Catalytic Cracking of High Density Polyethylene Pyrolysis Vapor over Zeolite ZSM-5 towards Production of Diesel

N F A Ghaffar¹, A Johari*¹,2, T A T Abdullah¹,2 and A Ripin¹,2

¹ School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
² Centre of Hydrogen Energy, Institute of Future Energy, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

*anvar@utm.my

Abstract. The upsurge in the amount of plastic pollution has drawn the attention of various researchers in finding the best solution for plastic waste treatment. Pyrolysis of high density polyethylene using ZSM-5 catalyst has been investigated using two-staged reactors consisting of a pyrolysis reactor and a catalytic fixed bed reactor. The effect of the heating rate (2 °C/min, 6 °C/min, 10 °C/min, 14 °C/min, 18 °C/min) of the pyrolysis reactor and reaction time (75 min, 90 min, 105 min) were studied on the yield of products and the quality of pyrolytic oil products. The quality of pyrolytic oil produced was evaluated based on the gross calorific values (GCV) and the paraffin, olefin, naphthenic and aromatic (PONA) compounds distribution, which were used to compare with conventional fuel. The highest yield of oil product was obtained at a reaction time of 75 minutes, where it was 61.05 wt.%, with solid product yield of 0.41wt.% and gas product yield of 38.54wt.%, at a heating rate of 2°C/min. The GCV of oil products were within the range of that of conventional diesel (44 – 45 MJ/kg). The pyrolytic oil products contained mainly C₁₀ to C₂₄ hydrocarbon compounds, which were diesel range hydrocarbon. In terms of the PONA distribution, the composition of paraffin was larger for most of the products, while the composition of naphthenes and aromatic were relatively small with respect to the range for conventional diesel.

1. Introduction
Plastics are one of the most commonly used materials for the production of consumer use objects due to its low cost, durability, malleability, resistance to most chemicals and most importantly, lightweight. However, the disadvantage of plastics is far more alarming. This is due to the inability of plastics to decompose in a short period of time. “Over 300 million metric tons of plastics are produced in the world annually, and about 50% of this volume is for disposal applications, product that are discarded within a year of their purchase” [1]. In fact, in Malaysia, the plastics manufacturing industry contributes to RM12.96 billion export sales in 2015 compared to 9.4 billion in 2010 [2]. Hence, the local production of plastics in Malaysia has been growing steadily and is expected to further expand due to its economic contribution to Malaysia’s overall economy. As a consequence, there will be an upsurge in the number of plastic wastes, especially for single-use plastic products.

Currently, the conventional management of municipal solid waste (MSW) including plastic waste in Malaysia is through landfilling [3]. Unfortunately, this type of waste management, especially non-
sanitary landfill, is not an efficient way for the treatment of plastic waste since it takes up too much space and does not fully contain the plastic from polluting the land and ocean. Besides that, mechanical recycling is also another type of treatment of plastic waste in Malaysia. It is a process whereby the plastic wastes are recycled to produce new plastic resin. Nevertheless, it can only handle a single type of plastic and thus, requires rigorous presorting steps before the process takes place. Also, a water treatment facility is required to treat the contaminated water from cleaning the feedstock, which will be an added cost for installation and operation [4].

Furthermore, plastic waste can also be treated thermally whether through incineration, gasification or pyrolysis [5]. Incineration of waste is a process used to generate electricity by using waste as fuel to produce steam. Typically, incineration of waste is performed on MSW which consists of non-recyclable plastics rather than all types of plastic waste. However, this method causes the emission of toxic and hazardous gases from the combustion of plastic, which will necessitate an air purification system in order to filter the pollutants from entering the atmosphere [6]. Besides that, gasification is another process of thermal treatment performed by heating waste at high temperatures to produce syngas. The feedstock can be either purely plastic waste or co-fed with biomass to manipulate the quality of syngas. Similar to incineration, gasification requires a series of syngas purification system due to the formation of CO₂, NOx, and SOx from the reaction with air [6]. Feed pretreatment steps are also required since the process occurs at high temperatures and short residence times. Consequently, additional cost is needed for the overall gasification plant operation [6].

