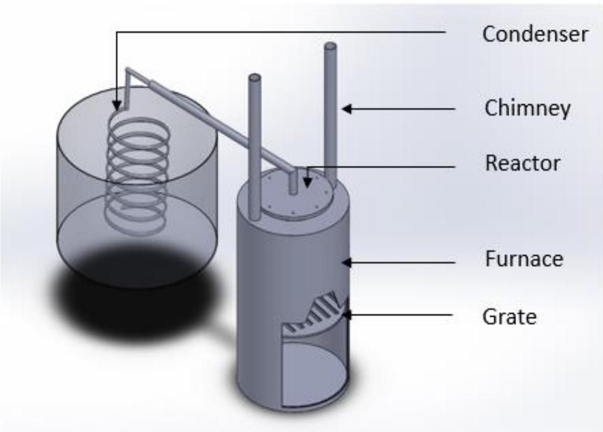

Fig.1 CAD Model of the Pyrolysis Reactor

The design and construction of different components of the batch type pyrolysis reactor are briefly described below:

Reactor

For fast pyrolysis, it is important to rise the temperature inside the reactor as quickly as possible. Aluminium has a good thermal conductivity which confirms high heat transfer rate. So, Aluminium could reduce the problem of heating rate. Considering this, aluminium was selected for designing the reactor. The reactor was a cylindrical chamber with lid that could be made air-tight with silicon gasket and nut-bolts. The dimensions of the reactor are: diameter of the reactor cylinder was 20.32 cm with a height of 12.70 cm. The bottom of the reactor was made oval shaped for well circulation of flame.

The construction of the different parts of the pyrolysis reactor were fabricated using the locally available raw materials. In fact, the inner part of a rice-cooker was converted to be used as reactor. The lid was converted to be an air tight system by using silicon gasket and nut-bolts. A K-type thermocouple was provided within the reactor to notice the inside temperature. The photographic view of the constructed reactor is shown in Fig. 2.

Fig. 2 Photographic view of the Reactor

The reactor was housed inside the furnace from the top. The gap between the reactor bottom and the grate was adjusted to get maximum heat. The furnace with the reactor was installed upon a frame structure made from MS angle bar. Arc and gas welding were used in the fabrication process.

Furnace

For better fuel economy, it is necessary to transfer most of the heat of combustion to the reactor and reduce the heat transfer to outside from the furnace body. The lower the heat loss, the lower the mass of fuel needed for combustion. Mild steel has relatively lower thermal conductivity than aluminum. So, Mild steel was used as designing material of the furnace body. A grate was designed to keep the biomass fuel over it. Sufficient clearance was made between the reactor bottom and the grate and the furnace wall was ensured to pass the exhaust gas produced from combustion. A chimney was provided for ensuring natural draught. Two gates were provided, one at the bottom of the grate for removing ash after burning the biomass fuel and another slightly above the grate for charging the fuel to the furnace. These two will also supply necessary oxygen required for combustion. Based on this, the dimensions of the furnace are:

Diameter of the furnace = 35.56 cm.
Height of the furnace = 63.5 cm.
Clearance between the reactor and furnace = 7.62 cm.
Distance of the grate from the furnace bottom = 25.4 cm.
Height of the chimney = 76.2 cm.
Diameter of the chimney = 5.08 cm.

As mentioned before, the furnace was constructed from mild steel. The metal sheet was formed to give the shape of a cylinder with the desired diameter. The grate was fixed 15.24 cm below the reactor bottom. The photographic view of the furnace is shown in Fig. 3.

Fig. 3 Photographic view of the Furnace

Condenser

Condenser is a device that is used to convert the condensable vapor from its gaseous state to liquid state by cooling. In this process, the latent heat is taken up by the cooling water and the latent heat is exchanged with water. The amount of liquid extracted greatly depends on a good condenser. So, the condenser should be made up of material of good thermal conductivity to transfer heat efficiently to the cooling fluid. For this reason, copper tube was selected due to its high thermal conductivity.

Copper tube was bent spirally to make the condenser in the form of a coil. The length of the condenser tube was about 365.76 cm and the diameter of the tube was about 1.27 cm. The coil was immersed inside a bucket containing cold water. The gaseous vapor from the reactor goes through the condenser coil and by exchanging the latent heat to the water, the vapor was condensed to liquid state. The photographic view of the condenser is shown in Fig. 4.

Fig. 4 Photographic view of the Condenser

4. Experimental Setup and Procedure

After construction of the batch type pyrolysis reactor, the system was installed in the Heat Engine Laboratory of the Department of Mechanical Engineering of KUET. The K-type thermocouple with temperature display was fitted to the lid of the reactor to notice the inside temperature of the reactor. Waste plastic materials such as polyethylene, saline bottle and saline bag were collected from nearby clinics and hospitals. At first, the raw materials were washed, cleaned and sun-dried to remove the moisture. Then they were cut into small pieces of about 3 – 4 cm in size for making easy charging. The photographic view of final setup, raw materials and post-treated raw materials are shown in Fig. 5, Fig. 6 and Fig. 7 respectively.

Fig. 5 Photographic view of Final Setup

After treatment, the raw material was weighed before charging into the reactor and 300g of raw material was charged through the top by opening the lid of the reactor. The lid was fastened by nuts and bolts. Silicon gasket was used to make the reactor airtight.

