

Light Hydrocarbons Produced from High Density Polyethylene (HDPE) Waste using Fractional Column Distillation

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Abstract

High density polyethylene (HDPE) waste plastic was investigated into a lab scale and produced light hydrocarbon fuel by using fractional column distillation. Two step process applied with this experiment 1st step process produced short to long chain hydrocarbon and 2nd step process produced only light hydrocarbon fuel without using any kind of catalyst. 1st step temperature range used 100-420 °C and 2nd step temperature range used for light hydrocarbon 40-60 °C. The first fraction fuel collected is light carbon gasoline grade fuel and 2nd fraction fuel is heavier is labeled as diesel grade fuel. Light hydrocarbon fuel density is 0.72 gm/ml. produced light hydrocarbon fuel is analyzed using GC/MC, FT-IR and DSC equipments.

Keywords: HDPE, Fuel, Hydrocarbon, waste plastic, fractional distillation, GC/MS, FTIR

1. Introduction

Currently, the USA generates ~30 million tonnes of plastic waste materials, 280 million automotive tires and 66 million tonnes of waste paper each year. All these wastes are discarded and end up in sanitary landfills. With existing recycling efforts, only 4% of the waste plastics are reused. Waste plastics occupy ~21 vol. % of US landfills'. Increasing the recycling rate for plastics will require innovative and cost-effective recycling technologies. Recycling plastics back to their fundamental feedstocks has been one area of active research and shows promise in overcoming many of the problems that plague conventional recycling processes. These new technologies have been called 'feedstock recycling' or 'advanced recycling technologies' and include processes such as methanolysis of polyesters and thermal depolymerization of polyolefins. Advanced recycling technologies that recycle mixed plastics back to liquid petroleum feedstocks are being evaluated worldwide to understand better their technical feasibility, process economics and logistical viability. Plastics waste recycling can be categorized into four mode. Primary recycling deals with conversion into products similar in nature to the original product. Secondary recycling involves conversion into products of different forms for less demanding applications. Tertiary recycling converts wastes into basic chemicals or feedstocks [1]. Quaternary recycling retrieves energy from wastes through combustion. An example of the last type is incineration of wastes for power generation. Secondary recycling, which involves grinding, remelting, and re-forming of the waste materials into lower-value products such as fillers and fibres, has been a more common practice for recycling plastic wastes until now. In the USA, only 2% of the plastics waste is handled by this method. Nevertheless, plastics wastes after a number of primary and secondary recycling steps have to be treated in the tertiary of quaternary mode. Due to strong opposition from the public regarding the incineration of waste materials, this method can no longer be an important mode of waste recycling. As a consequence, the tertiary mode of recycling of plastics wastes is gaining momentum as an alternative method. Also, the petroleum and petroleum chemical companies have started to realize that this technology can be integrated into their daily operations. Moreover, if a landfill tax of some \$30-60 per tonne, which is the cost of landfilling of these materials at present, can be charged, then the process becomes profitable. This has been proved by various pilot and demonstration plants processing various types of plastic wastes in Germany, Japan, the USA and elsewhere'. Companies such as Amoco, Shell, BP, Chevron, Esso, Veba, RWE and Fuji Recycle have R & D programmes to evaluate this approach. Recently, BASF announced that it plans to build a \$175 million commercial recycling plant to convert plastics wastes into a mixture of naphtha, olefins and aromatics. Most of these R & D programmes deal with hydrolysis, ethanolysis and ammonolysis for condensation polymer such as poly (ethylene terephthalate) and polyurethane; hydrogenation, pyrolysis, gasification, hydrocracking, coking and visbreaking for addition polymers such as polyolefins, polystyrene and catalytic cracking. Thus, liquefaction has been proposed as a possible recycling method for

