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Design, fabrication and performance test of a fixed bed batch type pyrolysis plant with scrap tire in Bangladesh

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ABSTRACT

This paper presents the design and construction of a fixed bed batch pyrolysis reactor. The reactor is further used for the production of pyro oil from scrap tire. The result shows that reactor yields a maximum pyro oil of 42 wt% at the temperature of 400 °C with a feed size of 15 cm^3. The produced pyro oil has a higher viscosity of 4.5 cSt and heating value of 42.5 MJ/kg. Thus pyro oil cannot be used directly in engine operation but as a furnace oil or fuel in boiler operation. The char is potential for using as a fertilizer, production of conveyor belt and footwear.

1. Introduction

The gradual increasing of energy demand pressurize find out new alternative technique and available source that can mitigate current fuel crisis. Pyrolysis is one of the latest renewed interesting and reliable thermochemical technique to recover energy from any kind valuable source. It is the process of heating the feedstocks at an oxygen free atmosphere and the products are pyro-oil, char, and gas. These pyro oil can be used as a fuels and char for the manufacture of activated carbon (Kumaravel, Murugesan, & Kumaravel, 2016). A pyrolysis reaction scheme is shown in Fig. 1. Due to the simple operation and low operating cost, pyrolysis is widely used for the production of pyro oil or char (Ly, Kim, Choi, Woo, & Kim, 2016). A lot of works have been developed on pyrolysis in traditional reactors such as fluidized-bed (Ly et al., 2015; Yanik, Stahl, Troeger, & Sinag, 2013), fixed bed (Aguiar, Márquez-Montesinos, Gonzalo, Sánchez, & Arauzo, 2008; M. R.; Islam, Tushar, & Haniu, 2008; Quan, Gao, & Song, 2016), rotary kiln (A. M. Li et al., 1999), vacuum (De Jongh, Carrier, & Knoetze, 2011), free-fall (Zhang, Xu, Zhao, & Liu, 2007) reactors etc. regarding product distribution at different operating conditions. Whilst recently the pyrolysis of terrestrial biomass has received a great deal of attention at various experimental conditions from rice husk and rice straw (Fu et al., 2011), palm (Abnisa, Arami-Niya, Daud, & Sahu, 2013), orange peel (Aguiar et al., 2008), tamarind seed (Kader, Islam, Parveen, Haniu, & Takai, 2013), and jute dust (Choudhury, Chutia, Bhaskar, & Kataki, 2014).

Every year 90000 tons waste tire generated across the country (Bangladesh) which is the major part of the total wastes (M. R. Islam, Islam, Mustafi, Rahim, & Haniu, 2013). Major part of this waste tires are normally dumped in an open field and it leads extreme accidental explosive fires including higher toxic emission. This waste tire is also a potential living field of mosquito breeding and other vermin. On the other hand, scrap tire contain highly oil content and its products has higher heating value. Thus, it is the high time to recover energy from waste tire because of their energy potential as well as minimization of waste (Martínez et al., 2013; Williams, 2013).

In Bangladesh, there is no large commercial pyrolysis plant employed for the production of pyro oil. Thus it is necessity to massive experiment on a pyrolysis plant and study the feasibility of

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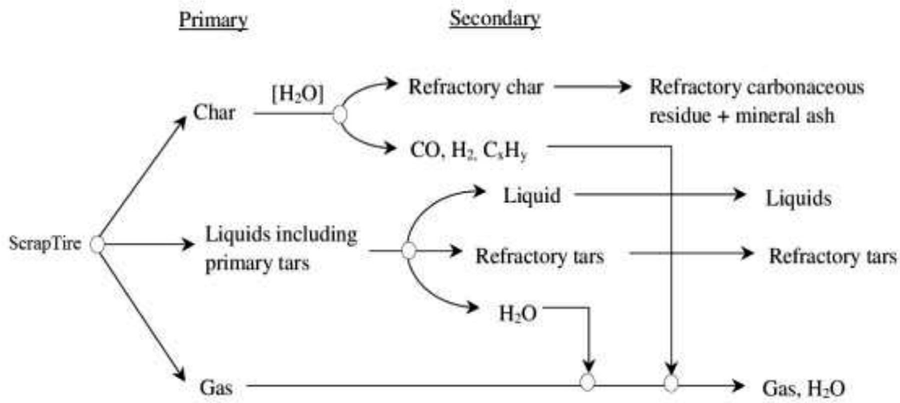

Fig. 1. Pyrolysis reaction scheme of scrap tire (R. Li et al., 2016).

scrap tire in pyrolysis for the production of pyro oil as well as others valuable products. Since, fixed bed reactor is most convenient for pyrolysis system, thus in this study a fixed bed reactor is designed and fabricated for the pyrolysis of scrap tire. The performance of this reactor is also investigated. The pyrolysis products is analyzed according to ASTM standardized tests.

