Pyrolysis Process Studies for Post Consumer Polyethene Waste Conversion and Upgrading of the Pyrolysis Oil

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Abstract: *There is a rising concern on the extensive environmental impacts resulting from unsustainable methods for management of post consumer waste plastics (PCPW) in Kenya. This study was conducted on conversion of PCPW into fuel gas and oils. Low Density Polythene (LDPE), High Density polythene (HDPE) and Polypropylene (PP) were heated in a locally assembled pyrolysis reactor at temperatures ranging between 200-500 $^\bullet C$ and with heating rates of 5-15 $^\bullet C$ / minute. Fractionation was conducted to refine the resultant crude oil into petrol at 150 ^oC and diesel at 350 ^oC. 359.64 g ±1.67, 348.21 g ±0.97 and 301.22 g ±1.5 of crude oil for 500 g of HDPE, LDPE and PP resulted respectively. Diesel, petrol char and wax yields obtained were (72%±1.50, 70%±1.32, 60%±1.67) (6%±0.46, 8.3%±0.37, 6%±0.54), (1 %±0.67, 5 %±1.21, 2 %±0.57) and (1%±0.27, 1.03%±0.42, 1%±0.32)grams for HDPE, LDPE and PP respectively. Mean values for petrol and diesel yields for HDPE and LDPE did not differ significantly with ($t_{observed} < t_{calculated}$) for paired T-test (at 95 % confidence level). Over 90%±1.87 conversion of plastic waste into fuel products was achieved. The plant was economically viable with an energy consumption of less than 5% of the total energy in 0.5 kg of waste plastics.*

Keywords: Pyrolysis; Plastic, Waste, Energy.

1. Introduction

Plastic is a light, durable synthetic material that has found a lot of use in the modern world [1]. The plastic material comes in various types depending on its application. Polypropylene (PP) is the most widely used plastic type in the world today followed by Polyethylene (PE) [2].There are many other forms of other plastics whose applications depend on intended purpose.

Large production and use of plastics for various applications has resulted in huge volumes of plastic wastes [3]. This has lead to proliferation in the environment as a result of accumulation and fragmentation of plastic waste [4]. Most of this waste is non-degradable and highly resistant to light, acids and other tough conditions[5]. Some of the negative impacts resulting from poor waste plastic disposal include; choking and starving marine and wildlife, littering the surrounding environment and blocking drainage systems and water bodies [6]. Burning of plastics in open fires, landfills or by use of municipal solid wastes (MSW) incinerators releases toxic gas emissions. These gases include the persistent organic pollutants (POP's) such as dioxins and furans [7]. Studies have proved that this gases are carcinogenic and have endocrine disrupting effects in a wide range of biota [1]. Other emissions include the Green House Gases (GHG's) that cause global warming [8]-[9].

Plastic is derived from oil refining waste products that constitute petrochemicals produced from fossil oil and gas [10]. Plastics are therefore a potential source of energy when recycled to produce fuels [11]-[12]. Kenya suffers from Insufficient and high cost of energy that affects economic growth [13]-[14]. Plastic waste recycling for energy recovery is yet to be exploited in most of the developing countries where advanced Municipal Solid Waste (MSW) management technologies such as pyrolysis are yet to be fully implemented [15]. Recycling of post-consumer plastic waste for energy recovery through a cost effective and an environmentally friendly process could become an alternative means of obtaining cheap fuel [10] This calls for the development of a home grown pyrolysis process system and carrying out optimization studies of the process so as to make it economical and implementable.

2. Methodology

2.1 Sample collection and preparation

Plastic waste materials of LDPE, HDPE and PP were collected from the open dumpsites. Samples were washed with water and detergent. The cleaned samples were sun-dried and sorted out according to resin codes developed by the Society of Plastic Industries (SPI). The samples were sliced and pelletized into small pieces of dimensions of 2 mm and stored in polyethene bags.

2.2 Pyrolytic Reactor design

The pyrolysis process was conducted in a pyrolysis reactor made of mild steel and stainless steel. The reactor has a height of 20 cm, an external diameter of 11 cm and an internal diameter of 8 cm and a 2 kW electric coil. The

reactor was capped with a ball valve to make it airtight and fitted with an outlet tube system at the top. The tubes had an outer diameter of 300 mm and an inner diameter of 200 mm. The tubing system was passed through a condenser made of a 20 L container that was filled with cold water at room temperature. A pressure gauge of 1- 250 bars was connected to the top of the reactor. A thermocouple with digital temperature readout was connected to the reactor to control and monitor the internal reaction temperature during the pyrolysis process. High purity Nitrogen gas was purged into the reactor at a flow rate of 2 L/min to maintain an oxygen free environment. The reactor was heated to a temperature range of 200 to 350 °C using a 2 kw electric coil for a period of 1-2 hours. The pyrolysis batch reactor used for oil production in this study is as shown in Figure 1.