Pyrolysis is a thermal treatment of plastic waste at high temperatures without the presence of oxygen, but with an inert environment. Unlike other types of thermal treatment, this option can handle highly contaminated and heterogeneous plastic feedstock and requires few pretreatment steps making it more economically attractive among the others. Flue gas clean up system will not be a main concern since the gas product will be contained and treated prior to its utilization as fuel [5]. Pyrolysis of plastic also produces high calorific value pyrolytic oil and gas which matches conventional fuels that could be easily marketed and used in gas engines to produce electricity and heat [5]. Catalytic pyrolysis seems to be more efficient in producing high-quality oil due to the ability of the catalyst to reduce the amount of impurity, dictate the chemical composition in the product and manipulate the amount of yield of certain products [7]. The results of product yields also vary depending on the type of catalyst used, whereby highly acidic catalyst typically yield higher gas product [8] while catalyst with lower acidity yield higher liquid product [9-10]. Thus, in order to increase the yield of liquid product, a lower acidity catalyst is preferred, which resulted in the use of zeolite ZSM-5 catalyst of SiO₂:Al₂O₃ ratio of 1000 since a larger ratio indicates lower acidity as studied by Shirazi et al., [11].

Most of the experiments performed on catalytic pyrolysis using zeolites are unable to emulate the chemical composition of real diesel or fuel with respect to the paraffin, olefin, naphthenic and aromatic (PONA) compounds distribution since some of them either have an unbalanced amount of paraffin, olefin, naphthene, and aromatics or contain mostly aromatics or olefin compounds [12-16]. Therefore, it is vital to analyze the PONA distribution of pyrolytic oil product and compare with that of conventional diesel. This will help to determine the necessary compounds required to be manipulated to best replicate the PONA distribution of conventional diesel to imitate its physical and chemical properties [17]. This study will explore the possibility of producing diesel range pyrolytic oil from the catalytic cracking of high density polyethylene (HDPE) pyrolysis vapor using ZSM-5 catalyst and performing analysis on the pyrolytic oil products with respect to the PONA compounds distribution.

2. Experimental
2.1. Raw material and catalyst
HDPE pellets of size 3 x 4 x 1 mm (W x L x H) were obtained from Polyethylene Malaysia Sdn. Bhd. Zeolite ZSM-5 catalyst with Si/Al ratio of 1000 in powder form, was procured from Acros Organics. The catalyst was pressed and sieved to a particle size of 1.0 – 1.4 mm and was heated for 4 hours at 500°C to remove the adsorbed gas or other impurities. The HDPE was characterized on the proximate analysis according to a method described by Wong [18] and thermal analysis by the thermogravimetric
analyzer (TGA-50, Shimadzu). The ZSM-5 catalyst was characterized based on BET surface area analysis (SA3100 Beckman Coulter) and its acidity properties by temperature-programmed desorption of ammonia (TPD-NH₃) using chemisorption analyzer unit (Micromeritics Autochem II 2920).

2.2. Pyrolysis experiment

The experiment was carried out in a two-staged pyrolysis catalysis batch reactor as shown in Figure 1. Nitrogen gas, which was used as a carrier gas, was flown for 5 minutes through the reactor, where the pyrolysis took place at the horizontal reactor while the catalytic cracking occurred at the vertical reactor. The plastic sample, weighing 5 g, was placed on two ceramic combustion boats in the horizontal reactor, where it was heated using an electrical heater at a heating rate of 2°C/min until the desired temperature of 525 °C. The nitrogen flowrate was set at 60 cm³/min. After the temperature in the pyrolysis reactor reached 525°C, the reaction time was set at 90 minutes (for the heating rate variable). 0.5 g ZSM-5 catalyst was placed on a stainless steel mesh in the vertical fixed bed reactor, held at the middle part of the reactor by a steel ring, where it was preheated using an electrical heater at the final temperature, 525°C, of the pyrolysis reaction. Once pyrolysis took place, the volatile components flowed out of the pyrolysis reactor and through the ZSM-5 catalyst placed inside the fixed bed reactor. The reacted condensable products from the fixed bed reactor were liquefied in three units of cold trap condensers. The first condenser contained liquid nitrogen as the cooling agent while the subsequent units contained an ice bath with added ethanol. The residual solid of HDPE in the pyrolysis reactor and the oil products in the condenser collected were weighed to determine the yield of the solid and oil products. The oil product was kept at 5°C in a refrigerator prior to analysis.