2. Materials and method

2.1. Feed stocks

The bus tire used as a feed materials for this experiment were collected from at Rajshahi, Bangladesh. The used tire normally contain elastomer, carbon black, steel, zinc oxide, and sulphur. Thus maintaining the uniform characteristics, tire were chopped into four different sizes (10 cm^3, 15 cm^3, 20 cm^3 and 25 cm^3) from the lot. This sample represents the characteristics of whole tire.

2.2. Plant design

The reactor (height: 990 mm, diameter: 480 mm) constructed in this experiment was made of stainless steel having a feeder header (height: 80 mm, diameter: 120 mm) at the top and an exit (diameter: 200 mm) for char removal at bottom of the reactor. At first a concrete slab supported by concrete wall was placed inside underground holes as base of the pilot plant. Then reactor was placed on the hole of the concrete slab. There are four ash ports in the slab for removing ash. For providing uniform and faster heating, two halves hexagonal stainless steel pipe (diameter: 19 mm, total length: 2740 mm) installed inside the reactor in u-shape (bending radius: 76 mm). The heat is supplied to the reactor by a fuel burner. It has two openings for providing solid fuel into the furnace. There was another exit port at the top of the reactor which was connected to the two vertical condenser (length: 1520 mm, diameter: 170 mm) as well as an oil reservoir (length: 470 mm, diameter: 360 mm). Two condenser were designed for capturing higher quantity of pyrolytic oil from condensable gas. The cooling was done by passing the cold water through the condenser. When the temperature of the reactor reaches at requires level, product volatile expands and raises its pressure, which leads the volatile comes out fast from the reactor through the condenser. A fraction column (height: 1830 mm, diameter: 160 mm) was installed between reactor and condenser for the separation of heavy components from the light fraction of condensable gas under the action of gravity. The heavy fraction usually blocks the connecting pipe (channels) and accumulates inside the reservoir. There was a flanges at the bottom for cleanup heavy oil fraction from the fraction column. A digital K-type (Cromel-alumel) pyrometer was inserted into the reactor through cover plate for measuring the reactor temperature. The whole system was well insulated for no loss of heat as well no air enter in to the system. The pictorial and schematic presentation in shown in Figs. 2 and 3 respectively. The dimension of each components of the pyrolysis plant is shown in Table 1

2.3. Experimental procedure

The visible foreign material adhere on the surface of the scrape tire was firstly cleaned by water and then desiccate. The oxygen free atmosphere was created within the reactor by compressed nitrogen gas. The scrap tires were carried into the dryer for initial warm up condition by chimney flue gas. Finally, the scrap tires (20 kg) were fed into the fixed bed pyrolysis reactor. The temperature of the reactor was varied 300-500 °C. The reactor was heated at an increasing rate up to first 100 min 300 °C (±20 °C), next 50 min for 400 °C (±20 °C) and next 30 min for 500 °C (±20 °C). When the temperature inside the reactor was reached a pyrolytic temperature, the gaseous product was passed through the condenser where the inlet temperature of cooling water was 22-26 °C and outlet temperature was found to be 35-40 °C. Finally, the reactor was kept for natural cool down after completing the pyrolysis of the feed materials. Then the char was pushed out from the reactor, liquid was collected from the reservoir and weighted. The product yields (oil, char and gas) were determined by the following Eq. (1), Eq. (2)

Fig. 2. Pictorial representation of experimental setup.