plastics. Among the various methods available, high-temperature thermal liquefaction has been overlooked. In this study, high-temperature thermal liquefaction of commingled consumer plastics to produce transportation fuel was studied. The objective was to propose a reaction pathway for the formation of various products during thermal liquefaction of plastics and to develop a kinetic model for the thermal liquefaction of mixed waste plastics for the first time. Studies of the thermal cracking of polyethylene to transportation fuels have been conducted in many recent studies. A method has been developed utilizes thermal decomposition of high-density polyethylene was at 250-450°C in stainless steel reactor [2]. It was found that the distillate yield increased at higher temperature, which also accelerated the formation of gases and trace amount coke. Secondary reactions such as saturation, isomerization, cyclization and aromatization were found to occur at high severity. Various types of aliphatic and aromatic compounds are emerged in the analysis of fuel. In contrast, the same reaction carried out using fractional distillation at different temperature separated different categories produced fuel such as types of gasoline, naphtha, aviation, diesel and fuel oil as well as more light gases. The distillates contained more olefins, less saturates and very little aromatics compared with those various compounds. Ng et al. also studied the catalytic cracking of the thermal waxy products from high density polyethylene in a reactor at lower temperature. The thermal cracking of the high density polyethylene product produced high yields of gasoline and other valuable fuels products of better quality than from the thermolysis of polyethylene, with little dry gas, coke and heavy cycle oil [3-6].

2. Method and Materials

2.1. Sample Collection and Preparation

Waste HDPE milk container collected from local city grocery store were used as raw sample materials. After collection the milk container is washed with liquid soap and kept in a different container for waste water treatment. Washed milk container are dried in room temperature and cut into small pieces using scissors. Small pieces milk container were transferred into a grinder machine for grinding. Grounded HDPE waste plastic sizes are 3-4 mm. then grounded waste plastic transfer into reactor for liquefaction process.

2.2. Pre-analysis

Before starting the liquefaction, the grounded HDPE waste plastic per analysis by using GC/MS with CDS pyroprobe. Raw materials were analyzed by GC/MS for checking chromatogram compound with different retention time. GC/MS analysis result are descript into result and discussion part. FT-IR (Spectrum 100) was used raw material analysis purposed and checks the raw materials functional group and wave band energy which is reflect band caloric value. TGA used for raw materials onset temperature measuring and how much percentage fully volatile and which temperature finished the experiment was indicated. EA-2400 was used for raw material carbon, hydrogen and nitrogen percentage determine.

2.3. Process Description

The thermal degradation process has been conducted in a small scale with high density polyethylene plastics into laboratory, this waste plastic type were investigated singly. For small-scale laboratory process the weight of input waste plastics ranges from 300 grams (seen fig.1). The process of converting the individual waste plastic to alternative hydrocarbon fuel begins with heating the solid plastic without the presence of cracking catalyst under atmosphere to form liquid slurry and temperature range used for thermal degradation process from 100-420 °C, condensing the vapor with standard condensing unit to form liquid hydrocarbon fuel termed into HDPE plastic fuel.

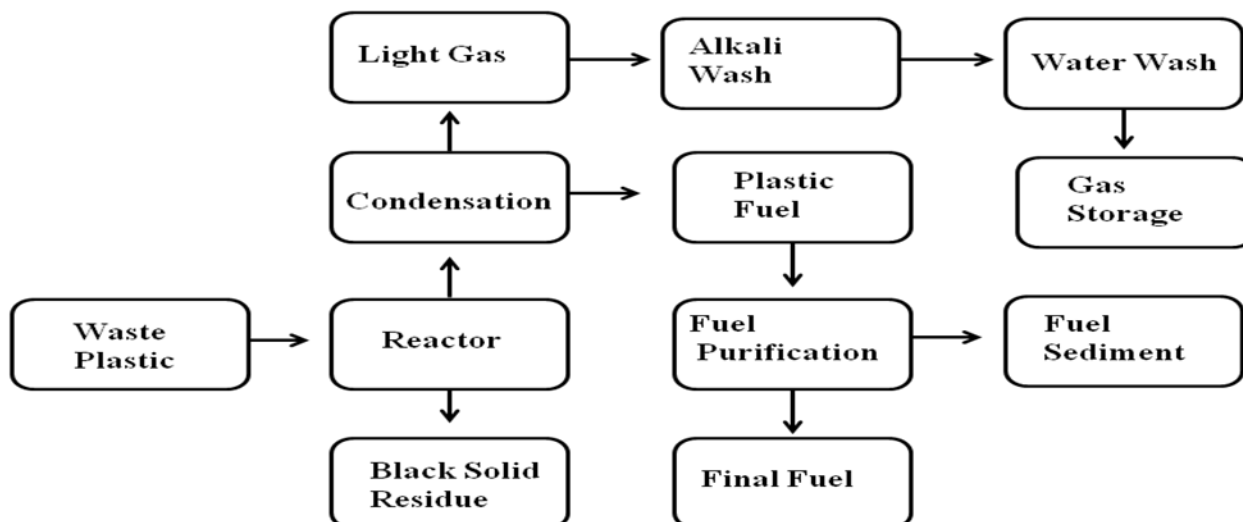


Fig. 1: Fuels production process of HDPE waste plastic (step-1)