![Figure 1. Experimental set-up diagram](image)

The experiment was then repeated at heating rates of 6°C/min, 10°C/min, 14°C/min and 18°C/min. The experiment was also repeated based on the heating rate that gives the maximum yield of oil product where, it was performed at reaction times of 75 minutes and 105 minutes, to investigate the effect of reaction time on the pyrolysis experiment.

2.3. Analysis of Products

2.3.1. Yield of Products. The yield of solid, oil and gaseous products collected in each run was calculated using Equations (1), (2), and (3) as follows.
Solid yield (wt.%) = \[ \frac{\text{Mass of solid residue in the ceramic boat (g)}}{\text{Mass of HDPE feedstock (g)}} \times 100\% \] (1)

Oil yield (wt.%) = \[ \frac{\text{Mass of condensed product in the cold trap (g)}}{\text{Mass of HDPE feedstock (g)}} \times 100\% \] (2)

Gas yield (wt.%) = \[ \frac{\text{Mass of HDPE feedstock (g)} - \text{Mass of oil product(g)} - \text{Mass of solid product(g)}}{\text{Mass of HDPE feedstock (g)}} \times 100\% \] (3)

2.3.2. Analysis of Oil Products. A bomb calorimeter manufactured by IKA C2000, was used to determine the Gross Calorific Values (GCV) of the oil products. The chemical composition of the oil products was determined using gas chromatography coupled with a mass selectivity detector (GCMSD). Prior to the analysis, the oil products were diluted with n-hexane solution (Analytical Reagent) at a volume ratio of 1 to 9. The GCMSD was equipped with a 30 m × 0.25 mm capillary column of 5% phenyl-methylpolysiloxane (HP-5). Chromatographic peaks were identified by means of NIST standard reference database. The compounds detected in the oil products were classified based on the carbon number distribution and the paraffin, olefin, naphthene and aromatic chemical groups (PONA) distribution. These results were compared with that of conventional diesel based on a study by Farrell et al., [17].

3. Results and Discussion

3.1. Proximate and thermal analysis of HDPE polymer

Table 1 summarized the proximate analysis of HDPE feedstock. The result showed that HDPE feedstock contained mostly volatile matter, which consisted of 99.52 wt.%. The high amount of volatile matter signified a large amount of volatile components from HDPE that can be condensed into liquid product [19]. A small amount of moisture content, was also observed, which might be due to the moisture from the air onto the sample during storage. The ash content was minimal, which was about 0.10 wt.%. Besides that, there was no amount of fixed carbon observed in the HDPE sample.

| Type of Content | Weight (%) |
|-----------------|------------|
| Moisture        | 0.38       |
| Volatile Matter | 99.52      |
| Ash             | 0.10       |
| Fixed Carbon    | 0.00       |
| Total           | 100.00     |

Figure 2 shows the thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of the HDPE feedstock. The TG curve showed that the decomposition of HDPE occurred in a single step pattern. Based on the DTG curve, the peak decomposition temperature was 473°C. Therefore, the minimum temperature for the pyrolysis was set at 525°C, which is higher than the temperature of 473°C, to ensure the feedstock had been fully decomposed. The shoulder or smaller peak before the decomposition peak was due to the presence of impurities such as plasticizers or additives that are common in polymer plastics in addition to low heating rate usage [35].
3.2. Surface area and TPD-NH$_3$ analysis of ZSM-5 catalyst

The result for the surface area analysis was reported in Table 2. The result was compared with other ZSM-5 catalyst used in a similar study for the catalytic cracking of HDPE pyrolysis vapor. The BET surface area for the catalyst used in this study was 359.85 m$^2$/g, with a total pore volume of 0.2261 cm$^3$/g and a micropore volume of 0.0901 cm$^3$/g. On the other hand, the BET surface area for the catalyst from the other study was lower, which was 266 m$^2$/g. Besides that, the total pore volume and micropore volume of the catalyst used were higher than the one in this study, which were 0.3500 cm$^3$/g and 0.2300 cm$^3$/g, respectively.

