Design and fabrication of a fixed-bed batch type pyrolysis reactor for pilot scale pyrolytic oil production in Bangladesh

To cite this article: Mohammad Abdul Aziz *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **184** 012056

IOP Conf. Series: Materials Science and Engineering **184** (2017) 012056 doi:10.1088/1757-899X/184/1/012056

Design and fabrication of a fixed-bed batch type pyrolysis reactor for pilot scale pyrolytic oil production in Bangladesh

Mohammad Abdul Aziz[1], Rami Ali Al-khulaidi[1], MM Rashid[1], M.R Islam[2], MAN Rashid[3]

[1]International Islamic University Malaysia, Department of Mechatronics Engineering Jalan Gombak, 53100 Kuala Lumpur, Selangor, Malaysia
[2]Rajshahi University of Engineering & Technology, Department of Mechanical Engineering, Bangladesh
[3]International Islamic University Malaysia, Department of Material and Manufacturing Engineering Jalan Gombak, 53100 Kuala Lumpur, Selangor, Malaysia

E-mail: abdul.aziz07me@gmail.com

Abstract. In this research, a development and performance test of a fixed-bed batch type pyrolysis reactor for pilot scale pyrolysis oil production was successfully completed. The characteristics of the pyrolysis oil were compared to other experimental results. A solid horizontal condenser, a burner for furnace heating and a reactor shield were designed. Due to the pilot scale pyrolytic oil production encountered numerous problems during the plant's operation. This fixed-bed batch type pyrolysis reactor method will demonstrate the energy saving concept of solid waste tire by creating energy stability. From this experiment, product yields (wt. %) for liquid or pyrolytic oil were 49%, char 38.3 % and pyrolytic gas 12.7% with an operation running time of 185 minutes.

1. Introduction

The civilization of human growing rapidly and transportation becomes an important part of human life. The faster the rate of population, it tends to increment of vehicles which leads higher transportation[1].Every year, more than 450 factories produce over 1.5 billion tons of tires around the world. In Bangladesh alone, 120000 tons are produced annually. Bangladesh's energy consumption by fuel type consists of natural gas (61.82 %), furnace oil (21.68%), diesel (7.75%), imported power (4.86%), coal and hydro power (1.86%). The total installed electricity generation capacity is 12339 MW. However, imported coal and petroleum oil, Bangladesh's annual gross domestic product disrupted 2% and 60% gas consumed from national grid gas production unit[2]. The precious land is being occupied by waste scrap tires which may affects environment seriously. Natural firing operation in bricks field that has been done by using waste tires. Moreover, burning of waste carried out emissions that are highly toxic to humans. Finally, rain water is known to carry waste to larger areas, causing disease. Advancements in technology have minimized the problem of solid waste tires in the environment. The process of pyrolysis involves feed stock being fed into an oxygen-free environment in a reactor and heated, with inlet and outlet temperatures being sufficiently high (between 550°C and 680°C) [3].

In recent years, many advances in research in the field of pyrolysis have occurred. The gross calorific value (GCV) of pyrolysis liquids is 41-44 MJ/kg. Past research groups examined the composition of pyrolysis gas fraction. Several research groups reported it to contain higher percentages of CH_4(methane) C_2H_6(ethane) C_4H_6(butadiene) and hydrocarbon gases. The gross calorific value (GCV) of approximately $37MJ/m^3$, a value sufficient to provide the energy required by the pyrolysis process. They found the (GCV) of pyrolysis oil to be 33.7 MJ/kg, 37 MJ/kg, 40 MJ/ kg[4] and 41 MJ/kg –44 MJ/kg[5] in the fixed-bed reactor. Where the temperature stayed within the range of 400°C-700°Cand the operations lasted for 4 hours. Solid products in these experiments made up 47% - 63%, liquid products 30% - 43% and gas products 2.2% - 4.4% [6].

Meanwhile, many different experimental procedures were done for the production of pyrolysis liquid products from solid tire waste including fixed-bed, fluidized–bed, vacuum and spouted bed reactors [5]. In the fixed-bed fire-tube heating pyrolysis system, the maximum liquid and char yield was 52 wt. % and 35 wt. %, for bicycles and rickshaws respectively. For truck tires, the liquid yield and char yield came to 60 and 23 wt. %, respectively. The heat value of liquid of rickshaw and truck tires was found to be 41 MJ/kg and 40.7 MJ/kg, respectively [11]. However, for car tires, the maximum liquid yield and char yield came to 50 and 40 wt. %, respectively. For car tires, the liquid yield and char yield came to 45 wt. % and 28 wt. %, respectively. The heat value of liquid and char was found to be 42.2 and 35.6 MJ/kg, respectively [12]. A burgeoning research area is the use of the pyrolytic oil in a single cylinder, 4-stroke, water-cooled DI diesel engine with varying load[7].

