Conversion of Waste Polypropylene into Hydrocarbon fuel – Analysis of the Effect of Batch Size on Reaction Time and Liquid Yield

E. P. Rohan, N. K. Hettiarachchi and B. Sumith

Abstract: Conversion of waste plastics (Polypropylene) into hydrocarbon fuel was investigated by using a reactor system which consists of a reactor, a condenser and a liquid-gas separator. A maximum waste to fuel conversion of over 99% has been achieved with approximately 47% of liquid yield and 52% of gas yield. The liquids and gasses obtained from the experiments were analysed using a gas chromatograph/mass spectrometer unit (GC/MS). Analysis results show that the escaped gas is non condensable at ambient temperature and mainly consists of methane, propylene, isobutane and isobutylene. The analysis results also show that the liquid obtained in the experiments consists of many linear, branched and aromatics hydrocarbon compounds in the range of C₅ to C₁₀.

Waste polypropylene samples different in weight were used for the experiments to investigate the effects of batch size on the reaction time and the liquid yield at near atmospheric slightly positive pressure. No N₂ purging or vacuuming of the reaction zone was used at the start of the experiments. The experimental results showed that the percentage of liquid yield increase with the increase of batch size. The experimental results also showed that the reaction time of 500 g batch size was 100 minutes and that was increased approximately by 15 minutes for every additional 500 g of sample fed into the reactor in respective batches.

Keywords: Waste plastics, Thermal cracking, Batch size, Reaction time, Liquid yield.

1. Introduction

Disposal of solid waste has become one of major environmental issues in Sri Lanka. That is further aggravated by non-bio degradable solid waste like plastic and polythene because the polymer compounds used in plastic and polythene are hardly degradable in a natural manner and causes numerous negative environmental impacts.

Sri Lanka's consumption of crude oil has increased from 90,000 barrels per day in 2011 to 92,000 barrels per day (14.5 million litres/day) in 2012 while having zero natural gas consumption [13]. Municipal Solid Waste (MSW) generation in Sri Lanka is over 6,400 tons/day; about 85 % of collected waste is subjected to open dumping [10]. Approximately 6% of MSW is comprised of plastic waste [11]. Thus the plastic waste generation in Sri Lanka can be estimated at 384 tons/day and above 85% of it end up by land filling causing huge environmental pollution and energy loss in the form of embodied energy of plastic. Afore mentioned waste plastic could be converted into hydrocarbon fuel by thermal

pyrolysis; from 1kg of waste plastic, a maximum of 1 litre of oil can be produced [14]. Thus, theoretically 380,000 litres/day of fuel can be produced and 2.5% of crude oil demand can be supplied by the fuel generated by waste plastic in the country while reducing environmental pollution from post consumer waste plastic.

Recycling of plastic waste has gained increasing attention as the land filling and incineration become more expensive and less accepted due to the environmental impacts. More attention is thus being given to new recycling methods which have high energy recovery values and

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are more environmentally attractive. Pyrolysis is one of the promising methods for the treatment of mixed and contaminated plastic wastes. In pyrolysis, plastics are thermally degraded to produce useful liquid hydrocarbons, which can then either be added to existing fuel or solvent product, or returned to a refinery where they can be added to the feedstock [12].

Many researches have been conducted on conversion of waste plastic to fuel. In most of researches very small samples of waste plastics or sometimes virgin plastics were used for the experiments in very small reactor systems as discussed in the literature. Sometimes these results are difficult to implement in practical situations. On the other hand, large scale waste plastics to fuel conversion plants have been developed in the world. However, there are many problems that have come up to be solved in near future. The present challenges include the minimization of process barriers such as wax formation and line clogging, minimization of production cost, difficulty in transportation of waste plastic due to its large volume. One of the ways to reduce cost of the process, difficulty in transportation and minimization of process barriers is to develop a novel and more efficient small scale plant for the process of waste plastic to fuel conversion which would be operating with simplest mechanisms, could be manufactured at low cost and should be compatible to Sri Lankan conditions. A network of such plants can be distributed across the cities to enable recovery of a sizeable fraction of the post-consumer waste plastic generated in the cities. Therefore designing and development of small scale reactor system for waste plastics to fuel conversion process is timely important.