Table 2. Nitrogen adsorption-desorption analysis of ZSM-5 catalyst

| Catalyst | Si/Al ratio | BET Surface Area (m$^2$/g) | Micropore Surface Area (m$^2$/g) | Total Pore Volume (cm$^3$/g) | Micropore Volume (cm$^3$/g) | Reference |
|----------|-------------|-----------------------------|----------------------------------|-----------------------------|-----------------------------|-----------|
| ZSM-5    | 1000        | 359.85                      | 190.22                           | 0.2261                      | 0.0901                      | This study|
| ZSM-5    | 20          | 266.00                      | -                                | 0.3500                      | 0.2300                      | [37]      |

The total amount of ammonia desorbed by the ZSM-5 catalyst was indicated by the peak area of the curve in Figure 3. Based on the result obtained, the total ammonia desorbed was 0.051 mmol NH$_3$/g of catalyst. Since the ZSM-5 catalyst used had a Si/Al ratio of 1000, then a smaller value was anticipated, which indicated low acidity [11].

3.3. Product Yield

The result of product yields from different heating rates was summarized in Table 3. Note that the time taken to reach the final temperature in Table 3, corresponds to the time taken for the temperature to
increase from room temperature of 25°C to the designated final temperature of 525°C in the horizontal reactor, based on varying heating rate. As the heating rate increased from 2°C/min to 18°C/min, the solid yield decreased from 0.32 to 0.02 wt.%. The decrease in solid yield was due to the rise in the rate of degradation of HDPE sample feedstock as the heating rate increased. Since at 18°C/min, the HDPE sample feedstock degraded faster, the amount of solid residue left was smaller compared to lower heating rates. This was in agreement with studies by Singh et al., [20] and Efika et al., [21] who conducted pyrolysis of mixed plastic waste and refuse-derived fuel, respectively.

Table 3. Effect of heating rate on product yields

| Heating rate (°C/min) | Time taken to reach final temperature (min) | Solid yield (wt.%) | Oil yield (wt.%) | Gas yield (wt.%) |
|-----------------------|---------------------------------------------|-------------------|-----------------|-----------------|
| 2                     | 250                                         | 0.32              | 59.37           | 40.31           |
| 6                     | 83.3                                        | 0.19              | 55.27           | 44.54           |
| 10                    | 50.0                                        | 0.11              | 50.48           | 49.41           |
| 14                    | 35.7                                        | 0.10              | 47.88           | 52.02           |
| 18                    | 27.8                                        | 0.02              | 51.52           | 48.46           |

However, in terms of oil and gas yields, the oil product yield decreased while the gas product yield increased overall, as the heating rate increased. At a higher heating rate, the rapid degradation of polymers allowed further cracking of the hydrocarbons to form short-chain polymers with low carbon numbers, which consisted of mostly gases. As indicated in Table 3, it took only 27.8 minutes for the pyrolysis reactor to reach the final temperature of 525°C, at a heating rate of 18°C/min. As a result, at a higher heating rate, the decomposition rate of HDPE is higher, which resulted in a higher yield of gas products. This also resulted in a decrease in oil products since more HDPE is vaporized and flowed out through the gas outlet in the sweeping gas environment. Thus, higher heating rates increased the yield of gas products and decreased the yield of oil products.

Table 4 summarized the product yields based on different reaction times at a constant heating rate of 2°C/min. This heating rate was chosen due to the highest oil yield produced from the previous experimental run as per Table 3. The result showed that the solid yield declined from 0.41wt.% to 0.16wt.% as the reaction time increased from 75 minutes to 105 minutes. Since more heating time was allocated, then more HDPE polymer was degraded into volatiles in the pyrolysis reactor, leaving a small amount of the polymer as solid product. Thus, increasing the reaction time decreased the yield of solid product in the reactor.

Table 4. Effect of reaction time on product yields

| Reaction time (minute) | Solid yield (wt.%) | Oil yield (wt.%) | Gas yield (wt.%) |
|------------------------|-------------------|-----------------|-----------------|
| 75                     | 0.41              | 61.05           | 38.54           |
| 90                     | 0.32              | 59.37           | 40.31           |
| 105                    | 0.16              | 55.72           | 44.12           |

In terms of oil yield, the highest oil yield, 61.05 wt.% was obtained at the lowest reaction time, which was 75 minutes. As the reaction time increased, the yield of oil products decreased. Reversibly, as the reaction time increased, the yield of gas products increased. This was due to the increase in heating time in the pyrolysis reactor causing more volatile products to flow through the catalysis reactor and form shorter chain hydrocarbon. This is because the heating time of the HDPE feedstock in the reactor is longer which leads to secondary reactions among the volatiles [23-24]. This includes further cracking
of volatiles to non-condensable gases, which are compounds of carbon number C1 to C4, rather than condensable gases, which are compounds of carbon number C5 and above. As a result, longer reaction time leads to more formation of gas products which typically consists of compounds of carbon number C1 to C4 [25] and hydrogen. These findings, whereby the gas yields were higher, and the oil yields are lower at higher reaction time, were in accord with studies by Adnan et al., [26] and Miandad et al., [27].