In this research, solid tire wastes are processed to pyrolysis oil, solid char and gases. This conversion system is done using a fixed-bed fire-tube heating reactor system. The techno-economic appraisement was conducted taking into account three different sizes of plants: medium commercial scale (144 tons /day), small commercial scale (36 tons /day), and pilot scale (3.6 tons /day). The liquid produced from the plant should be used for boiler operation and upgraded liquid production[8]. However, the solid waste tires are being used for energy production by pyrolysis oil production. The reaction pathway of pyrolysis is shown in Figure 1.

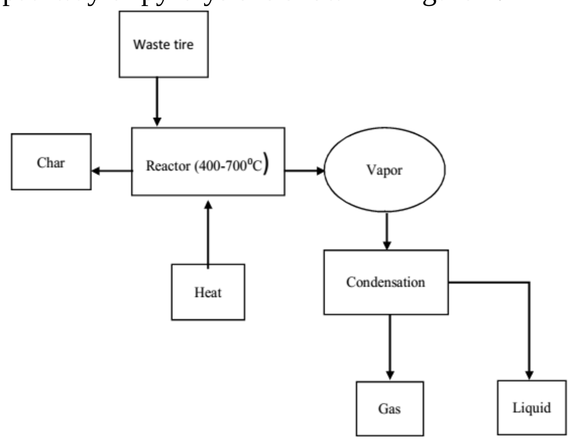

Figure 1. Reaction pathway of pyrolysis process.

2. Design & Fabrication of Fixed-Bed Reactor

The design and fabrication of a fire-tube heating reactor for the batch type fixed-bed pyrolysis unit was the major part of the project and thesis work. The fire-tube heating reactor system of pyrolysis unit was designed on the basis of the size of the system. It was designed so that sufficient amount of feed material could be taken into it, and in a way that there would be a short vapor residence time in the reactor, which would promote a high yield of pyrolysis liquid product.

IOP Conf. Series: Materials Science and Engineering **184** (2017) 012056 doi:10.1088/1757-899X/184/1/012056

The selection of the size of the fixed-bed reactor depended upon the amount of feed to be taken into the reactor. For maximum liquid production, the residence time of the mixture of volatile liquids and gases produced is very important. For simplicity of design, a cylindrical reactor was considered. Due to the corrosive nature of pyrolytic liquid, stainless steel was used as a reactor material. The reactor's height was 990 mm, while the diameter was 400 mm. The reactor had a through type feeder, 250 mm in diameter. This feeder was covered by a flat plate with the help of nut-bolts. Inside the reactor, there were three u-shaped spirals and two semi-hexagonal stainless steel pipes, 19 mm in diameter. The total length of each spiral pipe was 1370 mm and the bending radius was 76 mm. The pipes provided uniform and fast heating inside the reactor. At the bottom of the reactor, there was another throught of 200 mm diameter for char removal. A fixed-bed pyrolysis reactor is shown in Figure 3 before installation and after reactor installation. The annular shaped reactor shield was made while inside wall of reactor was made of 2 mm thick mild steel sheet and outer side being made by 2 mm thick GP sheet. The total length of the furnace 249 cm and length of reactor shield 60.96 cm and internal diameter of the reactor shield 4 cm. The dimensional view of fixed bed reactor shows by Figure 2.

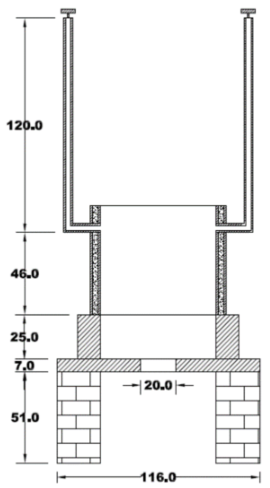

Figure 2. Dimensional view of fixed bed reactor.

Figure 3. Fixed-bed batch type pyrolysis reactor before installation (left) and after reactor installation (right).

2.1 Reactor shield

Reactor shield is a most important component in fixed bed pyrolysis reactor and consisting of four main parts. Two parts are portable and other two parts are fixed. The reactor shield was made of annular shaped consisting of 2 mm thick mild steel sheet while the outside was made of 2 mm thick GP sheet. Moreover, the hollow portion was filled with glass wool for insulating the material. Figure 4 represents the dimensional view of reactor shield.