The produced HDPE fuel density is 0.77 g/ml; in equivalent to obtaining the liquid hydrocarbon fuel we also received light gaseous hydrocarbon compounds (C₁-C₄) which resembles natural gas individual plastic to fuel production average yield 90%, light gas 6 % and solid residue 4% in 1st step process. 1st step batch process experiment took time 4-5 hours and also input electricity for every individual experiment 13- 15 kWh for 1 gallon production. Produced fuel purified by RCI fuel purification system to remove all water and other sediments.

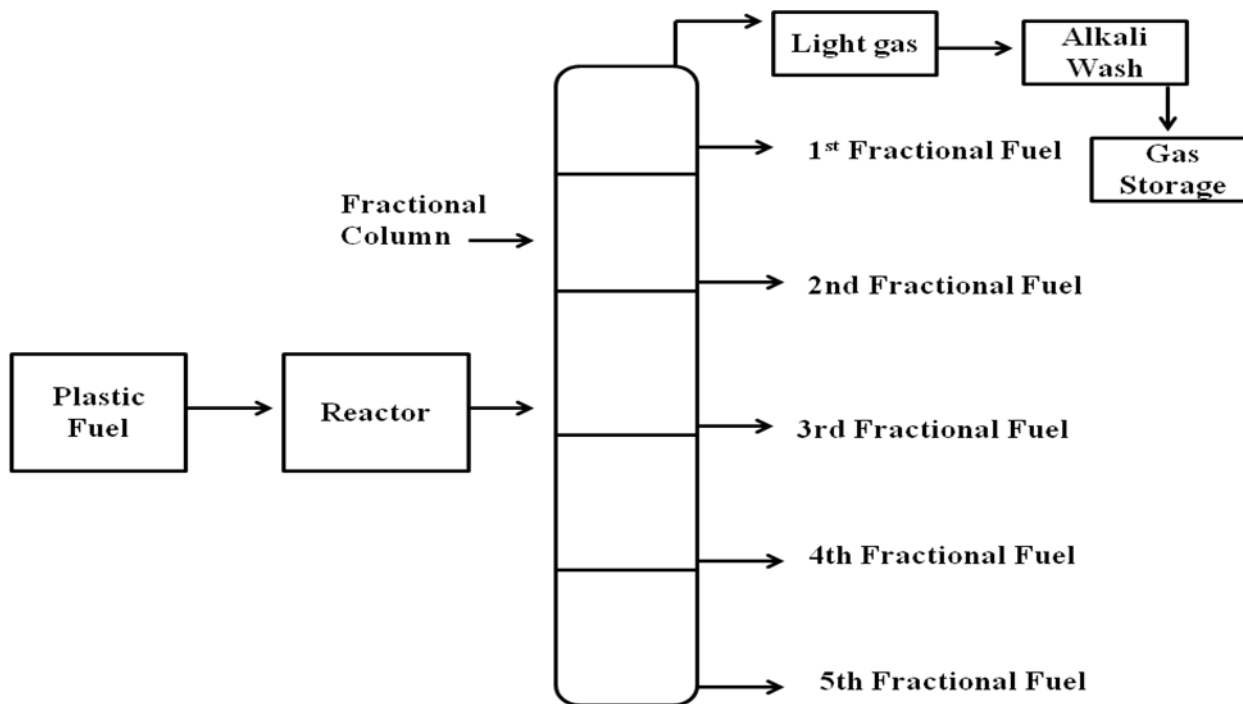


Fig. 2: Waste plastic fuel to 1st fractional fuel production process (step-2)

For 2nd step process fractional distillation column HDPE plastic fuel were put into reactor for further distillate the fuel with different temperature profile for fractional column produced 5 (five) category fuels (see fig.2). For 1st fraction fuel temperature setup to be collected at 40-60 °C, 2nd fraction fuel temperature setup at 110-120 °C, 3rd fraction fuel temperature setup at 180-200 °C, 4th fraction fuel temperature setup at 260-280 °C and 5th fraction fuel temperature setup at 320-360 °C. 1st fractional fuel density is 0.72 gm/ml, 2nd fractional fuel density is 0.78gm/ml, 3rd fractional fuel density is 0.80 gm/ml, 4th fractional fuel density is 0.82 gm/ml and 5th

fractional fuel density is 0.84 gm/ml. During 2nd fractional distillation period a type of light gas is also produced and is clean with alkali wash and after wash the cleaned light gas is stored in a gas cylinder for future use and analysis.