2. Literature Review

In this research work the possibility of using a small scale reactor system to convert waste plastic into a hydrocarbon fuel and the optimum process parameters to obtain maximum liquid yield were investigated. The effect of different parameters such as operating pressure and batch size on the liquid yield and reaction time was investigated and experimentally improved. Experimental results showed that the developed reactor system has the capability of converting waste plastics (polypropylene) into liquid and gaseous fuel with over 99% conversion at the improved process conditions. The effect of batch size on

liquid yield and reaction time is discussed in this paper.

2.1. Waste plastic Pyrolysis

Pyrolysis involves the heating of plastic waste at temperatures between 220 and 900 °C, in oxygen-free conditions at various residence times. Three different cracking processes such as hydro cracking, thermal cracking and thermal catalytic cracking are reported as different pyrolysis processes. Thermal and thermal catalytic cracking of waste plastic have been investigated by many researchers in the past. The liquid yield obtained is in the range of 24% to 99%, and the solid residue left in the reaction zone is in the range of 1% to 16% [2-7, 12].

The highest liquid yield of 99% has been achieved by Rabia Rehman et al. in their experiments with Silica catalyst for 10 g of polyethylene and 1.0 g of catalyst. Rehman R. et al. also found that in the thermal degradation, liquid product was obtained at 300 °C with only 72% conversion. But with the use of catalyst the total conversion of polyethylene was nearly 100% with all catalysts. Further, reaction time for the experiments with catalyst ranged from 60 to 75 min and for the thermal deprivation it was 185 min for 10 g of polyethylene sample [2].

Pasl A. Jalil reported that 89% of maximum liquid yield with 8% and 2% of gas and solid residue with MCM-41 catalyst. The liquid yield of 81% with 10% and 9% of gas and solid residue has been achieved in the thermal cracking experiment. The liquid obtained in the thermal cracking experiment consist of 90% of waxy materials. Three grams (3 g) of PE pellets were used in all the experiments conducted in a glass batch reactor under atmospheric conditions [3].

Moinuddin Sarker et al. investigated the thermal cracking of LDPE and PP mixture. The waste plastic samples used for the experiments were washed, dried and cut into size of 3-5 mm. Waste sample consisting of 300 g of LDPE and 300 g of PP was used for the experiments in a vertical steel reactor in the temperature range of 100 °C to 400 °C. In the first phase of the experiment the waste sample was melted and turned in to liquid slurry. When temperature is increased to 270 °C, the decomposition starts and liquid slurry turns into vapour. The liquid and gas yield in the experiments were 90% and

6% respectively with 4% of solid residue left in the reactor. The gas generated during the thermal cracking process consists of some light gasses such as methane, ethane, propane and butane. The GC/MS analysis showed that the liquid obtained in the experiments consist of 72 hydrocarbon compounds ranging from C₅ to C₂₇ [4].

Moinuddin Sarker et al. also investigated thermal cracking of LDPE, PP and PS mixture. Similar experimental conditions as in the previous experiments were used. The reaction time of experiments was 5 to 5.5 hours. The liquid and gas yield in the experiments were 89.5% and 6% respectively with 4.5% of solid residue left in the reactor. The GC/MS analysis showed that the liquid obtained in the experiments consist of 85 hydrocarbon compounds ranging from C₅ to C₂₇ [5].

Martin Bajus et al. investigated the thermal cracking of seven component polymer blends comprising of HDPE, LDPE, LLDPE, PP, PET and PVC. 17 g of sample was subjected to thermal cracking under atmospheric pressure at temperatures of 450 °C and 500 °C. The maximum liquid yield of 66% with 3.5% of solid residue in the reaction zone was achieved at 450 °C temperature in a reaction time of 92 min. The liquid obtained consist of both oil and waxes. The same investigation showed that the mixture of oil and wax generation in thermal cracking of PP was 85% with 1% solid residue at same operating conditions [6].