2.2 Oil or gas burner

An oil burner is a very important part of furnace. The proper firing of burner can maintain the proper heating temperature as well as required temperature for reactor operation. Two burners were designed in such a way so that they can burn the fuel from both side of the furnace. They covered the proper heating inside the furnace. Burners allow flowing of both air and fuel to the furnace.

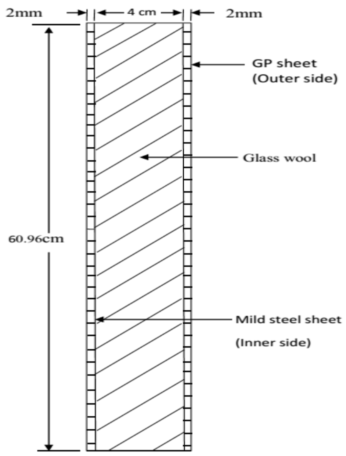

Figure 4. Dimensional view of reactor shield pyrolysis reactor.

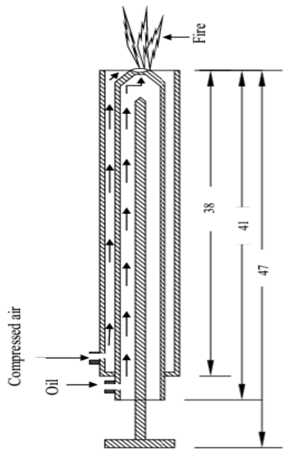

Figure 5. sectional view of burner for furnace heating.

Compressed air was passed through the outside pipe having 3.8 cm diameter. Fuel was supplied through the inner pipe having 2.8 cm diameter with a flow controlling screw. An orifice was introduced at the outer face of the burner to flow the air-fuel mixture at high speed. By controlling the flow of fuel through burner, required heating rate may be maintained. Figure 5 represents sectional view of burner for furnace heating.

3. Condensation principle

To yield liquid oil from pyro-gas, the condensing system is necessary. In condensation system the gas can be reduced to liquid by decreasing its temperature and increasing its pressure. Condensers are typically used as pretreatment devices. They are used ahead of incinerators or absorbers to reduce the total gas volume to be treated by these more expensive pieces of equipment. When hot vapor steam contacts a cooler surface, heat is transferred from the hot gases to the cooler surface. As the temperature of the vapor stream is lowered, the average kinetic energy of the gas molecules is reduced. Ultimately, the gas molecules are slowed down and crowded together so closely that the attractive forces between the molecules cause them to condense to liquid. Two conditions aid condensation: low temperature (so that the gas molecules are low) and high pressure (so that the gas molecules are brought closer). The actual conditions at which the particular gas will condense depend on its physical and chemical properties.

Condensers fall into two basic categories: contact condensers and surface condensers. In a contact condenser, the gas stream and coolant are physically mixed. The coolant and condensed vapors leave the device by separate exits. The surface condensers are also called shell and tube heat exchangers. The temperature of the coolant is increased, so that their devices also act as heaters. The diameter of condenser and length was 15 mm and 170 mm respectively. The outer shell diameter of condenser was 11.71 cm. In figure 6 and 7 presents thermal decomposition of organic solid wastes and dimensional view of condenser. A solid horizontal condenser with a pyro gas inlet, a pyro gas outlet, a hot water outlet and a cold water inlet is shown in Figure 8.

3.1 Selection of materials for separator and condenser

Due to low cost, availability and high operating temperature, a mild steel sheet was chosen to fabricate the separator and condensers. The chemical composition of the mild steel is: carbon 0.42% – 0.48%, silicon 0.15% – 0.35%, manganese 0.6% – 0.9%, phosphorus 0.030%, Sulphur 0.035%.

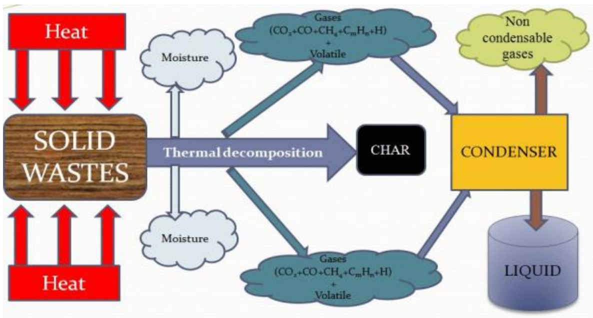

Figure 6. Thermal decomposition of organic solid wastes.