3. Results and Discussion

3.1. Analytical Technique

Perkin Elmer FT-IR (Spectrum 100) used for raw sample per analysis and liquid fuel sample analysis. Raw waste plastic sample analyzed by diamond crystal plate KRS 5 check there functional group and band energy value. Liquid fuel sample was analyzed by NaCl cell 0.025 mm thickness. Both samples were analyzed by same parameters used such as scan number 32, resolution 4 and range 4000-450 cm⁻¹.

Perkin Elmer EA-2400 analyzer was used for raw waste plastics carbon; hydrogen and nitrogen percentages determine and follow ASTM method ASTM D5291.a. Carrier gas was used helium, oxygen and nitrogen.

Perkin Elmer Thermogravimetric (TGA Pyris-1) was used for raw waste plastics onset temperature measuring. Temperature range used starting 50 to 800 °C and temperature ramping range used for onset temperature 10 °C/min. Helium gas used as a carrier at 20 psi.

Perkin Elmer Gas Chromatography and Mass Spectrometer (Clarue 500 series) used for raw waste plastic and liquid fuel analysis. Raw sample analysis purposed was used pyroprobe (CDS 5000 series) to volatile solid sample and transfer into GC column. For liquid sample analysis purpose we used an auto sampler system. GC temperature profile for liquid sample analysis was initial temperature 40°C and hold for 1 min and final temperature 325 °C, hold for 15 min. total experiment run time 44.50 minutes. GC column length 30 meter and mass program set up start mass 35 to 528 and ion mode EI+. Perkin Elmer Elite- 5MS Capillary Column Length is 30 meter, 0.25 mm ID, 0.5 um df, Maximum Program Temperature 350°C, Minimum Bleed at 330 °C. GC Program set up for sample analysis. Initial temperature 40 °C, in temperature 325 °C, temperature ramping 10 °C per minute, final temperature hold for 15 minute. Total sample run time is 44.50 minute. Sample inject volume is 0.5 µL, helium used as a career gas, Split Flow=101.0 ml/minute and mass program set up type MS scan, Ion Mode EI+, Data format - Centroid, Start Mass 35.00, End Mass 528.00, Scan Time (Sec) 0.25, Start Time (min) 1.00, End Time (min) 44.50. For Perkin Elmer GCMS analysis purposes a National Institute of Standard Testing (NIST-2002) mass spectral libraries software is used as library compound and in the analysis only those compounds are detected by their trace mass and retention time.

Perkin Elmer Differential Scanning Calorimeter (DSC) was used for liquid fuel boiling point and fuel enthalpy value indication. Program temperature range was 0-400 °C and temperature ramping rate was 10 °C/min. Carrier gas was nitrogen at 20 ml/ min.

3.2. Pre-analysis Result

In GC-MS analysis of HDPE solid raw sample we used CDS pyroprobe 5000 series. Pyroprobe volatile the solid HDPE raw sample and send to the capillary column in terms of inject volatile sample. On the basis of retention time different types of compounds emerged. High numbers of retention time high number of carbon compounds are noticed (C₃ to C₂₂). Only several compounds are mentioned here as example in the initial state of analysis result index at retention time 2.14, compound is Propane (C₃H₆), retention time 2.23, compound is 3-Butyne-1-ol (C₄H₆O), retention time 2.42 2-Pentene, (C₅H₁₀), retention time 2.61, compound is 1,3-Pentadiene (C₅H₈). In the middle index of the analysis chart at retention time 4.18, compound is Heptane (C₇H₁₆), retention time 5.86, compound is 1,7-Octadiene (C₈H₁₄), retention time 6.94, compound is 1,4-Octadiene, (C₈H₁₄), retention time 9.04, compound is Nonane, (C₉H₂₀), retention time 9.37, compound is Cyclopentane, 1-methyl-2-(2-propenyl)-, trans- (C₉H₁₆), retention time 11.77, compound is Cyclodecane (C₁₀H₂₀) etc.