Figure 1: Pyrolysis batch reactor

2.3 Pyrolytic conversion of HDPE, LDPE and PP waste plastics

Batches of 500 g of pellets were introduced in the pre-warmed reactor at 200 °C. Nitrogen gas was purged into the reactor at a flow rate of 2 L/min. The sample was heated at temperatures ranging between 200-350 °C and with heating rate of 5 °C /minute. The non-condensable gases produced from the reactor were evacuated using the outlet tube system. The gases were passed through a condensation chamber that was operated at room temperature and the condensed oil stored in appropriate glass bottles and gases flared. The remaining solid residue was weighed for each batch and stored in pre-cleaned containers. Optimization studies were carried out by varying reactor temperature within the range of 200-350 °C, 350-450 °C and 450-500 °C respectively and at heating rates of 5, 10 and 15 °C /minute. Reaction times were also varied and catalysts used. The effects of temperature, reaction times and use of catalysts were correlated with the distribution of gas, liquid and residues yield

2.4 Mass balance analysis

The mass balance was determined after the reaction by weighing the raw material and the products using an analytical balance model G R-200 with an accuracy of 0.1 mg. This was done using equation 1:

$$\text{Input}_{(x\ g)} = \text{Crude oil}_{(g)} + \text{Char}_{(g)} + \text{Gas}_{(g)} \cdots \cdots (1)$$

The mass of the gas was obtained by mass differences.

2.5 Fractional distillation of crude oil

Upgrading of the crude oil was done through fractional distillation. x mL aliquots of the crude oil was transferred into a 1 L round bottomed flask connected to a rotary evaporator model R- 200 fractionating column. The system was heated within temperature range of 150 to 350 °C. Petrol and diesel were recovered in separate volumetric flasks at temperatures of 150 °C and 350 °C respectively.

2.6 Cost benefit analysis

Cost benefit analysis was conducted through comparison of the monetary value in energy input and output. The energy input was calculated as total energy used during pyrolysis and fractionation as indicated in equation 2 to 4. An assumption was made that all input energy was consumed and that there were no energy losses.

The Input (energy) used by the reactor for pyrolysis of 500 g HDPE and during Fractional distillation:

$$\text{Input energy: Reactor}_{(2\ kWh\ \times 0.15\ USD/\ kWh)} + \text{Fractional distiller}_{(1\ kWh\ \times 0.15\ USD/\ kWh)} = 0.45_{\ USD} \cdots \cdots (2)$$

$$\text{Output energy: Petrol}_{(6\%\ \times 1.01\ USD)} + \text{Diesel}_{(72\%\ \times 0.90\ USD)} = 0.69\ USD \cdots \cdots (3)$$

$$\text{Difference: Output energy}_{(0.69\ USD)} - \text{Input energy}_{(0.45\ USD)} = 0.24\ USD + Z_{Nm^3\ /\ USD\ (Fuel\ gas)} \cdots \cdots (4)$$

2.7 Energy Consumption

Energy consumption for pyrolysis of HDPE was conducted according to equation 5 to 8.

$$\text{Energy input} = \text{Energy output} \cdots \cdots (5)$$

Energy equivalents: 1 kWh = 3.6 MJ

$$\text{Energy input: Reactor}_{(reactor\ 2\ kWh\ \times 3.6\ MJ + fractional\ distiller\ 1\ kWh\ \times 3.6\ MJ)} = \text{Electricity consumption}_{(10.8\ MJ)} \cdots \cdots (6)$$

Energy output: Petrol (0.2949 m^3) × calorific value (41.92 MJ/m^3) + Diesel (0.35964 m^3)×calorific value (46.10 MJ/m^3) = 204.96 MJ $\cdots \cdots$ (7)

Energy consumption: Energy input (10.8 MJ) / Energy output (204.96 MJ) = 5.27% + Z MJ/$_{Nm^3}$ (fuel gas)$\cdots \cdots$ (8)

3. Results and Discussion

3.1 Pyrolysis products from HDPE, LDPE and PP

Crude oil and solid residue (char) obtained from the pyrolytic reactor are as shown in Figure 2 a, 2 b and 2 c.