S.L. Low et al. used 40 g samples of pure polymer resins in the thermal cracking experiments. The maximum liquid and gas yields of 77% and 22% with 1% of solid residue in the reaction zone have been achieved for pure PP resins supplied in the form of atactic-PP solid wax. S.L. Low et al. also investigated the effect of heating rate on the product yield. This investigation showed that the optimum heating rate for thermal cracking of a PP was 33 °C/min [12].

Sachin Kumar et al. conducted thermal cracking experiments for 20 g samples of HDPE in a semi batch reactor made of stainless steel tube at a heating rate of 20 °C/min and at temperatures ranging from 400 to 500 °C. The maximum liquid yield of 24% and the solid residue amount of 4% was achieved at 450 °C temperature [7].

Thermal cracking process can be conducted with a simple set of devices compared with other cracking processes like hydro cracking and thermal catalytic cracking. There is no requirement of special type of reactors like fluidized bed reactor used in thermal catalytic cracking to obtain proper contact between plastic and catalyst, no requirement of catalyst and operating at near atmospheric pressure (slight positive pressure) simplifies the thermal cracking process further. A decent liquid yield can also be obtained by thermal cracking even though it has some disadvantages like consumption of considerable amounts of energy compared with catalytic cracking.

Thermal cracking of polyolefin is a high energy, endothermic process requiring temperatures of at least 350–500 °C [8]. The extent and the nature of these reactions depend on the reaction temperature, heating rate, residence time of the liquid and gaseous products in the reaction zone and the pressure in reaction zone.

In addition, reactor design also plays a fundamental role, as it has to overcome problems related to the low thermal conductivity and high viscosity of the molten polymers. Several types of reactors have been reported in the literature, the most frequent being batch reactor, semi batch reactor and screw kiln reactor [2-9, 12].

During the thermal cracking process, the polymeric structure is broken down, producing smaller intermediate species (radicals or ions). These fragments can further react and produce a mixture of smaller hydrocarbon molecules, being liquid, gas, or solid in nature. Apart from de-polymerization reactions, many secondary reactions may occur, including side group or substitute reactions, such as chain scission, unsaturation, cross-linking, group substitution, or elimination, cyclization, etc.

2.2. Hydrocarbon Fuel

Gasoline, Diesel and Kerosene are the main types of hydrocarbon fuel used in the world.

Conventional gasoline is mostly a blended mixture of more than 200 different hydrocarbon liquids ranging from those containing 4 carbon atoms to those containing 11 or 12 carbon atoms [16]. The material safety data sheet (MSDS) for unleaded gasoline shows at least 15 hazardous chemicals occurring in various amounts, including benzene (up to 5% by volume),

toluene (up to 35% by volume), naphthalene (up to 1% by volume), trimethylbenzene (up to 7% by volume), methyl tert-butyl ether (MTBE) (up to 18% by volume, in some states) and about ten others [17]. Hydrocarbons in gasoline generally exhibit low acute toxicities, benzene and many anti-knocking additives are carcinogenic [18]. Complete burning of gasoline releases CO_2 and H_2O to the environment except some dioxides of S and N. Toxic materials like benzene, methyl benzene also burn like any other hydrocarbon in a plentiful supply of O_2 to release CO_2 and H_2O and with limited O_2 it would release CO as well [19].

Petroleum-derived diesel is composed of about 75% saturated hydrocarbons (primarily paraffins) and 25% aromatic hydrocarbons (including naphthalenes and alkylbenzene) [20]. The average chemical formula for common diesel fuel is $\text{C}_{12}\text{H}_{23}$, ranging approximately from $\text{C}_{10}\text{H}_{20}$ to $\text{C}_{15}\text{H}_{28}$ [21]. Complete combustion of diesel would also release CO_2 and H_2O to the environment with some dioxides of S and N.

Kerosene, also spelled kerosine, paraffin or coal oil, is used for burning in lamps and domestic heaters or furnaces, as a fuel or fuel component for jet engines. The chemical composition of kerosene depends on its source, but it usually consists of about 10 different hydrocarbons, each containing 10 to 16 carbon atoms per molecule and the main constituents are saturated straight-chain and branched-chain paraffins, as well as ring-shaped cycloparaffins (naphthenes) [22].