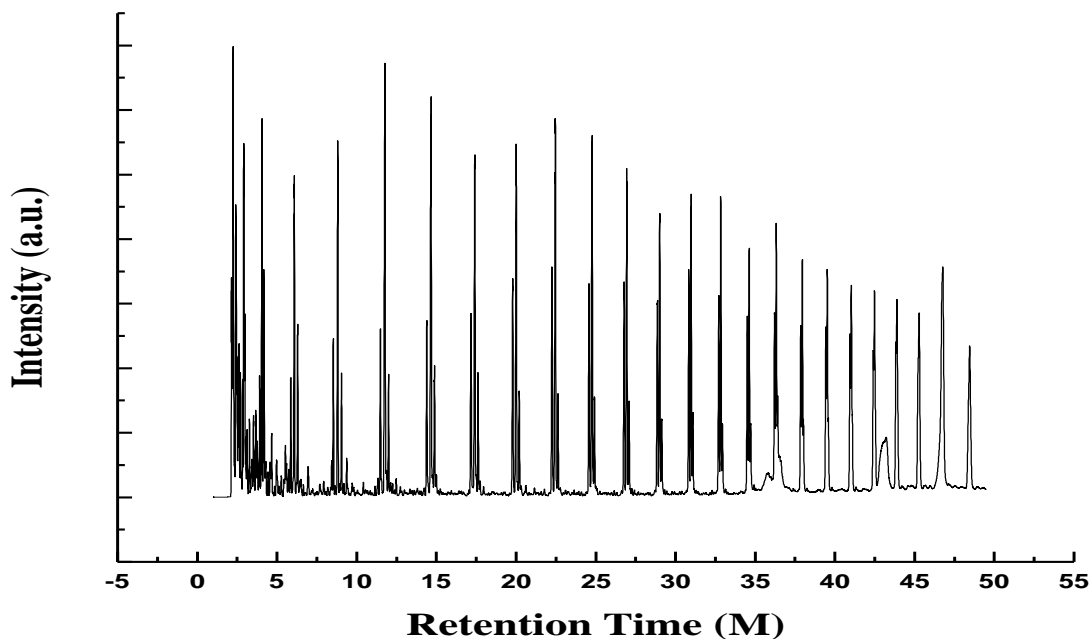


Fig. 3: HDPE raw

materials GC/MS chromatogram

At the end of the analysis result index chart at retention time 11.99, compound is 1-Decane, ($C_{10}H_{22}$), retention time 14.66, compound is 1-Undecene ($C_{11}H_{22}$), retention time 26.77, compound is 1,15-Hexadecadiene ($C_{16}H_{30}$), retention time 31.08, compound is Octadecane ($C_{18}H_{38}$), retention time 32.93, compound is Nonadecane, ($C_{19}H_{40}$), retention time 34.71, compound is Eicosane ($C_{20}H_{42}$), retention time 36.41, compound is 1-Heneicosane, ($C_{21}H_{44}$), retention time 43.89, compound is 1-Tetracosanol ($C_{24}H_{50}O$), retention time 45.28, compound is 9-Tricosene, (Z), ($C_{23}H_{46}$) and ultimately retention time 46.76, compound is 17-Pentatriacontene ($C_{35}H_{70}$) as well.

FT-IR analysis is done by ATR (Attenuated Transmittance Reflectance.) In HDPE raw plastics following types of functional groups appeared such as wave number 2915.41 cm^{-1} , functional group is C- CH_3 , wave number 2847.92 , functional group is C- CH_3 , and wave number 1472.55 cm^{-1} , functional group is CH_3 , wave number 1462.30 cm^{-1} , functional group is CH_3 and wave number 730.18 cm^{-1} , functional group is - $CH=CH$ (cis) as well.

HDPE raw waste plastic TGA Onset Results: Onset X1 $50.42\text{ }^\circ\text{C}$, Y1 100.430 %, X2 $406.98\text{ }^\circ\text{C}$, Y2 70.224 %, Onset X394.09 $^\circ\text{C}$, Onset Y 100.036 %. Peak Results: Area X1 $50.42\text{ }^\circ\text{C}$, Y1 -0.026 %/min, X2 $793.72\text{ }^\circ\text{C}$, Y2 -1.476 %/min. Peak 406.98 $^\circ\text{C}$ and Peak Area -41.613 %.