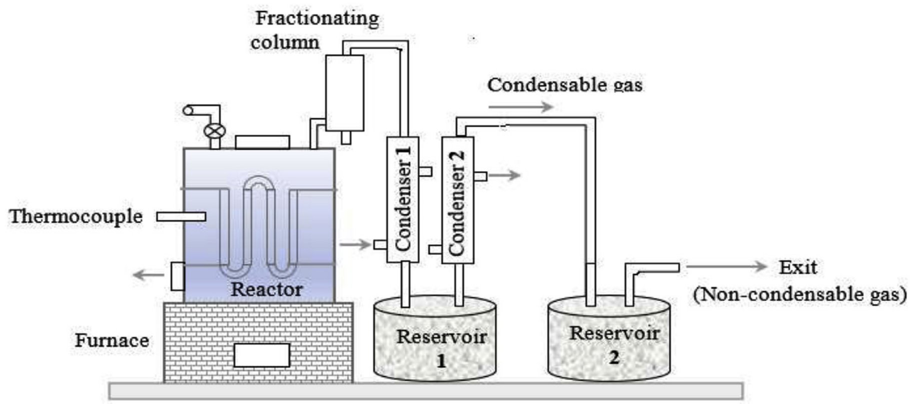

Fig. 3. Schematic arrangement of pyrolysis plant setup.

and Eq. (3) respectively. This whole procedure was repeated for three times and the average value of each measured parameter was presented as the result.

$$\text{Pyro oil yield (wt.\%)} = \frac{m_{oil}}{m_{feedstocks}} \times 100\% \quad (1)$$

$$\text{Char yield (wt.\%)} = \frac{m_{char}}{m_{feedstocks}} \times 100\% \quad (2)$$

$$\text{Gas yield(wt.\%)} = 100\,\% - [\text{Char yield(wt.\%)} + \text{oil yield(wt.\%)}] \quad (3)$$

2.4. Feedstocks, pyro oil and char characterization

The differential thermogravimetric (DTG) behavior of scrap tire was done over the temperature range of 0–650 °C using a Pyris Diamond DTG analyzer (Perkin Elmer). The samples (15–20 mg) were heated at two different constant heating rate of 10 and 60 °C/min while maintaining a constant nitrogen flow rate of 100 mL per minutes. The ultimate analysis was carried out using an EA 1108 elemental analyzer. The oxygen have been determined by difference knowing the weight percentage of C, H, N and S. The proximate analysis of the feedstocks and products was carried out according to ASTM standards.

3. Result and discussion

3.1. Characterization feedstocks

The proximate and ultimate analysis of scrap tire is shown in Table 2. The feedstocks which moisture content less than 10 wt% can transfer heat quickly in the pyrolysis reactor. The scrap tire for this study was very low (0.82 wt%) which ensures suitable for thermal conversion in pyrolysis process (Rahman & Aziz, 2018). The high value of volatile matters (63.40 wt%) of the scrap tire is a strong indication of capability of high percentage of liquid fuel production (M. N. Islam, Islam, Beg, & Islam, 2005). The ash content and fixed carbon content were found to be 2.47 and 33.31 wt% respectively. The higher amount of carbon content (80.3%) in the tire are suitable for char production. The oxygen and nitrogen content of in the feedstocks was not too high. The heating value (HHV) of scrap tire were found to be 30.3 MJ/kg which were within literature study 28–40 MJ/kg (M. R. Islam et al., 2013).

3.2. DTG analysis of tire

DTG curves of scrap tire for two different heating rate of 10 and 60°C°min^{-1} are shown in Fig. 4. There were two stages in the pyrolysis process with one dominant peak for both of the heating rates. The initial weight loss (up to 350 °C) was due to the evaporation of moisture content of the feedstock (Rahman & Aziz, 2018). The main weight loss (peak at around 400 °C) can be attributed due to the decomposition of natural organic/inorganic compounds with the formation of a huge amount of volatiles (M. R. Islam, Haniu, & Beg, 2008). About approximately 80% weight loss occurred in this stage, thus is stage is called active pyrolysis zone. The weight loss rate became quite slow above 400 °C; this was because the violent cracking of organic/inorganic compounds finished at this stage.

3.3. Influence of temperature

The influence of pyrolysis temperature on products distribution is shown in Fig. 5. Initially the plant run with feed size 20 cm^3. The

Table 1
Pyrolysis plant design dimension.

Components	Made of and thickness	Length/height	Diameter	Inlet diameter	Outlet diameter	Other/remarks
Fractionating column	MS (1 mm)	1830 mm	160 mm	63 mm	63 mm	–
Condenser	MS (1 mm)	1520 mm	170 mm	63 mm	63 mm	–
Reactor	MS	990 mm	480 mm	120 mm	63 mm	–
Furnace concrete column	Bricks (250 mm)	780 mm	500 mm	–	–	–
Furnace Concrete slab	Bricks (150 mm)	–	600 mm	125 mm (center hole)	–	–
Furnace contrete wall	Bricks (70 mm)	510 mm	510 mm	–	–	–
Furnace reactor shield	GP sheet (2 mm)	990 mm	480 mm	–	–	Insulator: Glass wool (40 mm thickness)
Oil reservoir tank	GP sheet (2 mm)	470 mm	360 mm	–	–	–
Supply line	GI pipe (2.3 mm)	–	63 mm	–	–	–

MS – Mild steel, GP - Galvanized plain, GI- Galvanized iron.