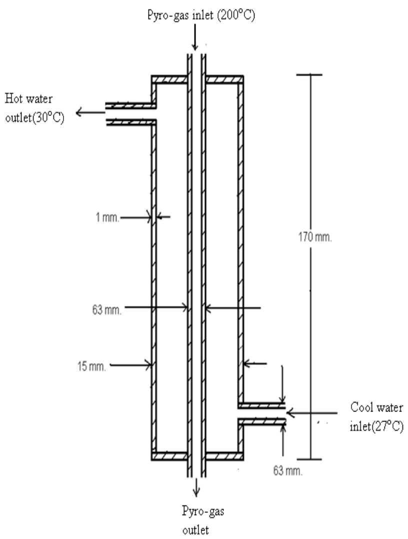

Figure 7. Section view of vertical condenser with dimensions.

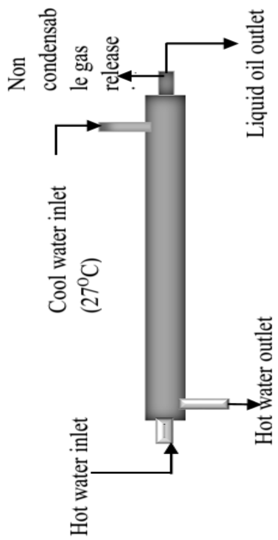

Figure 8. Solid horizontal condenser.

4. Pyrolysis unit operation process

In pyrolysis, the thermal decomposition of waste tires in the absence of oxygen causes them to undergo cracking into simpler organic constituents. Inside the pyrolysis plant, the breaking of chemical bonds occurs through the processes of decomposition and vaporization. The temperature range in which pyrolysis can occur is from 250℃ to 500℃ or 250℃ to 900℃ for some special pyrolysis operations. Shredding tires makes it easier to extract higher amounts of liquid oil products and gases, while temperatures higher than 450℃ cause the yield of oil and solid tire-derived char to decrease relative to gas production[9].

The main factor that will allow accurate calculation of the batch type fixed-bed reactor's performance is the proper assembly of the pyrolysis unit. The generic features of the fixed-bed fire tube heating reactor system have been illustrated in research literature [10-13]. This pyrolysis unit contains a lot of components, such as: a fixed-bed fire-tube heating reactor chamber, a gravity feed type reactor feeder, two ice-cooled condensers, a N_2 gas cylinder, a N_2 gas pre-heater, an air compressor, a char collection bag, and thermocouples. Adequate assembly of these various components was the most important task needed to allow better performance of the plant. At first, a concrete slab supported by four pillars was placed inside underground holes at the base of the pilot plant. Then, the furnace was made on the concrete slab by using fire bricks. Two bumers were connected at the bottom of the furnace. Then reactor chamber was placed on the furnace, supported with two m d steel rods. Next, the insulated side walls were placed around the reactor. A cover plate was attached to the top of the furnace. Two fixed parts of the side wall were attached to the exhaust pipes and the other two portable parts were connected with the fixed parts by means of nuts and bolts. Then, a gas flow line with a gate valve was connected to the fractionating column. The purpose of the fractionating column was to separate the heavy compounds from volatile liquids and gases. Thus, proper flow of gases through the pipes was maintained by separating the heavy compounds of high density as well as those with a high viscosity.

The fractionating column was attached to a vertical condenser, which was in turn connected to a horizontal condenser. A digital pyrometer probe was inserted into the reactor through the cover plate. The fractionating column and the gas pipe lines were supported by a metallic stand and insulated by glass wool with a thickness of 3 cm. Finally, a hole was made for the liquid collector at the outlet of the horizontal condenser. Figure 9 and 10 show the flow diagram and photograph of the completely assembled pilot scale pyrolysis unit, respectively.

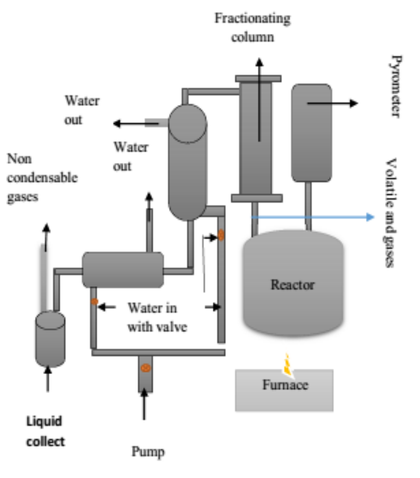

Figure 9. Flow diagram of the pyrolysis process.

Figure 10**.** Photograph of pilot scale pyrolysis unit.