3. Experimental Process

3.1. Raw Materials

Plastics considered in this paper were representative of the major groups of plastics commonly found in municipal wastes. Clean, moisture free textile packaging mainly consist of polypropylene (PP) collected from textile shops were used as the feed of the experiment carried out. Different batch sizes of waste samples were used for the experiments as received without cutting to make small pieces. In order to maintain consistency of samples, same type of textile packaging was selected by visual inspection for each experiment.

3.2. Plastic De-polymerization Apparatus

Plastic de-polymerization apparatus mainly consist of three devices: a reactor, a condenser and a liquid-gas separator.

The semi batch reactor made of stainless steel having a loading capacity of 3 kg (polypropylene bags) is the heart of the system. The semi batch reactor was heated by a set of electric heaters of 5 kW fitted on the outside body. A pressure gauge with 0.02 bar sensitivity and a thermocouple inserted into a thermo well was fitted on the reactor lid.

A condenser was used to condense the gasses generated in the cracking process under the water cooling at room temperature and atmospheric pressure. A liquid-gas separator equipped with a demister was used to separate liquid and gasses after the condenser.

Figure 1 - Developed Plastic De-polymerization Apparatus.

The experimental apparatus was improved to avoid losses which may be arisen due to the liquid reflux to the reactor, liquid carry over with the hot gasses and minor leakages through the fittings.

3.3. Procedure of Experiments

In a typical experiment, the waste sample was loaded to the semi batch reactor as received and reactor lid was closed. The condenser was connected to the reactor and the heater was switched on. The temperature and pressure was measured at every 5 min. In the first phase of the experiment, the reactor outlet valve was closed and the temperature of the sample was allowed to increase until 300 °C in order to melt them. The pressure in the reactor was increased near to 1.5 bar in the first phase of the

experiment. The reactor valve was opened after reaching 300 °C temperature and the generated gasses were allowed to pass through the condenser where condensation of gasses takes place at room temperature and atmospheric pressure under water cooling. The pressure of the reactor was reduced to near atmospheric slightly positive pressure (around 0.06 bar) after opening the reactor discharge valve. The non condensable gasses were safely vented to the atmosphere using a 20 m long vertical duct line. Heating was continued at near atmospheric slightly positive pressure (around 0.06 bar) until the gas generation is stopped. The condensed liquid in the liquid-gas separator and the residue left in the reactor were collected after the experiment and measured by a scale for weight. The gas yield was calculated by the difference of sample weight and the sum of liquid and solid residue weight.

4. Results

No N₂ purging or vacuuming of the reaction zone was carried out at the start of the experiments or during the experiments. Even though no N₂ purging or evacuation of the reaction zone was done, the possibility of combustion of the sample at the start of the experiment is low as the amount of O₂ retained in the closed reaction zone is limited. Further, any remaining O₂ is successfully purged by the generated hydrocarbon gasses and a hydrocarbon gaseous environment is maintained in the reaction zone during the experiments. Therefore, pyrolysis of waste plastics takes place in the reactor in an O₂ free environment during the experiments.

4.1. Yields

In order to investigate the effect of batch size on the reaction time and the liquid yield, six experiments were carried out at 450 °C set temperature. The set temperature was maintained by switching the heaters on and off. The experiments were repeated for each batch size to check the consistency of results. Table 1 shows the volume and percentage of liquid yield, percentage of gas yield (calculated), percentage of solid residue in the reactor and reaction time for different batch sizes. Figure 2 shows the variation of reaction time with sample size and Figure 3 shows the variation of reactor temperature with time.

According to the Table 1, the reaction time for 500 g batch was 100 min and that was increased by approximately 15 min for every additional 500 g of sample fed into the reactor in respective batches. Also the reaction time of the experiments have shown an approximately linear variation with the batch size as shown in Figure 2. Approximately same heating pattern for each experiment was observed in the temperature range of 300 °C to 400 °C as shown in Figure 3.

