

Pyrolytic Reactor for Fuel Oil Recovery from Plastic Waste: A Review

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Abstract: Plastic have woven their way into our daily lives and now pose a tremendous threat to the environment. As petroleum is the main source of plastic manufacturing, the recovery of plastic to liquid oil through pyrolysis process has a great potential since the oil produced has high calorific value comparable with the commercial fuel. The process of converting waste plastic into value added fuels is explained as viable solution for recycling of plastic. The available plastic waste could categorize as low density polyethylene (LDPE), high density polyethylene (HDPE) and polypropylene (PP). A series of tests were carried out at a temperature range of 350 to 550°C. The experiments were conducted on domestic plastic waste. Under pyrolysis condition plastic waste was decomposed into three products viz., pyrolytic oil, producer gas and solid residue. The oil recovered from plastic waste by pyrolysis has similar physical properties of the petroleum oil. This paper reviewed the pyrolysis process for each type of plastics and the main process parameters that influenced the final end product such as oil, gaseous and char. The key parameters that were reviewed in this paper included temperature inside the reactor, type of reactors and residence time of pyrolysis.

Keywords: Alternate fuel, plastic waste utilization, pyrolysis and pyrolytic oil.

I. Introduction

A plastic material is any of a wide range of synthetic or semi-synthetic organic solids that are mouldable. Plastics are typically organic polymers of high molecular mass, but they often contain other substances. They are usually synthetic, most commonly derived from petrochemicals, but many are partially natural. Due to their light weight, durability, energy efficiency, coupled with a faster rate of production and design flexibility, the plastics are employed in entire gamut of industrial and domestic area. Plastics production in India further rises to 4.77 MT in 2005–2006 (Banerjee *et al.*, 2014), maximum of which is polypropylene (PP) and high-density polyethylene (HDPE). Among different types of plastic polymer, low-density polyethylene (LDPE) demonstrates maximum growth in consumption in India closely followed by HDPE and PP. On an average, the commodity plastics viz. PE, PP, PVC, and polystyrene (PS) accounts 80% of the total plastic consumption in India. In 1990–1991, the per capita consumption of plastics in India was 0.8 kg but within a decade, per capita consumption significantly increases to 3.5 kg. However, it is still far below than the global average (18 kg). However, the projected estimates of per capita plastics consumption in 2021 may reach to a substantial figure of 10.9 kg, which seems a realistic considering the rapidity with which plastics are replacing its competitive materials. Annually 1.3 MT of plastic waste is generated in India, which is 36% of total India's plastics consumption. Nearly, 42% of total generated plastic waste is recycled in India by 20,000 recycling industries with total potential of 0.37 MT/annum.

Every year human produce nearly 280 million tons of plastic, and much of that plastic ends up in the environment, harming marine life and other ecosystems (Chanashetty and Patil 2015). The chemical bonds that makes plastic so durable makes it equally resistant to natural processes of degradation. Since plastics are non-biodegradable in nature, it is very difficult to eliminate the waste plastics from nature. The majority of the plastic waste ends up in landfills, and becomes a carbon sink where it may take up to 1000 years to decompose and potentially leak pollutants into the soil and water. The uncontrolled incineration of plastic produces polychlorinated dibenzo-p-dioxins, a carcinogen. So, converting the waste plastic into crude oil will have two benefits. Firstly, the hazards caused due to plastic waste can be reduced and secondly, we can obtain some amount of oil from it, which can be further purified to be used as a fuel in different areas such as domestic fuel, fuel for automobiles and industries etc. Thereby, our dependency on fossil fuels will reduce to a certain extent.

II. MATERIAL AND METHODS

Pyrolysis is a thermo-chemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). It involves the simultaneous change of chemical composition and physical phase, and is irreversible. The word is coined from the Greek-derived elements pyro "fire" and lysis "separating" (Rai 2004). Additionally, the scale of pyrolysis plants is more flexible than incineration plants (Chen *et al.*, 2014). Now a days, pyrolysis is getting attention for its flexibility to generate a combination of solid, liquid and gaseous products in different proportions just by the variation of operating parameters such as temperature or heating rate. It also provides an opportunity of transforming materials of low-energy density into bio-fuels of high-energy density, at the same time recovering high value chemicals. One of the great advantages of this process is that many types of raw material can be used, including industrial and domestic residues. Different types of pyrolysis have been developed: fast, intermediate, slow. In practice, the processes of thermal treatment of waste can operate with a small amount of air present. The fractions of municipal solid waste (MSW) subjected to pyrolysis mainly consist of paper, cloth, plastics, food waste and yard waste. Prerequisite for the successful application of pyrolysis is the appropriate choice of input materials and the setting of optimal process conditions. For these reasons, the suitability or unsuitability of selected types of waste and their mixtures for the pyrolysis process has been verified many times by laboratory experiments with subsequent a

assessment of the quantity and quality of the individual products of pyrolysis (Grycova *et al.*, 2016).