Table 2
Proximate and ultimate analysis of scrap tire.

Proximate analysis (wt.%)		Ultimate analysis (wt.%)	
Moisture	0.82	Carbon (C)	80.3
Volatile	63.40	Hydrogen (H)	7.18
Fixed carbon	33.31	Nitrogen (N)	0.50
Ash	2.47	Oxygen (O)	8.33
HHV (MJ/kg)	30.3	Others	3.69

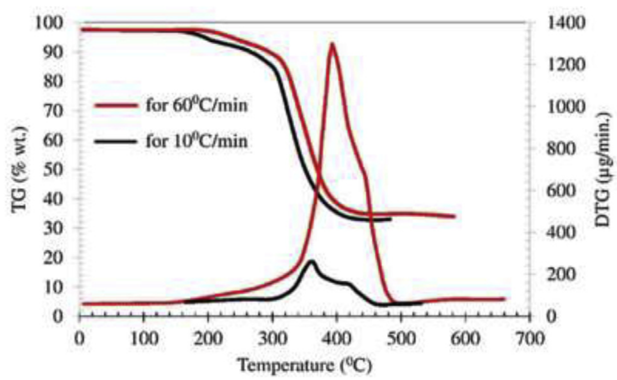

Fig. 4. Thermogravimetric analysis of scrap tire.

gaseous product yields increase with the increase of temperature while char production rate just opposite in nature with gases. The pyro oil yield increase upto 400 °C, above that temperature it again decrease. The higher temperature caused secondary decomposition of some oil vapors into permanent gasses and consequently yielding more gas (Rahman & Aziz, 2018). The maximum percentage of pyro oil yield of 40 wt% obtained at 400 °C due to the complete decomposition of feedstocks. This temperature is further confirmed by DTG analysis.

3.4. Influence of particle feed size

The influence of particle feed size on products distribution is shown in Fig. 6. The temperature of the reactor was kept constant near about 400 °C. Pyro oil increase upto particle feed size of 15 cm^3 and above this size the yields again decrease while the char yields just opposite in nature. The gas yield increase over the feed size range. The maximum pyro oil yield of 42 wt% for feed size 15 cm^3 with the formation of 44 wt% char and 14 wt% gas. The heat flow

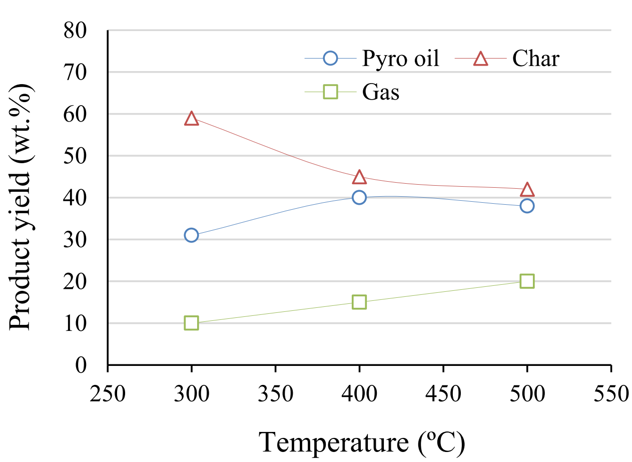

Fig. 5. Pyrolysis product distribution with temperature.

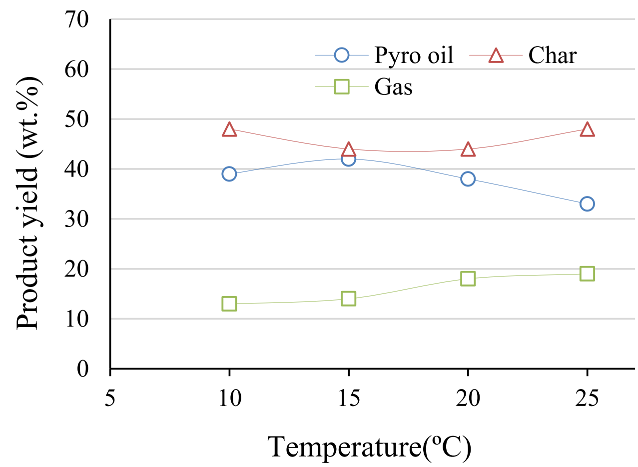

Fig. 6. Pyrolysis product distribution with feed size.

rate in the larger feed size comparatively lower due to its lower thermal conductivity as compared to smaller feed size. So heat can transfer only to a certain depth which results incomplete decomposition of larger feed. Thus increased in char yields and decreased in pyro-oil and gas yields (Kader et al., 2013).