Thermal decomposition of polypropylene begins in the temperature range of 227 °C to 302 °C [1]. Also, the most sensitive temperature range for the decomposition of PP is 328 °C to 410 °C [15]. Therefore, due to the similar heating pattern observed in the 300 °C to 400 °C temperature range as shown in Figure 3, cracking process take place regardless of batch size and cause to shorten total reaction time of large batch sizes.

Figure 2 - Variation of Reaction Time with Batch Size.

Experimental results also show that the liquid yield increase from 36.80% to 47.03%, when the weight of the waste sample increases from 500 g to 3000 g. The space remaining and the amount of oxygen in the reactor were decreased with large batch sizes. Therefore the combustion of a part of the sample which might be occurred at the start of the experiment reduces at large batch sizes. Also the reduced air space left in the reactor at large batch sizes increase the potential of reducing secondary reactions which may increase the amount of

gaseous products. Thus the liquid yield is increased at large batch sizes.

The solid residue left in the reactor ranged from 0.4% to 0.9% in the experiments. This is very small compared with the data found in the literature. Each experiment was continued until the gas generation is stopped. It may be the reason to end up with very little solid residue amounts in the experiments.

4.2. Liquid and Gas Analysis

The liquids and gasses obtained from the experiments were analysed using a gas chromatograph/mass spectrometer unit (GC/MS).

The gas analysis results (Figure 4) show that the escaped gas is non condensable at ambient temperature and mainly consists of methane, propene (propylene), isobutane and 1-propene, 2-methyl (isobutylene). Four peaks were observed in the analysis at 2.006, 2.047, 2.099 and 2.132 min respectively.

First peak was matched 82% with the standard curve of methane and it was 80% of total. Second, third and fourth peaks were matched 52%, 78% and 91% respectively with the standard curves of propylene, isobutane and isobutylene. The percentages of propylene, isobutane and isobutylene were 13%, 3% and 3% of total respectively.

According to the GC/MS analysis of gasses, escaping gas from the thermal cracking process is a combustible mixture in air. Further, complete combustion of gas mixture in atmosphere will release CO₂ and H₂O to the environment.

The liquid analysis results (Table 2 and Figure 5a and 5b) show that the liquid obtained in the experiments consists of forty six compounds of linear, branched and aromatic hydrocarbon in the range of C₅ to C₁₀ with high concentration of C₇ and C₈ hydrocarbons.

Table 1 - Product Yield and Reaction Time in the Thermal Cracking Experiments at 450°C Set Temperature.

Batch Size (g)	Reaction Time (min)	Liquid Yield		Gas Yield	Solid Residue
		Volume (ml)	Percentage		
500	100	230	36.80%	62.40%	0.80%
1000	115	470	37.20%	61.90%	0.90%
1500	130	750	39.87%	59.66%	0.47%
2000	150	1050	40.60%	58.50%	0.90%
2500	165	1380	42.80%	56.76%	0.44%
3000	180	1860	47.03%	52.56%	0.41%

Figure 3 - Variation of Reactor Temperature with Time.

First 38 peaks out of forty six are shown in Figure 5a and 5b. 20th peak was matched 95% with the standard curve of toluene and it was 13% of total. 35th and 10th peaks were matched 97%, 96% respectively with the standard curves of benzene,1,3-dimethyl (m-xylene) and benzene. The percentages of m-xylene and benzene were 11% and 5% of total respectively. All other compounds in the liquid were in the range of 0.01% to 4.60% of total.

Benzene is mainly a carcinogenic liquid and xylene and toluene have some toxicity as well. But the combustion of benzene, toluene and other aromatics hydrocarbons in a plentiful supply of O₂ would release CO₂ and H₂O to the environment as discussed in the literature.

4.3. Analysis of net energy return

The liquid yield of 1411 g (1860 ml) and gas yield of 1577 g were obtained at the batch size of 3000 g in a reaction time of 180 min. The calorific value of liquid fuel and gaseous fuel obtained from the experiments were found to be 43.5 MJ/kg and 42.7 MJ/kg respectively. The power of the heater used to heat the sample was 5 kW.