3.3 Liquid Fuel Analysis

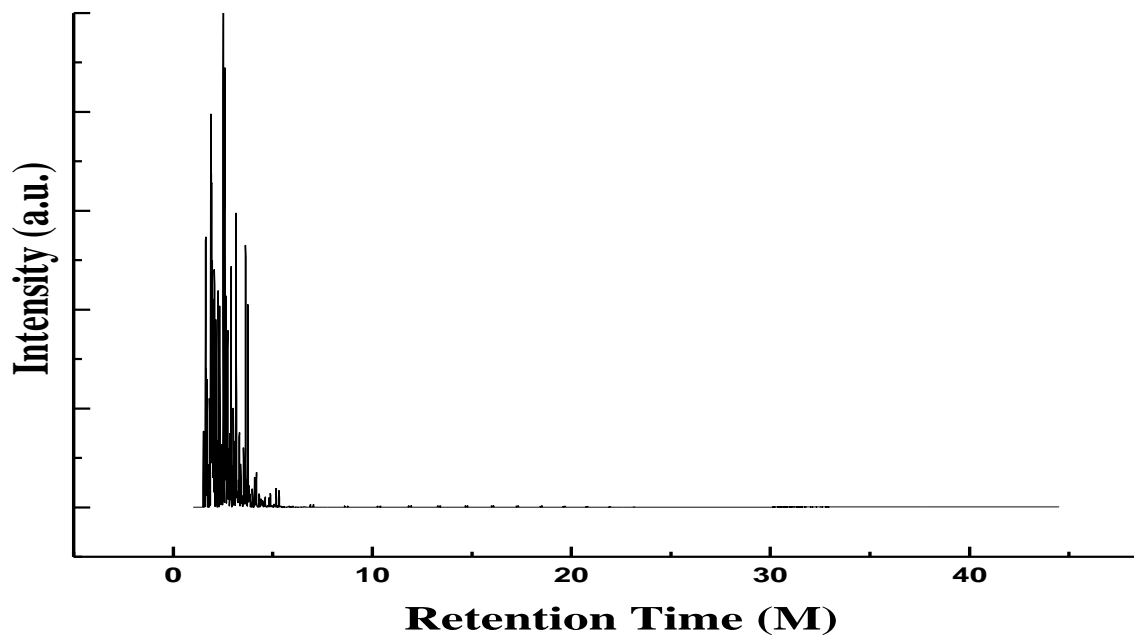


Fig.4:

GC/MS Chromatogram of HDPE fuel to 1st fractional fuel

Table 1: GC/MS Chromatogram of HDPE fuel to 1st fractional fuel compound list with different retention time

Peak Number	Retention Time (M)	Trace Mass (m/z)	Compound Name	Compound Formula	Molecular Weight	NIST Number
1	1.51	41	Propane	C ₃ H ₈	44	18863
2	1.63	41	3-Buten-1-ol	C ₄ H ₈ O	72	114446
3	1.83	43	Butane, 2-methyl-	C ₅ H ₁₂	72	291251
4	1.88	41	2-Pentene, (E)-	C ₅ H ₁₀	70	291780
5	2.07	53	1,3-Pentadiene	C ₅ H ₈	68	291890
6	2.26	67	1,3-Pentadiene, (Z)-	C ₅ H ₈	68	160480
7	2.52	55	3-Hexene, (Z)-	C ₆ H ₁₂	84	496
8	2.60	41	Hexane	C ₆ H ₁₄	86	291337
9	2.91	56	Cyclohexane	C ₆ H ₁₂	84	291493
10	3.02	79	1,3-Cyclopentadiene, 5-methyl-	C ₆ H ₈	80	419
11	3.16	82	Cyclopentene, 1-methyl-	C ₆ H ₁₀	82	107747
12	3.39	79	Cyclopentene, 3-methylene-	C ₆ H ₈	80	151094
13	3.54	67	Cyclohexene	C ₆ H ₁₀	82	114431
14	6.63	56	1-Heptene	C ₇ H ₁₄	98	19704
15	3.75	71	Heptane	C ₇ H ₁₆	100	61276
16	4.09	81	Cyclopentane, 1-methyl-2-methylene-	C ₇ H ₁₂	96	62523
17	4.18	83	Cyclohexane, methyl-	C ₇ H ₁₄	98	118503
18	4.32	69	Cyclopentane, ethyl-	C ₇ H ₁₄	98	940
19	4.40	79	Cyclopropane, trimethylmethylene-	C ₇ H ₁₂	96	63085