5. Experimental procedure for the complete pyrolysis unit

In the production of tires, several materials and substances are used in tire processing plants[14]. The materials are: elastomer, which is natural or synthetic rubber; reinforcing agents such as carbon black; plastificants, which are hydrocarbon oils; vulcanizing agents, which are sulphur and sulphur components; accelerating agents to facilitate sulphur's action; and protective agents such as anti-oxidizing agents, stabilizers, etc.

IOP Conf. Series: Materials Science and Engineering **184** (2017) 012056 doi:10.1088/1757-899X/184/1/012056

Most primary raw materials are natural rubber, which is derived from the tree ***Hevea Brasiliensis***. Some parts of a processed tire cannot be separated and this waste is disposed in landfills. Process flow diagram of fixed bed pyrolysis reactor is shown in figure 11. Typical tire compositions for new and used tires are presented in Table 1.

Table 1. Typical tire compositions for new and used tires.

Tire compositions	New tires (wt %)	Used tires (wt %)
Elastomer	45	43
Carbon black	22	21
Steel	25	27
Zinc oxide	2	2
Sulphur	1	1
Other oils	5	6

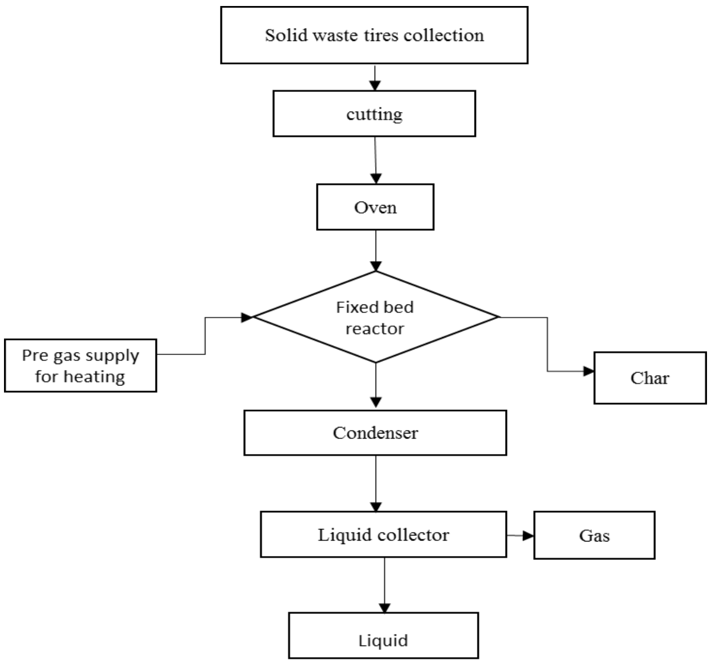

Figure 11. Fixed bed pyrolysis process flow diagram.

For this pyrolysis experiment, a sample of a feed size tire was heated in a fixed batch type pyrolysis plant at 300℃ and at 410℃[14]. The yields of char and liquid were measured in comparison to the primary initial staring materials. Coke yield ($wt.$ %) = $a/\ W_s$ × 100, tar yield (wt. %) = b/W_s× 100.

Where, a = weight of semi coke; b = weight of tar; W_s = initial weight of the sample.

A running pyrolysis unit for tire oil production was set up in the pyrolysis plant[15] Dry feed material was weighed and fed to the reactor and the experimental setup was checked properly. A high temperature adjustable gasket was used to seal the joints and fittings of the pipe lines and flange plates. A temperature measuring pyrometer probe was inserted into the reactor chamber. Subsequently, compressed air and fuel were supplied to the burner for burning the air fuel mixture into the furnace. For adjusting the prop heating, the flow of air and fuel was controlled by flow regulating valves. The temperature variations were measured by a digital pyrometer. The gas flow control valve was opened

IOP Conf. Series: Materials Science and Engineering **184** (2017) 012056 doi:10.1088/1757-899X/184/1/012056

before starting gas production, and a water flow rine was opened to condensers for condensing the gases into liquid. Liquid was collected into a liquid collector at the outlet of the horizontal condenser. Moreover, the temperature of non-condensable gases and water was measured by thermometers.

The time calculation was done by means of a hand watch, and after the completion of pyrolysis oil production, the gas flow control valve was closed so that no air would enter into the reactor to bum the hot char. After all the portable side walls of the furnace were removed and cooled, the reactor's temperature rose to 50℃. Finally, char was removed from the reactor and both the liquid and char were weighed in order to get product distribution in weight percentage ($wt.\%$) of total feedstock.