Amount of energy consumed = $(5 \times 180)/60$
 = 15 kWh
 = 54,000 kJ

Amount of energy contain in the liquid fuel = $43.5 \times 10^6 \times 1.411$
 = 61,378 kJ

Amount of energy contain in the gaseous fuel = $42.7 \times 10^6 \times 1.577$
 = 67,338 kJ

Total energy return = 61,378 + 67,338
 = 128,716 kJ

Net energy return = 128,716 – 54,000
 = 74,716 kJ

Net energy return per kg of waste = 24,905 kJ/kg

Figure 4 – GC/MS Analysis of the Gas Escaped in the Thermal Cracking of Waste PP.

Table 2 - GC/MS Chromatogram Area Present Report of the Liquid Formed in the Thermal Cracking of Waste PP.

peak #	R.T. min	first scan	max scan	last scan	PK TY	peak height	corr. area	corr. % max.	% of total
1	1.626	216	230	232	rBV	8573039	12575556	5.35%	0.728%
2	1.809	253	261	270	rVV4	8095719	22296213	9.48%	1.290%
3	1.892	271	275	285	rVV	17302322	39355849	16.74%	2.277%
4	1.974	285	289	294	rVV2	8928067	18274859	7.77%	1.057%
5	2.021	294	297	306	rVV	7015698	20127478	8.56%	1.165%
6	2.110	308	312	316	rVV	9506503	17464848	7.43%	1.010%
7	2.151	316	319	321	rVV	9166122	13967413	5.94%	0.808%
8	2.181	321	324	327	rVV4	15928231	29141390	12.39%	1.686%
9	2.269	334	339	346	rVV2	19936456	50244822	21.37%	2.907%
10	2.364	346	355	360	rVV	26021254	85166873	36.22%	4.928%
11	2.417	360	364	375	rVV	10260843	24038765	10.22%	1.391%
12	2.511	375	380	383	rVV2	10358433	21189717	9.01%	1.226%
13	2.706	407	413	423	rVV	16634654	46537253	19.79%	2.693%
14	2.801	423	429	443	rVV	5783021	18692560	7.95%	1.081%
15	2.942	444	453	460	rVV4	5951452	17943385	7.63%	1.038%
16	3.019	461	466	474	rVV2	5407063	15380298	6.54%	0.890%
17	3.179	484	493	506	rVV5	15044740	55495381	23.60%	3.211%
18	3.308	507	515	521	rVV5	5218659	18365266	7.81%	1.063%
19	3.409	523	532	543	rVV6	8812571	40119090	17.06%	2.321%
20	3.592	544	563	581	rVV4	27111806	235147834	100.00%	13.605%
21	3.810	595	600	606	rVV	6835118	13876424	5.90%	0.803%
22	3.946	619	623	634	rVV2	9429032	19156965	8.15%	1.108%
23	4.064	635	643	646	rVV	6437513	12376608	5.26%	0.716%
24	4.158	654	659	668	rVV2	5398181	14932047	6.35%	0.864%
25	4.306	677	684	694	rVV2	12423076	30911630	13.15%	1.788%
26	4.530	715	722	731	rVV3	9558165	23281499	9.90%	1.347%
27	4.637	731	740	744	rVV	7560610	20603748	8.76%	1.192%
28	4.684	744	748	754	rVV	8729303	18814431	8.00%	1.089%
29	4.761	754	761	767	rVV	13827654	33330098	14.17%	1.928%
30	4.814	767	770	788	rVV4	4917291	22807096	9.70%	1.320%
31	4.985	788	799	808	rVV	18834088	60279428	25.63%	3.488%
32	5.203	825	836	846	rVV5	3578290	14438014	6.14%	0.835%
33	5.316	846	855	865	rVV	15596042	44293849	18.84%	2.563%
34	5.475	865	882	892	rVV	21524624	79613387	33.86%	4.606%
35	5.735	902	926	933	rVV2	29287655	194328889	82.64%	11.243%
36	6.189	992	1003	1008	rVV	13580892	44778083	19.04%	2.591%
37	6.272	1009	1017	1026	rVV	23632551	76984984	32.74%	4.454%
38	6.372	1027	1034	1043	rVV2	6178506	15251419	6.49%	0.882%
39	7.092	1145	1156	1173	rVV	4057155	13922231	5.92%	0.806%
40	8.013	1303	1312	1329	rVV	4031550	11965598	5.09%	0.692%
41	8.297	1348	1360	1365	rVV	11529411	37092488	15.77%	2.146%
42	8.533	1388	1400	1426	rVV	10111788	29014966	12.34%	1.679%
43	8.922	1456	1466	1474	rVV	4345822	12203445	5.19%	0.706%
44	9.454	1545	1556	1568	rVV2	10726071	51535706	21.92%	2.982%
45	11.496	1888	1902	1923	rBV	5338667	19150364	8.14%	1.108%
46	13.415	2203	2227	2250	rVB7	1862991	11927153	5.07%	0.690%