Table 2.1. Main operating parameters for pyrolysis process

Parameters	Conventional	Fast	Flash
Pyrolysis Temperature ($^{\circ}\text{K}$)	550 – 900	850 – 1250	1050 - 1300
Heating rate ($^{\circ}\text{K/s}$)	0.1- 1	10-200	>1000
Particle size (mm)	5 – 50	<1	<0.2
Solid residence (s)	300-3600	0.5-10	<0.5

(Source: Demirbas 2009)

There are different types of pyrolysis process. Conventional pyrolysis (slow pyrolysis) proceeds under a low heating rate with solid, liquid, and gaseous products in significant portions. It is an ancient process used mainly for charcoal production. Vapours can be continuously removed as they are formed. The fast pyrolysis is associated with tar, at low temperature (850–1250 $^{\circ}\text{K}$) and gas at high temperature (1050-1300 $^{\circ}\text{K}$). At present, the preferred technology is fast or flash pyrolysis at high temperatures with very short residence time. Fast pyrolysis (more accurately defined as thermolysis) is a process in which a material, such as biomass, is rapidly heated to high temperatures in the absence of oxygen (Singhad *et al.*, 2011).

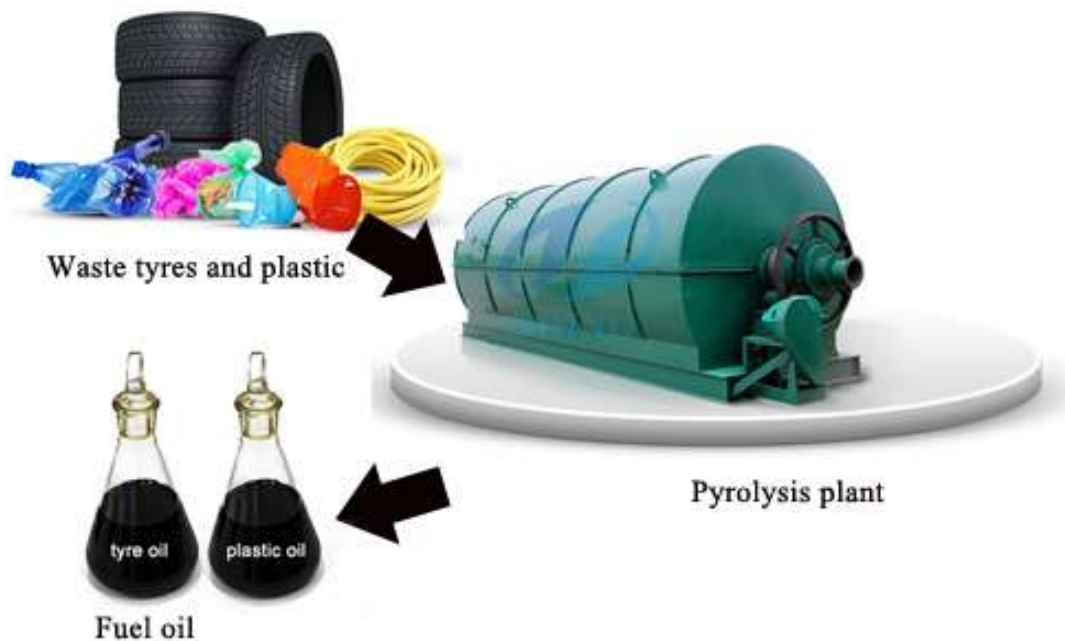


Fig 2.1. Pyrolysis of Waste Tyres and Plastic

2.1. Types of pyrolysis reactors used to utilize different domestic waste

The reactor type being used for the pyrolysis of waste has to be given great importance because of the large amount of heat to be transferred across the reactor wall to ensure material degradation. Reactors described in various literature used in the pyrolysis of different wastes include batch or semi-batch reactors, fluidized bed reactors. For many years, scientists have explored the mechanisms of this process in laboratories around the world, so slow, fast and intermediate pyrolysis are already well known. However, there is still a big challenge to make pyrolysis economically viable, thus the next studies should focus on the implementation of the latest developments in pilots and on an industrial scale.