Figure 2a: HDPE oil & char   **Figure 2b:** LDPE oil & char

Figure 2c: PP oil & char

Over 90% conversions of plastics to fuel hydrocarbons of gas and oil were achieved.

3.2 Effect of temperature on product distribution

Table 1 shows the percentage distribution results for pyrolysis products obtained at various temperature ranges. Diesel yield decreased with temperature rise, petrol and gas increased, while char and wax remained relatively constant

Table 1: Effect of temperature on product distribution

Parameters		Percentage product distribution for plastic pyrolysis		
	Reaction temperature range (°C)	PP	LDPE	HDPE
		Yield % (w/w)	Yield % (w/w)	Yield % (w/w)
Diesel	250-350	60±1.15	70±1.37	72±1.96
	350-450	55±0.59	69±1.43	68±1.30
	450-500	54±1.45	66±1.96	67±1.45
Petrol	250-350	6±0.63	8±0.76	6±0.53
	350-450	8.2±0.76	8±0.42	7±0.32
	450-500	9±0.43	9±0.25	8±0.64
Gas	250-350	32±0.39	17±0.33	21±0.14
	350-450	34±54	20±0.43	22.8±0.36
	450-500	35.4±21	23.2±0.2	23.3±0.22
Solid residue (char)	250-350	1±0.64	5±1.08	1±0.52
	350-450	2±0.52	2±1.87	1±0.73
	450-500	1±0.48	1±0.78	1±0.43
wax	250-350	1±0.83	1.5±0.87	1.4±1.23
	350-450	0.8±0.67	1±0.50	1.2±1.32
	450-500	0.6±0.58	0.8±1.97	0.7±0.98

3.3 Effect of temperature rise to reaction time for HDPE

As the temperatures increased, reaction time for HDPE decreased in the order 60 ± 2.37 >25± 1.05 > 15± 1.47 minutes respectively as shown in Figure 3a, 3b and 3c.
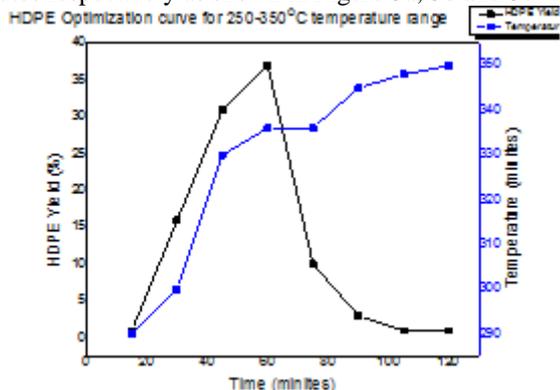

Figure 3a: optimization curve for HDPE at 200-350 ℃ temperature range
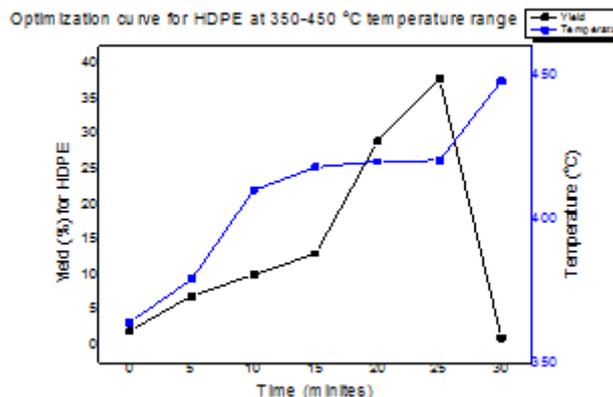

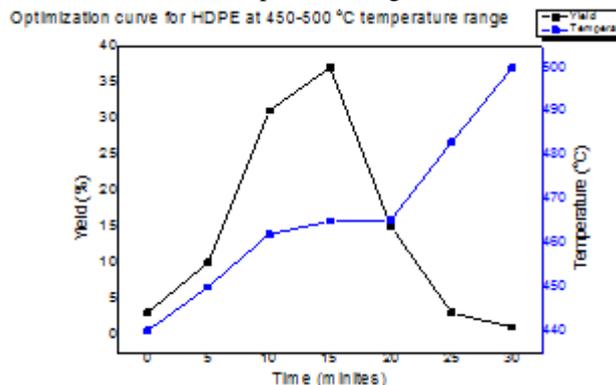**Figure 3b:** optimization curve for HDPE at 350-450 ℃ temperature range

Figure 3c: optimization curve for HDPE at 450-500 ℃ temperature range

3.4 Effect of increased heating rates to products distribution

Diesel yield decreased with increased heating rates, petrol and gas yield increased, char and wax yield remained relatively constant. These results can be observed in table 2.