3.5. Characteristic of pyro oil

The pyro oil obtained in this experiment was appeared in dark brown color with a smell of strong acidity (Fig. 7(a)). The physicochemical properties of pyro oil is shown in Table 3. The pyrolysis oil has a higher heating value (42.5 MJ/kg) than the used tire from which it is recovered (30.3 MJ/kg). The higher heating value of tire derived pyro oil was similar to furnace oil but lower than commercial diesel. Other hand, the density and viscosity of the pyro oil was also higher than diesel fuel whereas flash point was lower than diesel. Thus tire-derived pyro oils can be used as liquid fuels for industrial furnaces, power plants and boilers (Roy, Chaala, & Darmstadt, 1999). After purification or treatment this oil can be as a sole fuel or blending fuel in diesel engine.

3.6. Characteristic of char

The physiochemical properties of char obtained at 400 °C is shown Table 4, major components of the char is shown in Table 5 and pictorial representation is shown in Fig. 7(b). This heating value of the char was found to be 30 MJ/kg with moisture content of 4 wt%. The char can be graded as bituminous coal whose average typical heating value of 33 MJ/kg, moisture content of 4–6 wt% and carbon content 75–90% (Khurmi & Gupta, 2003). The high content of carbon, leading to the production of high value carbon materials that are used in various industries (i.e. production of footwear and conveyor belts etc.) (Rahman & Aziz, 2018; Roy et al., 1999). The higher mineral content in the char can be used as a fertilizer (M. R. Islam, Joardder, Hasan, Takai, & Haniu, 2011). ZnO and SiO_2 oxides

(a) (b)

Fig. 7. The produced (a) pyro oil (b) char from scrap tire.

Table 3
Physicochemical properties of pyro oil.

Property	Diesel[a]	Tire derived pyro oil[a]	Furnace oil[a]	This study
Flash point (°C)	>55	≤32	66–93	33
Pour point (°C)	−40 to −30	- 3 to −5	18–72	−5
Density (kg/m^3)	820–860	940–970	880–950	970
Viscosity cSt at 40 °C	2–4.5	4.6–4.9	–	4.5
Calorific value (MJ/kg)	44–46	40.8–42.5	43–45	42.5

[a] Data taken from M. R. Islam et al. (2013).

Table 4
Properties of tire pyrolysis chars.

Property	Ref.[a]	Ref.[b]	This study
Moisture (wt.%)	1.28	0.09	4
Calorific value (MJ/kg)	30	33.59	31
Ultimate analysis (wt.%)			
Carbon	80.82	90.27	83.34
Hydrogen	1.46	0.26	1.1
Nitrogen	0.53	0.16	0.40
Oxygen	–	–	11.88
Sulphur	2.41	1.22	3.35

[a] Data taken from Li, Yao, Chi, Yan, and Cen (2004).
[b] Data taken from Murillo et al. (2006).

Table 5
Analysis of major components in char.

Element	Concentration(g/kg)	Oxide	Content (wt.%)
Zn	294	ZnO	42.5
S	57	SiO_2	26.5
Ca	51	CaO_2	6.9
Fe	10	Fe_2O_3	1.6
Al	8	Al_2O_3	1.5
K	8	K_2 O	1
Na	7	NaO	1

occupied the maximum percentages in the char (Table 5).

4. Conclusion

A pilot plant is designed and constructed for the production of pyro oil from scrap tire via pyrolysis. The process offer the potential of economical production of attractive fuel in the sector of industrial energy research in Bangladesh. The reactor can produce a maximum pyro oil yield of 42 wt% at the temperature of 400 °C and particle feed size of 15 cm^3. The viscosity and heating value of the pyro oil detract direct use as a fuel in diesel engine but can be used in industrial furnaces, power plants and boilers. The char was graded as bituminous coal and suitable for the production of footwear and conveyor belts.

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