6. Collection and Preparation of Feed Material

The collected scrap tires originally manufactured by birla and apollow, two Indian brands. The tires were originally designed for use in trucks or buses and weighed about 50 kg each. The waste tires were collected locally from a dump site in Rajshahi, Bangladesh. The tire was steel cord free and cut into pieces of size 16 x 11 x 3 cm. Pieces measuring 20 x 12 x 3cm and 20 x 11 x 2.5 cm were also made. Figures 4.4 and 4.5 show a dump site for solid tire wastes and prepared tire feed, respectively. A typical dump site of scrap tires and the feed size of waste tires are shown in Figure 12.

Figure 12. Typical dump site of scrap tires (left), and feed size of waste tires (right).

7. Heating and cooling operation

The heating and cooling operation is a very important factor for a pyrolysis plant. The reactor and furnace were designed in such a way that the produced heat was transferred into reactor chamber quickly and uniformly. Initially, the recorded temperature was only 30℃, but after only ten minutes the temperature rose to 77℃ and the temperature reading was recorded. Finally, during the next 80 minutes of the reactor's operation, the reactor heated up at an increasing rate up to first 100 minutes of running maintained at constant temperature near about 430℃ ($\pm 100^{O}$C). The portable parts of the insulated side wall of furnace were removed for cooling purposes, and the next 10 minutes saw a temperature decrease until the temperature reached 500^{o} C. The total time for the reactor's heating and cooling operation was 360 minutes. The temperature distribution during the reactor's heating and cooling operation is presented in Figure 13 and 14.

8. Pyrolysis products from the pilot plant

From tire pyrolysis, three products were obtained: liquid, char and gases. Pyrolysis oil or liquid is the main product and char and gases are another two by-products containing higher gross calorific value which may be used as fuel for reactor heating purposes. In this experiment, a successful operation was carried out using four samples of waste tires.

IOP Conf. Series: Materials Science and Engineering **184** (2017) 012056 doi:10.1088/1757-899X/184/1/012056

The final results obtained from this pilot plant experiment are presented in Table 2. From the previous study, it was found that liquid production at the laboratory scale was slightly higher than that produced in a pilot plant For a particle feed size of 10 x 2 x 1cm, the maximum liquid, char and gas production was found to be 57, 26 and 17 *wt* %, respectively at an operating temperature of 475℃. Table 3 shows the pilot plant product yield distribution as compared to previous laboratory results. Table 4 shows the comparison of pyrolysis liquid with petroleum products. In figure 15 photograph of pyrolytic liquid (left), and photograph of char (right) are shown.

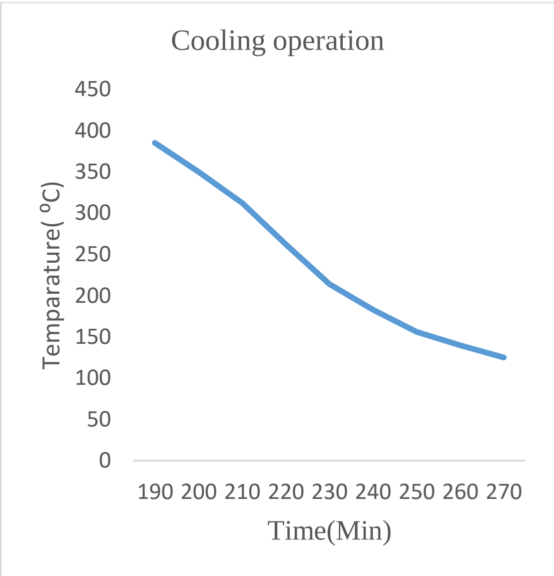

Figure 13. Temperature distribution during the reactor's cooling operation.

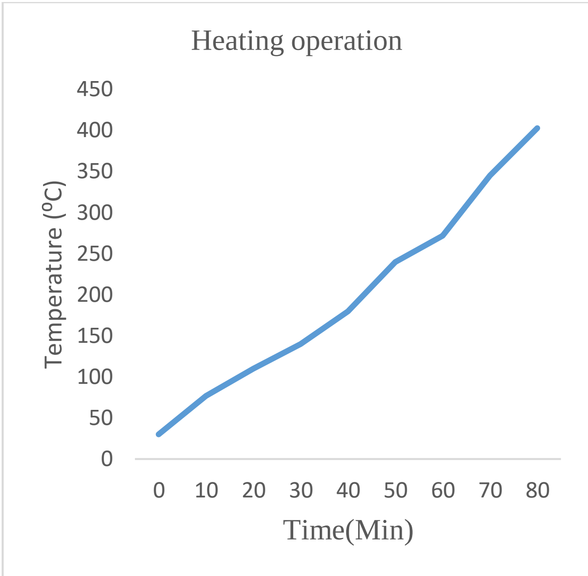

Figure 14. Temperature distribution during the reactor's heating operation.