2.1.1. Batch and semi-batch reactor

In most researchers utilized batch or semi-batch reactors for thermal and catalytic pyrolysis of plastic, as well as post-consumer plastic waste, as it is easy to control the process parameters. Some of the important parameters that were identified include reaction temperature, mass ratio of plastic: catalyst, and reaction time. The temperatures used for the process ranged in 300–900 $^{\circ}\text{C}$, and the reaction time 30-90 min (Shah *et al.*, 2010). In case of catalytic pyrolysis, mass ratio of reactant: catalyst varied from 30:1 to 2:1 was used to increase the product yield and selectivity. It is also possible to perform catalytic pyrolysis on polymer waste at low temperature (200 - 275 $^{\circ}\text{C}$). The reaction was carried out in a locally manufactured reactor, with the volume of 1 lit. The reactor was added with a pressure valve. During the pyrolysis process, the production of condensable vapour and fuel gases exerted pressure on the pressure valve, and the valve opened at certain pressure to release these products into condenser and collection system. Thermal pyrolysis of LDPE bags at 275 $^{\circ}\text{C}$ produced 48.6% (by wt.) of oil, 40.7% (by wt.) of gases, and 10.1% of char (by wt.). This result was comparable to some thermal pyrolysis process in batch reactor and fixed-bed reactor in laboratories. Catalytic pyrolysis of the polymer waste using zeolite at 255 $^{\circ}\text{C}$, on the other hand, was able to produce 51.19 % (by wt.) of oil, 35.88% (by wt.) of gases, and 12.50% (by wt.) of waxes. The oil was identified to be a mixture of hydrocarbons in the range of kerosene and petrol, and could be used as fuel after upgrading.

2.1.2. Fluidized bed reactor

Although pyrolysis of plastic waste in batch reactor is well studied, there are some drawbacks in its application in recycling industry (Elordi *et al.*, 2009). It is more favourable to develop a continuous pyrolysis process, as it does not require frequent materials charging and restarting the process. In addition, continuous pyrolysis process is also less labour-intensive. Trials were using fluidized bed reactors, due to several advantages they possess, including excellent mixing properties, as well as improved heat transfer from reactor to polymer, compared to batch reactors (Yuan *et al.*, 2014). As polymer waste can be fed into reactor at constant temperature, it is possible to produce a narrower and more uniform spectrum of products by manipulating the residence time of polymer waste in the reactor. However, care has to be taken to avoid bed de-fluidization, as this can easily happen when melted plastic sticks on the fluidized bed. The main components in the product gas were ethane and propane.

Fluidised-bed reactors were used to study the behaviour of fast pyrolysis and to investigate the secondary cracking of oil at longer residence times. Fluidised-bed reactors were characterized by a high heating rate and a good blending of the feedstock. Therefore, such reactors are widely used in laboratory studies in order to describe the influence of temperature and residence time on pyrolysis behaviour and products. This type of reactor seems to be a good solution for waste polymer pyrolysis (Chen *et al.*, 2014). A fluidized bed reactor (FBR) is a type of reactor device that can be used to carry out a variety of multiphase chemical reactions. In this type of reactor, a fluid (gas or liquid) is passed through a solid granular material (usually a catalyst possibly shaped as tiny spheres) at high enough velocities to suspend the solid and cause it to behave as though it were a fluid. This process, known as fluidization, imparts many important advantages to the FBR. As a result, the fluidized bed reactor is now used in many industrial applications.