Fig. 6 Photographic view of the Raw Materials

Fig. 7 Photographic view of post-treated Raw material

The reactor was then installed over the furnace from the top for the purpose of heating. Biomass fuel was put on the grate and then fired with a small amount of kerosene. The heating rate was maintained by opening/closing the gate. Initially, the gates were open to supply sufficient oxygen. Once the required temperature was reached, the gates were closed partially. The temperature was maintained at about 300 - 350ºC. Due to temperature rise within the reactor, the plastic is heated and starts to evaporate. Vapors were allowed to pass through to the condenser tube which was immersed in slightly cold water in the bucket. The condensable gases were converted to liquid oil. The liquid oil was collected in a pot placed below the condenser tube. The non-condensable gases were flared into the atmosphere. After obtaining liquid oil, various properties of the oil were measured and compared with the conventional oil.

5. Results and Discussion

Experimentation and Data Acquisition

The experiments were conducted with four types of raw materials viz, polythene, saline bottle, saline bag and mixed plastic. Mixed plastic was consisted of 50% saline bottle and 50% polythene on weight basis. For each set of experiments, three samples (except saline bag) were taken and the data obtained were averaged to make representative value. The liquid obtained after pyrolysis of different types of plastic wastes are shown in Fig. 8 (a), (b) and (c).

(a) (b) (c)

Fig. 8 Liquid obtained after pyrolysis (a) from polythene, (b) from saline bottle and (c) from saline bag

Data Collection

The data were collected during pyrolysis process and the results obtained from the tests are shown in Table 1 to Table 4. The average values for each set of experiments are also presented in the same table.

Table 1 Output data during Pyrolysis of Polythene

Sample No.	Feed material (g)	Liquid (%)	Gas (%)	Solid (%).
1	300	54.3	21.5	24.2
2	300	46.6	22.5	30.9
3	300	55.0	21.2	23.8
Avg.	**300**	**51.97**	**21.73**	**26.30**

Table 2 Output data during Pyrolysis of Saline bottle

Sample No.	Feed material (g)	Liquid (%)	Gas (%)	Solid (%).
1	300	54.0	16.3	29.7
2	300	57.3	16.6	26.1
3	300	60.0	17.5	22.5
Avg.	**300**	**57.10**	**16.80**	**26.10**

Table 3 Output data during Pyrolysis of Mixed Plastic

Sample No.	Feed material (g)	Liquid (%)	Gas (%)	Solid (%).
1	250	74.8	15.8	9.4
2	250	60.0	28.4	11.6
3	250	70.4	20.0	9.6
Avg.	**250**	**68.40**	**21.40**	**10.20**

Table 4 Output data during Pyrolysis of Saline bag

Sample No	Feed material (g)	Liquid (%)	Gas (%)	Solid (%).
1	300	41.0	39.5	19.5

The various properties of the obtained pyrolysis oil were tested in the Heat Engine Laboratory of Mechanical Engineering Department of KUET. The calorific value was determined by using Bomb calorimeter. Flash point and boiling point were determined by using Flash point and Boiling point measuring instrument. Density was measured in the laboratory using digital weighing balance and specific gravity measuring bottle. From the results shown in Table 1 to 3, it is clear that there is a variation in the yield of liquid, gas and solid for all three types of samples. The reason may be non-uniform heating of the reactor, because with biomass fuel maintaining a fixed temperature is very difficult. With same amount of feed material percentage yield of liquid is highest for mixed plastic (68.4%) and lowest for saline bag (41%).

All the properties were determined carefully and the average of each lot was considered as the representative value for that lot. The different properties of the obtained pyrolysis oil are compared with the properties of Diesel and Gasoline obtained from literature. They are shown in Table 5.

Table 5 Properties of Pyrolytic Oil in comparison to Diesel and Gasoline

Sample	Density (kg/m^3)	Calorific Value (MJ/kg)	Flash point (°C)	Boiling Point (°C)
Polythene	678.60	42.1	72	234
Saline Bottle	683.35	43.7	62	276
Saline Bag	703.80	36.5	78	244
Mixed plastic	603.40	41.5	66	268
Diesel	820-850	42-46	52-96	180-360
Gasoline	719-780	45.8	-43	95

From the above comparison, it is evident that the pyrolytic oil extracted from plastic waste have density very close to gasoline. Flash point and boiling point are within the range of diesel fuel. Calorific value also closed to diesel and gasoline except the oil obtained from saline bag. The calorific value of pyrolysis oil obtained from saline bag is relatively lower than the value of Furnace oil. Also, the color of the pyrolytic oil obtained from saline bag is blackish and during the experiment, very pungent odor was experienced.

6. Conclusion

Though plastic has become an integrated part of our daily life, it is non-degradable in nature and creates lot of problematic effect on the environment. Recycling of plastic could reduce this waste to some extent but it could not be a sustainable solution as repeated recycling might be harmful. Incineration is costly process. So, pyrolysis of these materials could be a relatively clean and effective means of reducing waste plastic. At the same time, this process will give an end product which could be used as fuel. So, converting plastics to liquid fuel might reduce the shortage of fuel in future.

7. References

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