3.4. Analysis of Oil Products

3.4.1. Gross Caloric Values (GCV) of Oil Products. Table 5 summarized the Gross Calorific Values (GCV) of the pyrolytic oil products for the parameters of heating rate and reaction time. The GCV of the oil products obtained were between 44 to 45 MJ/kg. All the GCV values were within the range of that of conventional diesel [28]. This is expected because HDPE had a high amount of volatile matter, which was 99.52 wt.%, as indicated in Table 1. As a result, the volatile matter contains hydrocarbon gases which have high energy content once the HDPE is combusted in a bomb calorimeter [16]. This lead to the high GCV values obtained for the pyrolytic oil products. Plastics, which originated from petroleum crude have high GCV values in the range of 44 – 46 MJ/kg, specifically for polyethylene derived pyrolysis products [22], [36].

| Parameters | Gross Calorific Value (GCV)/ MJ/kg |
|------------|-----------------------------------|
| Heating rate (ºC/min) | Pyrolytic oil products | Conventional diesel |
| 2 | 44.99 | |
| 6 | 44.81 | |
| 10 | 45.24 | |
| 14 | 44.77 | |
| 18 | 45.12 | |
| Reaction time (min) | | 44 - 46 |
| 75 | 45.10 | |
| 90 | 44.99 | |
| 105 | 43.88 | |

3.4.2. Chemical Composition of Oil Products. The chemical compounds in the oil products were classified based on carbon number and the Paraffin, Olefin, Naphthenic, and Aromatic (PONA) compound distribution. These classifications were selected as a means for comparison with the current standards of conventional fuel.

Figure 4(a) represents the effect of heating rate on the carbon number distribution of oil products, while Figure 4(b) represents the effect of reaction time. Based on the oil product analysis using GCMSD, the compounds detected in the oil products were classified based on the carbon number. The y-axis indicated the peak area percentage of compounds detected in the GCMSD analysis. In general, the oil products contained a high amount of C10 to C24 hydrocarbon compounds, which are diesel range compounds, while a minimum amount of C24+ hydrocarbon compounds, which are heavy oil range compounds as observed by other researchers using zeolite based catalysts [16], [9]. This shows that the ZSM-5 catalyst was effective in increasing the decomposition of HDPE to short-chain hydrocarbon compounds. With reference to Figure 4(a) and 4(b), the parameter of heating rate and reaction time had little or no direct influence on the carbon number distribution in the oil products. A similar result was also obtained by Tamri et al., [34], whereby the heating rate varied had little or no direct influence on the carbon number distribution of the pyrolytic oil products.
Tables 6 and 7 indicate the PONA distribution of the oil products with respect to conventional diesel. The oil products contained a high amount of paraffin compounds which ranged from 46 – 61% in the composition. Meanwhile, olefin, naphthenic and aromatic compounds were between the range of 9 – 22% depending on the parameters varied. Comparing the PONA distribution of oil products with the specification for conventional diesel, only a few of the oil products were able to meet the specification, which was from Table 6, oil products for heating rate 10°C/min, 14°C/min and 18°C/min. These oil products were only able to meet the specification for the paraffin and the aromatic compound groups. For Table 7, the pyrolytic oil products were not able to meet the specification for diesel where it contained a large amount of paraffin and a small amount of aromatics.
Table 6. Effect of heating rate on the PONA distribution of the oil products

| Heating rate (°C/min) | Compound composition (%) | | | |
|-----------------------|---------------------------|---|---|---|
|                       | Paraffin | Olefin | Naphthene | Aromatic |
| 2                     | 61.93    | 9.81   | 12.25      | 13.90   |
| 6                     | 58.66    | 11.34  | 16.10      | 12.41   |
| 10                    | 48.27    | 19.92  | 15.80      | 14.85   |
| 14                    | 46.45    | 16.94  | 14.41      | 20.84   |
| 18                    | 51.00    | 22.19  | 10.24      | 15.66   |
| Conventional diesel   | 25 - 50  | -      | 20 - 40    | 15 - 40 |