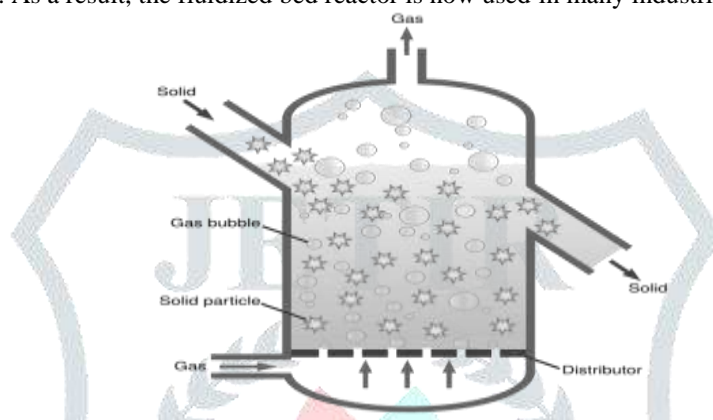


Fig. 2.1. Basic diagram of a fluidized bed

Table 2.1: Design of reactors and systems for plastic pyrolysis

Types of reactor	Types of materials
Batch and semi-batch reactor	Mixture of LDPE and PP; PE; PP MPW and MSW
Fluidized bed reactor	LDPE and PP; PVC ;MPW and MSW
Conical spouted bed reactor (CSBR)	HDPE; Mixture of LDPE, HDPE and PP
Fixed bed reactor	PET; PE

(Source: Wonga *et al.*, 2015)

The flow chart of pyrolysis of plastic waste is given in Fig.3.

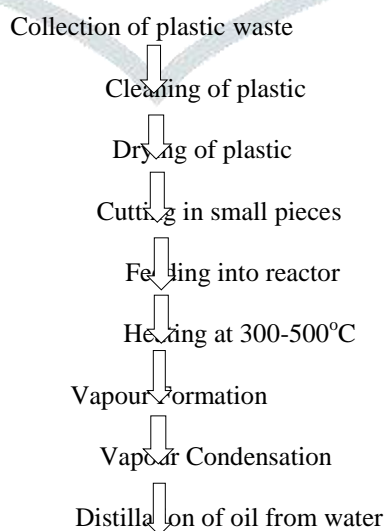


Fig 2.2. Flow chart of conversion of plastics waste into liquid fuel

III. RESULTS AND DISCUSSION

Usually the pyrolysis of waste is aimed at energy recovery, because the products often have good properties as fuels. Moreover, energy (especially electricity) is always a desirable product, which is easy to sell. Additionally, parts of the products can be combusted in

order to meet the pyrolysis energy demand. Pyrolysis also makes it possible to convert waste into an energy source for the home, and on a larger scale pyrolysis plants may use the pyrolysis products for other purposes, which increases the profitability of the process. The complex composition of pyrolytic oil and some properties of char could make them favourable as a raw material for some industry sectors and a few propositions are mentioned below (Jouhara *et al.*, 2017).

3.1. Pyrolytic gas

In general, it is possible to say that the composition of the pyrolytic gas is strongly dependent on the pyrolysis temperature and feedstock. Slow pyrolysis of biomass waste such as wood, garden waste and food residue at low temperatures (below 400 °C) produces small amounts of gas, which is high in CO₂, CO and light hydrocarbons. The gas heating value from slow pyrolysis is around 10-15 MJ/Nm³ and varies in dependence on temperature and heating rate. Fast pyrolysis of biomass produces gas with a heating value around 14 MJ/Nm³. On the other hand, higher temperatures (above 700°C), especially when pyrolysis is combined with gasification, produces syngas, which contains more hydrogen and carbon monoxide. The pyrolysis of plastics produces pyrolytic gas, of which the major components are hydrogen light hydrocarbons: methane, ethane, ethane, propane, propane, butane and butane. This gas has a significant calorific value, e.g. a heating value of gas from PP and PE varied between 42 and 50 MJ/kg (Jung *et al.*, 2010). The most suitable demand on pyrogas is its use as a source of the energy required for the pyrolysis process itself. However, the exhaust gas has to be controlled. Therefore, emission control units and gas cleaning devices should be used and it does not matter whether the gas will be combusted or not.

3.2. Pyrolytic oil

Pyrolytic oil offers more opportunities for use than gas, but, depending on the composition of the feedstock and the process parameters, the composition of the liquid product from pyrolysis may differ radically. Pyrolytic oils originating from biomass consist largely of the following compounds: acids, sugars, alcohols, ketones, aldehydes, phenols and their derivatives, furans and other mixed oxygenates. They can be used for the production of heat, electricity, synthetic gas or chemicals. Temperatures between 500 and 600°C provide the highest yields of oil, when biomass is processed with heating values of around 15-20 MJ/kg. On the other hand, pyrolytic oil from plastics has a higher heating value, about 30 -45 MJ/kg, depending on the polymer and it contains a smaller aqueous fraction. Physical properties such as viscosity, the research octane number and the motor octane number, pour point, flash point or Diesel index could be a good indication of pyrolytic oil quality as a fuel (Ahmad *et al.* 2015). The heating value of oils from mixed plastic waste could be estimated at 40 MJ/kg. Detailed information about oils obtained from different plastics and their mixtures with other waste. It can be summarized, that the liquid phase is usually the predominant product of the pyrolysis of plastics. Those oils are a valuable material, which can be used in a variety of ways.