Table 2. Product yield distribution for tire pyrolysis of different sizes.

Running time (min)	Feed size (cm)	Tire feed (kg)	Product yield (*wt* %)		
			Liquid	Char	Gas
180	16*11*3	35	48.5	37.7	13.8
210	20*12*3	33	48.4	38.1	15.3
185	20*11*3	30	49	38.3	12.7
180	19*12*3	32	46	37.5	16.5

Figure 15. Photograph of pyrolytic liquid (left), and photograph of char (right).

Table 3. Comparison of product yield distribution between a pilot plant and a laboratory unit.

Product yield (wt %)	**Pilot plant**	**Laboratory unit**
Liquid	48	53
Char	38	35
Gas	14	17

Some properties of the pyrolytic liquid produced were very close to petroleum products. The comparison between pyrolytic liquid and petroleum products is given in Table 4, while tire pyrolysis gas yields for different authors and experimental systems is shown in Table 5.

Table 4. Comparison between pyrolytic liquid and petroleum products.

Properties	Pyrolytic liquid	Diesel[7]	Furnace oil
Density (kg/m^3)	950	830	930
Viscosity (cSt)	4.0	2	6.2
HCV (MJ/kg)	42	46.5	46

Table 5. Tire pyrolysis gas yields taken from different authors and experimental systems.

Ref.	Liquid yield (wt %)	Temperature (^{o}C)	Reactor
[12]	$46 - 55$ wt%	$475° - 575°C$	Fixed-bed reactor
[16]	$30 - 45$ wt%	$500° - 550°C$	Fluidized bed reactors
This paper	49 wt%	$430° - 500°C$	Fixed-bed reactor
[17]	49.6 wt.%	$450° - 650°C$	Semi batch reactor

9. Environmental impact of pyrolysis plants and its remedy

During the process of pyrolysis, waste is disposed from the pyrolysis plant. This waste can be categorized by source of emission. Waste water in the tire pyrolysis plant is generated from general plant housekeeping works. A small amount of wastewater is produced from wet scrubber. The solid materials which adhere to the tires are cleaned with compressed air. Tires which have been exposed to road salt necessitate the use of water to remove the salt. For instance, it was reported that the amount of waste water produced from general housekeeping was 150 tons per month at a Shanghai plant[18]. The water is collected in a pond and is reused after removal of oil by a centrifugal separator.

The amount of oil averages 0.26 (about 390 liters per month). This oil is then sent to the furnace for combustion. In the pyrolysis plant, steel and gaseous wastes are produced and the composition of the gases is mostly hydrocarbons and hydrogen. The entire gaseous product is burned to provide heat energy for the pyrolysis process. In the case of pyrolysis, some non- condensable gases are emitted from the condenser: CO_2, CO, NO_X, and SO_X. Also, many fugitive and furan emissions are produced, as well as dioxins. To ensure pollution free pyrolysis plant fabric filters, more water and proper design is required.

10. Results and discussion

In this research, a few trial runs have been carried out at various operating conditions to reach maximum liquid production. The maximum liquid yield for tires was found to be 49 $wt.\%$ of feed. During condensation, it was found that the outlet temperature of the water from the condenser was 27°C, with the gas temperature reaching 68°C (Figure16). The outlet temperature was increased slowly and was raised up to 30°C. The pyro-gas inlet temperature in the condenser was 200°C and reduced to 38°C. There was a temperature rise of the water in the condensers of 3°C.

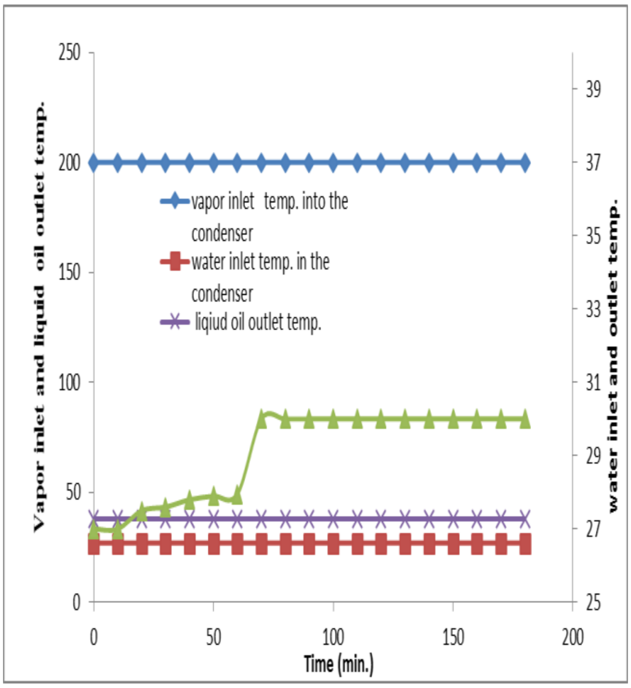

Figure 16. Temperature distribution of pyro-gas in the condensers, of the water inlet, and of the outlet of the condenser.