Table 7. Effect of reaction time on the PONA distribution of the oil products

| Reaction time (min) | Compound composition (%) | | | |
|---------------------|---------------------------|---|---|---|
|                     | Paraffin | Olefin | Naphthene | Aromatic |
| 75                  | 60.97    | 17.82  | 11.75      | 8.04    |
| 90                  | 61.93    | 9.81   | 12.25      | 13.90   |
| 105                 | 61.68    | 13.33  | 12.83      | 10.16   |
| Conventional diesel | 25 - 50  | -      | 20 - 40    | 15 - 40 |

Since HDPE is a polyolefinic compound, the depolymerization of HDPE produces a large number of olefins; whereby these olefins can further react to form aromatics through a tertiary reaction [29]. Hydrogenation of olefin compounds can also occur to form paraffin compounds [12]. Since a large amount of paraffin compounds were observed, it is suggested that hydrogenation of olefins occurred rapidly from the process. This finding was also observed in the catalytic upgrading of pyrolysis wax oil from municipal plastic waste, where the composition of paraffin compounds accounted for approximately 43wt.% using 80% Zeolite Y and 20% Clay as the catalyst [27].

Besides the formation of paraffin, the olefin compounds also played a major role in the formation of aromatic compounds. This can be achieved through the cyclization of olefin compounds through the Diels Alder reaction before undergoing aromatization to form benzene and other aromatic compounds. However, as seen in Tables 6 and 7, the aromatic compounds was still minimum compared to the range of 15 – 40% in conventional diesel. Small amounts of cycloolefin compounds were detected, which indicated that cyclization occurred on the catalyst pores but not significantly. Typically, cyclization and aromatization of the volatile products occur at the acidic sites inside the catalyst pores, to form aromatic compounds [18]. Kim et al., [31] were able to obtain higher formation of aromatic compounds using desilicated hierarchical ZSM-5, which is a more acidic catalyst rather than the commercial ZSM-5, which is a lower acidic catalyst from the co-pyrolysis of wood with a plastic polymer.

In addition to catalyst acidity, catalyst mesoporosity also affected the formation of aromatics hydrocarbon in the pyrolytic products [31]. This is because conventional ZSM-5 zeolites, which are typically microporous in structure limits the mass transfer of molecule reactants to only minuscule sized molecules [32]. Therefore, by increasing the size of catalyst pores, a larger amount of molecules can enter the pores and thus react with the acidic sites to form aromatic compounds. In this case, the aromatic compounds was minimum due to the lack of acidic sites on the ZSM-5 zeolite catalyst as a result of high SiO₂: Al₂O₃ ratio within the zeolite framework. The high SiO₂: Al₂O₃ ratio indicates that the zeolite framework contains a minimal amount of Al atom, which contributes towards the acidity of the catalyst. Since the amount of Al atom is low, the acidity or the density of acid sites within the catalyst is low [11]. Besides that, the ZSM-5 catalyst used was microporous in structure as shown in Table 2 earlier. This indicates that a limited amount of polymer reactants were able to enter the catalyst pores for the...
catalytic reaction. Thus, the acidity and the porosity of the catalyst used needs to be improved to modify the selectivity of PONA compound distribution in the oil products.

4. Conclusion
For both parameters, as the heating rate and reaction time increased, the solid and oil product yield decreased while the gas product yield increased. The GCV of all the oil products were within the specification for conventional diesel (44 - 45MJ/kg). For the carbon number distribution, all of the oil products contained more than 68% in peak area, of C_{10} to C_{24} hydrocarbon compounds, which are diesel/kerosene range hydrocarbon compounds. The PONA distribution of the oil products showed large amount of paraffin compounds while varying amount of olefin, naphthenic and aromatic compounds. Few of the oil products were able to meet the specified range for PONA distribution with respect to conventional diesel. It is suggested that more studies to be conducted in the future on the possibility of manipulating the PONA distribution of the pyrolytic oil products to match with that of conventional fuel for its potential application as alternative fuel.

Acknowledgments
The author would like to thank Universiti Teknologi Malaysia for the financial support provided through the Research University Grant 20H52 and 04G13.