3.3. Pyrolytic char

Pyrolysis conditions are usually optimized in order to maximize the liquid and gas products; however, a solid fraction named as pyrolytic char is also produced. This char mainly consists of a carbon-rich matrix that contains almost all the inorganic compounds present in the raw wastes and a significant amount of condensed by-products formed during the pyrolysis process and dispersed throughout the solid porous structure. The heating value of char obtained from co-pyrolysis of waste (mixture of biodegradable and non-biodegradable) is approximately 34 MJ/kg, which is comparable with typical coal. Char obtained in pyrolysis is not only a good fuel, but it can also be processed into activated carbon. At a temperature of 2000°C the char was completely carbonized with almost 100% carbon content. The use of waste materials to produce activated carbon is preferable because it reduces the cost of producing activated carbons. An interesting application of char from the pyrolysis of mixtures of wastes is its valorisation as an adsorbent of pollutants. Moreover, due to their potential adsorptive properties, the solid chars are good precursors for manufacturing activated carbons by means of physicochemical activation. The prevalent metal in char obtained from the co-pyrolysis of plastics and biomass is magnesium. Calcium (Ca), potassium (K) and iron (Fe) are significant elements in this char, too. However, zinc (Zn), chromium (Cr), nickel (Ni), molybdenum (Mo), manganese (Mn) and aluminium (Al) also appear (Bernardo *et al.* 2012). The carbonaceous materials obtained have sufficient quality to be reused as precursors for adsorbents. Another application of char from the pyrolysis of wood is its use as an organic fertilizer, which offers many advantages.

Table 3.1. Comparison of pyrolytic oil from some polymers with standard liquid fuels

Properties	HDPE	PP	Gasoline	Diesel
Heating value (MJ/kg)	40.50	40.80	42.50	43.00
Viscosity at 40°C (mm ² /s)	5.08	4.09	1.17	1.9 - 4.1
Density at 15 °C (g/cm ³)	0.89	0.86	0.780	0.87
Research octane number	85.30	87.60	81 - 85	–
Motor octane number	95.30	97.80	91- 95	–
Pour point, °C	-5	-9	-	6

(Source: Ahmad *et al.*, 2015)

Table 3.2. Comparison of HDPE, LDPE and PP with petrol and diesel

Fuel properties	HDPE	LDPE	Petrol	Diesel
Density (kg/m ³)	795.45	530.35	711 to 737	820 to 900
Viscosity (poise)	0.775	0.652	1.5 to 4	1 to 3.97
Specific gravity	0.776	0.655	0.82	0.81 to 0.96
Flash point (°C)	23	24	22	26
Fire point (°C)	27	28	25	29
Cloud point (°C)	Below 2	Below 0	1 to 3	2.5 to 4
Pour point (°C)	- 4.5 to -5	- 2	- 4 to - 20	- 2 to - 12
Colour	Yellow, light transparent	Pale yellow	Brown transparent	Dyed blue

(Source: Raj Kumar and Y. Tembhurne, 2016)

IV. CONCLUSIONS

The pyrolysis studied here presents an efficient, clean and very effective means of removing the debris that we have left behind over the last several decades. By converting plastics to fuel, we could solve two issues, one of the large plastic seas, and the other of the fuel shortage. This dual benefit, though will exist only as long as the waste plastics last, but will surely provide a strong platform for us to build on a sustainable, clean and green future and it would be a great boon to our economy. Pyrolysis gives ready-to-use fuels in an easy and safe way. The thermal decomposition of polymers produces oils with good qualities, which can be used both as a liquid fuel and as a source of chemicals and the char can be used as activated carbon or fertilizer. The developing technology of pyrolysis of plastic waste would allow the efficient utilization of plastic waste for fuel recovery.

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