Figure 5a - GC/MS Analysis of the Liquid Formed in the Thermal Cracking of Waste PP.

5. Conclusions

The reaction time for 500 g of waste PP batch was found to be 100 min and that was found to increase by approximately 15 min for each additional 500 g of waste PP sample fed into the reactor in respective batches. The liquid yield was found to be increased with increasing batch size. Therefore, the maximum batch size of 3 kg is suitable for the developed semi batch reactor in waste PP thermal cracking process to obtain a maximum liquid yield at an optimum reaction time.

The reaction times of the experiments have shown an approximately linear variation with the batch size and this could be compatible with any semi batch reactor which maintain consistent heating pattern for different batch sizes.

In the gas fraction, 80% of methane, 13% of propylene, 3% of isobutane and 3% of isobutylene were found. This escaping gas from the process was found to be a combustible mixture in air.

Figure 5b - GC/MS Analysis of the Liquid Formed in the Thermal Cracking of Waste PP.

Further, complete combustion of gas mixture in atmosphere will release CO_2 and H_2O to the environment. Therefore, this gas can be burnt as a heat source in the pyrolysis process and thereby energy demand of the process could be reduced.

It should be emphasized that, in the absence of polymeric chains in the feed with Chlorine or any other halogens and in the limited O_2 environment, one may conclude that the possibility of formation of Dioxins and Furans is very low. However, the possibility of PAH

being carried over with the gasses cannot be neglected.

A mixture of linear, branched and aromatic hydrocarbons in the range of C_5 to C_{10} with high concentration of C_7 and C_8 hydrocarbons was formed in the liquid products. In the analysis, maximum values obtained were 13% toluene, 11% m-xylene and 5% benzene. All other compounds found in the liquid were in the range of 0.01% to 4.60%. The hydrocarbon compounds found in the liquid were in the gasoline (C_5 - C_{12}) range. Therefore, further investigations of the properties are required to

determine its potential application as a fuel in internal combustion engines.

Combustion of benzene, toluene and other aromatics hydrocarbons in a plentiful supply of O₂ was reported to release CO₂ and H₂O to the environment. Therefore combustion of this liquid in an internal combustion engine would not release harmful gasses to the environment.

The net energy return of the process was found to be 24,905 kJ/kg at the improved process conditions of operating pressure and batch size. The net energy return could be increased further at an optimum set temperature and heating rate. Therefore further investigations are required to determine optimum set temperature and heating rate of the waste plastics to fuel conversion process to increase the net energy output.

Nomenclature

a-PP - Atactic polypropylene
 HDPE - High density polyethylene
 LDPE - Low density polyethylene
 PAH - Polyaromatic hydrocarbons
 PE - Polyethelene
 PET - Polyethylene terephthalate
 PS - Polystyrene

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Acknowledgement

This Research was funded by grant 11-152 of the National Research Council (NRC), Sri Lanka. The authors gratefully acknowledge the support of Dr. P. K. D. M. C. Karunaratne, Department of Chemistry Faculty of Applied Sciences of USJP for providing GC/MS report of end products.