Table 2: Effect of heating rates to product distribution

Parameter	Percentage product distribution for plastic pyrolysis for 200 - 350 °C temperature range			
	Heating rate	PP	LDPE	HDPE
		Yield % (w/w)	Yield % (w/w)	Yield % (w/w)
Diesel	5 °C/min	60±1.67	70±1.32	72±1.50
	10 °C/min	58±0.54	65.6±1.26	66±1.78
	15 °C/min	53±0.69	62.3±0.45	62.6±1.4
Petrol	5 °C/min	6±0.54	8.3±0.37	6±0.46
	10 °C/min	7±0.23	7.6±0.14	5±0.67
	15 °C/min	8±0.31	6.2±0.31	4±0.72
Gas	5 °C/min	31±1.04	15.77±1.46	20±1.08
	10 °C/min	33.4±1.3	22.97±1.21	26.7±1.9
	15 °C/min	34.7±1.6	34.2±0.43	32.2±2.7
Solid residue (char)	5 °C/min	2±0.57	5±1.21	1±0.67
	10 °C/min	1±0.5	3±0.54	1±0.67
	15 °C/min	1±0.72	1±0.37	1±0.43
wax	5 °C/min	1±0.32	1.03±0.42	1.0±0.27
	10 °C/min	0.6±0.34	0.95±0.65	1.3±1.05
	15 °C/min	0.8±0.57	0.6±0.50	0.8±0.17

3.5 Effect of catalyst on reaction time

The Reaction times and cracking temperatures were lowered significantly with $t_{calculated} > t_{critical}$ (One-way, paired t-test, n=0.05) as shown in Figure 4 and 5.
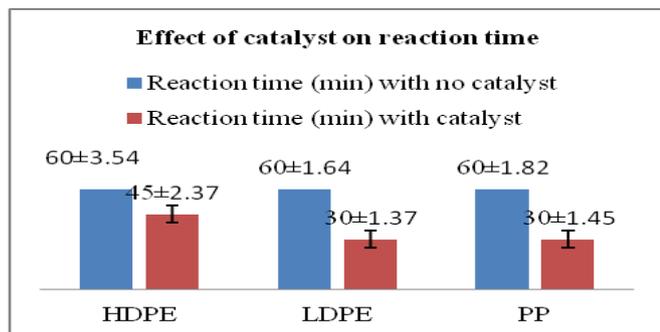

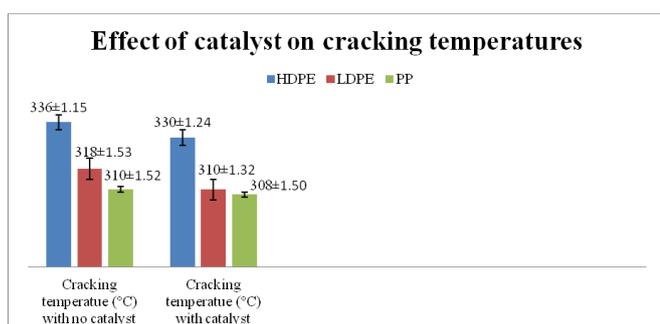**Figure 4:** effect of catalyst on reaction time

Figure 5: effect of catalyst on cracking temperatures

4. Conclusion

A rise in temperatures and heating rates resulted to shorter reaction times for the products in the reactor thus lowering the cost of production. As temperatures and heating rates increased, petrol and gas (light hydrocarbons) production increased significantly with ($t_{calculated} > t_{critical}$), diesel yields decreased but not in significant amounts with ($t_{calculated} < t_{critical}$) for one-way, paired t-test, (n=0.05). These results agree with the findings confirmed by [11] , [16]. The catalyst caused a significant increase in gas yield ($t_{calculated} > t_{critical}$ one-way, paired t-test, n=0.05) and a decrease in diesel yields. These results are similar to the observations and findings made by [17], [18]. Low heating rates of 5 °C/min and reaction temperature range of 350-450 °C provided best conditions for optimal production of diesel oils. These results agree with the findings made by [19]-[20]. The plant was found to be economically viable with less than 5% energy of the total energy in 0.5 kg HDPE plastics getting consumed.

5. Recommendation

Pyrolysis (for energy recovery) provides a solution to waste plastics management problem in kenyan urban centers and rural set-ups. It presents an alternative means of obtaining cheap and affordable fuel to the local community. Pyrolysis technology is thus recommended as the best recycling approach for plastics.

6. Acknowledgement

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104

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