11. Conclusion

In this fixed-bed batch type pyrolysis system reactor, temperatures ranged from 430℃ to 500℃ and a maximum pyrolysis oil yield of 49 $wt.\%$ was achieved. At higher temperatures, a secondary cracking reaction takes place, causing an increase in gaseous product. It was found that some properties of the pyrolytic oil produced were close to diesel fuels and other conventional fuels. The obtained gross calorific value of pyrolytic oil was significantly high, meaning it could feasibly be used as an alternative to fossil fuel after proper treatment.

References

[1] Aziz, M., et al., DESIGN AND DEVELOPMENT OF A COMPRESSED AIR MACHINE USING A COMPRESSED AIR ENERGY STORAGE SYSTEM. 2006.
[2] Bangladesh power dovelopment board,Key Statistics. 2016; Available from: http://www.bpdb.gov.bd/bpdb/.
[3] Xue, Y., et al., Fast pyrolysis of biomass and waste plastic in a fluidized bed reactor. Fuel, 2015. **156**(0): p. 40-46.
[4] Rada, E.C., et al., Energy recovery from tyres waste through thermal option. Scientific Bulletin, Politehnica University of Bucharest, Series D, Mechanical Engineering, 2012. **74**: p. 201-210.
[5] Osayi, J.I., S. Iyuke, and S.E. Ogbeide, Biocrude Production through Pyrolysis of Used Tyres. Journal of Catalysts, 2014. **2014**.

[6] Aydın, H. and C. İlkılıç, Optimization of fuel production from waste vehicle tires by pyrolysis and resembling to diesel fuel by various desulfurization methods. Fuel, 2012. **102**(0): p. 605-612.
[7] Nabi, A.R., et al., Purification of TPO (Tire Pyrolytic Oil) and its use in diesel engine. IOSR Journal of Engineering, 2014. **4**(3): p. 1.
[8] Islam, M., et al., Feasibility study for thermal treatment of solid tire wastes in Bangladesh by using pyrolysis technology. Waste management, 2011. **31**(9): p. 2142-2149.
[9] Antoniou, N. and A. Zabaniotou, Features of an efficient and environmentally attractive used tyres pyrolysis with energy and material recovery. Renewable and Sustainable Energy Reviews, 2013. **20**(0): p. 539-558.
[10] Berrueco, C., et al., Pyrolysis of waste tyres in an atmospheric static-bed batch reactor: Analysis of the gases obtained. Journal of Analytical and Applied Pyrolysis, 2005. **74**(1–2): p. 245-253.
[11] Musale, H., Y. Bhattacharyulu, and R. Bhoyar, Design Consideration Of Pyrolysis Reactor For Production Of Bio-Oil.
[12] Islam, M.R., et al., Valorization of solid tire wastes available in Bangladesh by thermal treatment. 2011.
[13] Karthikeyan, S., C. Sathiskumar, and R.S. Moorthy, Effect of process parameters on tire pyrolysis: a review. Journal of Scientific and Industrial Research, 2012. **71**(5): p. 309-315.
[14] Fernández, A.M., C. Barriocanal, and R. Alvarez, Pyrolysis of a waste from the grinding of scrap tyres. Journal of Hazardous Materials, 2012. **203–204**(0): p. 236-243.
[15] Lopez, G., et al., A CONICAL SPOUTED BED REACTOR FOR THE VALORISATION OF WASTE TIRES. 2010.
[16] Ringer, M., V. Putsche, and J. Scahill, Large-Scale Pyrolysis Oil. Assessment, 2006.
[17] Pradhan, D. and R. Singh, Thermal pyrolysis of bicycle waste tyre using batch reactor. Carbon (C), 2011. **57**: p. 74.41.
[18] Li, S.-Q., et al., Properties of pyrolytic chars and activated carbons derived from pilot-scale pyrolysis of used tires. Journal of the Air & Waste Management Association, 2005. **55**(9): p. 1315-1326.