References
[1] Singh P and Sharma V P 2016 Integrated Plastic Waste Management: Env. and Improv. Health Approaches Proc. Env. Sciences 35, 692 – 700
[2] Malaysian Plastics Man. Assoc. (2016, April 21). Perf. of the M’sian Plastics Ind. Retrieved 15th Sept, 2018 from: http://www.mpma.org.my
[3] Johari A, Ahmad S I, Hashem H, Alkali H and Mat R 2012 Econ. and env. benefits of landfill gas from MSW in Malaysia Renew. and Sust. Energy Reviews 16, 2907 -12
[4] Sharudin S D A, Abnisa F, Daud W M and Aroua M K 2016 A review on pyro. of plastic wastes Energy Conv. and Mgmt 115, 308–326
[5] Al-Salem S M, Lettieri P and Baeyens J. 2009 Recyc. and rec. routes of plastic solid waste (PSW): A review Waste Mgmt 29, 2625–43
[6] Al-Salem S M, Antelava A, Constantinou A, Manos G and Dutta A 2017 A review on thermal and cat. pyro. of PSW J. Env. Mgmt 197, 177-198
[7] Rehan M, Miandad R, Barakat M A, Ismail I M I, Almeelbi T, Gardy J, Hassanpour A, Khan M Z, Demirbas A and Nizami A S 2016 Effect of zeolite cat. on pyro. liq. oil Int. Biodeterioration & Biodegrad. 119, 162-175
[8] Marcilla A, Beltran M I and Navarro R 2009 Thermal and cat. pyro. of polyeth. over HZSM5 and HUSY zeolites in a batch reactor und. dynamic cond. Appl. Catalysis B: Environmental 86, 78–86
[9] Olazar M, Lopez G, Amutio M, Elordi G, Aguado R, Bilbao J 2009 Influence of FCC cat. steaming on HDPE pyro. prod. dist. J. Anal. and Appl. Pyrolysis 85, 359–365
[10] Wong S L, Ngadi N, Abdullah T A T and Inuwa I M 2016 Cat. Cracking of LDPE Dissolved in Benzene Using Nickel Impr. Zeolites Ind. & Eng. Chem. Research 55, 2543-55
[11] Shirazi L, Jamshidi E and Qhasemi M R 2008 The effect of Si/Al ratio of ZSM-5 zeolite on its morphology, acidity and crystal size Cryst. Res. Technol. 43, No. 12, 1300 – 06
[12] Lee K H, Noha S S, Shina D H and Seo Y 2002 Comparison of plastic types for cat. degrad. of waste plastics into liq. prod. with spent FCC cat. Polymer Degrad. and Stab. 78, 539–544
[13] Lee K H, Shin D H and Seo Y H 2004 Liq.-phase cat. degrad. of mix. of waste HDPE and polystyrene over spent FCC cat. Effect of mix. prop. of reactants Polymer Degrad. and Stab. 84, 123–7
[14] Abbas-Abadi M S, Haghighi M N and Yeganeh H 2013 Eval. of pyro. prod. of virgin HDPE degrad. using diff. process para. in a stirred reactor Fuel Proc. Tech. 109, 90–95
[15] Seo Y H, Lee K H and Shin D H 2003 Inves. of cat. degrad. of HDPE by hydrocarbon group type analysis. *J. Appl. Pyrolysis* **70**, 383–398

[16] Syamsiro M, Saptaoedi H, Norsujianto T, Noviasria P, Chenga S, Alimuddin Z and Yoshikawa K 2014 Fuel Oil Prod. from MPW in Seq. Pyro. and Cat. Reforming Reactors *Energy Procedia* **47**, 180–8

[17] Farrell J T, Cernansky N P, Dryer F L, Friend D G, Hergart C A, Law C K, McDavid R M, Mueller C J, Patel A K and Pitsch H 2007 Dev. of an Exp. Database and Kinetic Models for Sur. Diesel Fuels *SAE Technical Papers*, 1-27

[18] Wong S L 2016 Crack. of Low Density Polyethy. Diss. In Benzene To Liq. Fuels Using Zeolite-Based Cat. Ph.D. Thesis. Universiti Teknologi Malaysia

[19] Sharudin S D A, Abnisa F, Daud W M and Aroua M K 2017 Energy rec. from pyro. of plastic waste: Study on non-recycled plastics (NRP) data as the real measure of plastic waste *Energy Conv. and Mgmt* **148**, 925–934

[20] Singh R K, Raj B, Sadhukhan A K and Gupta P 2019 Impact of fast and slow pyro. on the deg. of mixed plastic waste: Prod. yield anal. and their char. *J. of the Energy Institute* **92**, Issue 6, 1647-57

[21] Efika E C, Onwudili J A and Williams P T 2015 Prod. from the high temp. pyro. of RDF at slow and rapid heating rates *J. of Anal. and App. Pyro*. **112**, 14–22

[22] Pinto F, Costa P, Guluyurtlu I, Cabrita I 1999 Pyro. of plastic wastes. 1. Effect of plastic waste comp. on prod. yield *J. Anal. and Appl. Pyro*. **51**, 39–55

[23] Biswas B, Singh R, Krishna B B, Kumar J and Bhaskar T 2017 Pyro. of azolla, sargassum tenerrimum and water hyacinth for prod. of bio-oil *Bioresource Tech.* **242**, 139–145

[24] Singh R K, Mondala S, Raj B, Sadhukhana A K and Gupta P 2019 Interaction of three categ. of tyre waste during co-pyro.: Effect on prod. yield and qual. *J. Anal. and Appl. Pyro*. **141**, 104618

[25] Singh R K and Raj B 2016 Time and temp. depended fuel gas gen. from pyro. of real world MPW *Fuel* **174**, 164–171

[26] Adnan, Shah J and Jan M R 2014 Thermo-catalytic pyro. of polystyrene in the pres. of zinc bulk cat. *J. of the Taiwan Inst. of Chem. Eng.* **45**, 2494–2500

[27] Miandad R, Nizam A S, Rehan M, Barakat M A, Khan M I, Mustafa A, Ismail I M I and Murphy J D 2016 Influence of temp. and reaction time on the conv. of polystyrene waste to pyro. liq. oil *Waste Mgmt* **58**, 250–9

[28] Staffell I March 2011 The Energy and Fuel Datasheet. Claverton Energy. Retrieved on 5th July 2019 from: http://www.claverton-energy.com/wordpress/wp-content/uploads/2012/08/the_energy_and_fuel_data_sheet1.pdf

[29] Onwudili J A, Insura N and Williams P T 2009 Comp. of prod. from the pyro. of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time *J. Anal. and Appl. Pyrolysis* **86**, 293–303

[30] Lee K H 2012 Effects of the types of zeolites on cat. upgrading of pyro. wax oil *J. Anal. and Appl. Pyrolysis* **94**, 209–14

[31] Kim Y M, Jeong J, Ryu S, Lee H W, Jung J S, Siddiqui M Z, Jung S C, Jeone J K, Jae J and Park Y K 2019 Cat. pyro. of wood polymer composites over hierarchical mesoporous zeolites *Energy Conv. and Mgmt* **195**, 727–37

[32] Lee H, Kim Y M, Jung K B, Jae J, Jung S C and Jeon J K 2018 Catalytic hydrodeoxygenation of Geodae-Uksae pyrolysis oil over Ni/desilicated HZSM-5 *J. Clean Prod.* **174**, 763–70

[33] Abbas A S and Shubar S D S 2008 Pyrolysis of High-density Polyethylene for the Prod. of Fuel-like Liquid Hydrocarbon *Iraqi J. of. Chem. and Petrol. Eng.* **9** No.1, 23-29

[34] Tamri Z, Yazdi A V, Haghighi M K, Abbas-Abadi M S and Heidarinasab A 2018 The effect of temp., heating rate, initial cross-linking and zeolitic cat. as key process and structural para. on the degrad. of natural rubber (NR) to produce the valuable HC *J. Anal. and Appl. Pyro*. **134**, 35–42
[35] Das P and Tiwari P 2018 The effect of slow pyro. on the conv. of packag. waste plastics (PE and PP) into fuel Waste Mgmt 79, 615-624
[36] Kamal D M and Zainuri F 2015 Green Product of Liquid Fuel from Plastic Waste by Pyrolysis at 900 °C J. Energy and Power Eng. 9, 40-44
[37] Ratnasari D K, Nahil M A and Williams P T 2017 Cat. pyro. of waste plastics using staged catalysis for prod. of gasoline range HC oils J. Anal. and Appl. Pyro. 124, 631-37