20	4.63	67	1-Ethylcyclopentene	C ₇ H ₁₂	96	114407
21	4.75	79	2,4-Heptadien-1-ol, (E,E)-	C ₇ H ₁₂ O	112	1645
22	4.82	91	Toluene	C ₇ H ₈	92	291301
23	4.88	81	Cyclohexene, 1-methyl-	C ₇ H ₁₂	96	231491
24	5.07	79	1,3-Cycloheptadiene	C ₇ H ₁₀	94	237922
25	5.17	41	1-Octene	C ₈ H ₁₆	112	1604
26	5.32	43	Octane	C ₈ H ₁₈	114	61242
27	5.83	95	1-Methyl-2- methylenecyclohexane	C ₈ H ₁₄	110	113437
28	6.01	83	Cyclohexane, ethyl-	C ₈ H ₁₆	112	113476
29	6.89	56	1-Nonene	C ₉ H ₁₈	126	107756
30	7.04	43	Nonane	C ₉ H ₂₀	128	228006

Fractional distillation process of HDPE fuel to 1st fractional fuel are performed in low temperature that is at 40°C and with that room temperature 25°C are added to cover up full temperature range. In the 1st fractional distillation of HDPE low carbon chain hydrocarbon are produced such as C₃ to C₉, analysis with GCMS of the 1st fractional fuel are similar to light fuel such as gasoline. GCMS analysis of HDPE 1st (Fig. 4 and table 1) fractional fuel's retention time suggests various aliphatic compounds are also present in the fuel. If we expedite detailed hydrocarbon analysis so that lots of compounds could be derived from the analysis but only selected compounds are taken in the analysis from those peak intensity that are high. Firstly consider comparatively low intensity compound as follows retention time 1.51 and trace mass 41 starting hydrocarbon compound is propane (C₃H₈), retention time 1.63 and trace mass 41 compound is 3-Butene-1-ol (C₄H₈O), retention time 1.83 and trace mass 43 compound is Butane-2-Methyl-(C₅H₁₂), retention time 1.88 and trace mass 41 compound is 2-Pentene-(E)(C₅H₁₀). and end of the analysis part with high intensity following types of compounds are noticed such as at retention time 5.17 and trace mass 41 compound is 1-Octene (C₈H₁₆), retention time 5.32 and trace mass 5.83 compound is 1-Methyl-2-Methylene-Cyclohexane(C₈H₁₄), retention time 6.01 and trace mass 83, compound is Cyclohexane-Ethyl- (C₈H₁₆), retention time 6.81 and trace mass 56, compound is 1-Nonene (C₉H₁₈) and ultimately retention time 7.04 and trace mass 43, highest hydrocarbon compound chain is Nonane (C₉H₂₀).

FT-IR Spectrum-100 analysis of HDPE fuel to 1st fractional fuel (fig. 5 and table 2) in favor of wave number several types of functional groups. In accordance with wave number 2943.78 cm⁻¹, 2732.94 cm⁻¹ and 2669.80 cm⁻¹ functional group is C-CH₃, wave number 1894.94 cm⁻¹, 1822.70 cm⁻¹ and 171835 cm⁻¹ compound is Non-Conjugated and wave number 1642.41 cm⁻¹, 1603.34 cm⁻¹, functional group is Conjugated. Then wave number 1461.88 cm⁻¹, functional group is CH₂/CH₃, wave number 1379.71 cm⁻¹, functional group is -CH₃, wave number 991.45 cm⁻¹ and 911.04 cm⁻¹ functional group is -CH=CH₂, ultimately wave number 727.59 cm⁻¹ and 674.10 cm⁻¹, functional group is -CH=CH-(cis). Energy value are calculated, using formula Energy=hv, where h=plank constant, v=frequency of photon and v=cW, therefore, E=hcW, where C=the speed of light (3x10¹⁰ cm/sec), W=wave number in cm⁻¹. According to the equation high wave number light has more energy than low wave number light such as wave number 2943.78 cm⁻¹ (C-CH₃), energy=5.84X10⁻²⁰ J, wave number 1894.94 cm⁻¹ (Non-Conjugated) energy, E=3.76X10⁻²⁰ J, wave number 1461.88 cm⁻¹ (CH₂/CH₃) energy, E =2.90X10⁻²⁰ J and ultimately wave number 911.04 cm⁻¹ (-CH=CH₂) energy, E=1.80x10⁻²⁰ J.

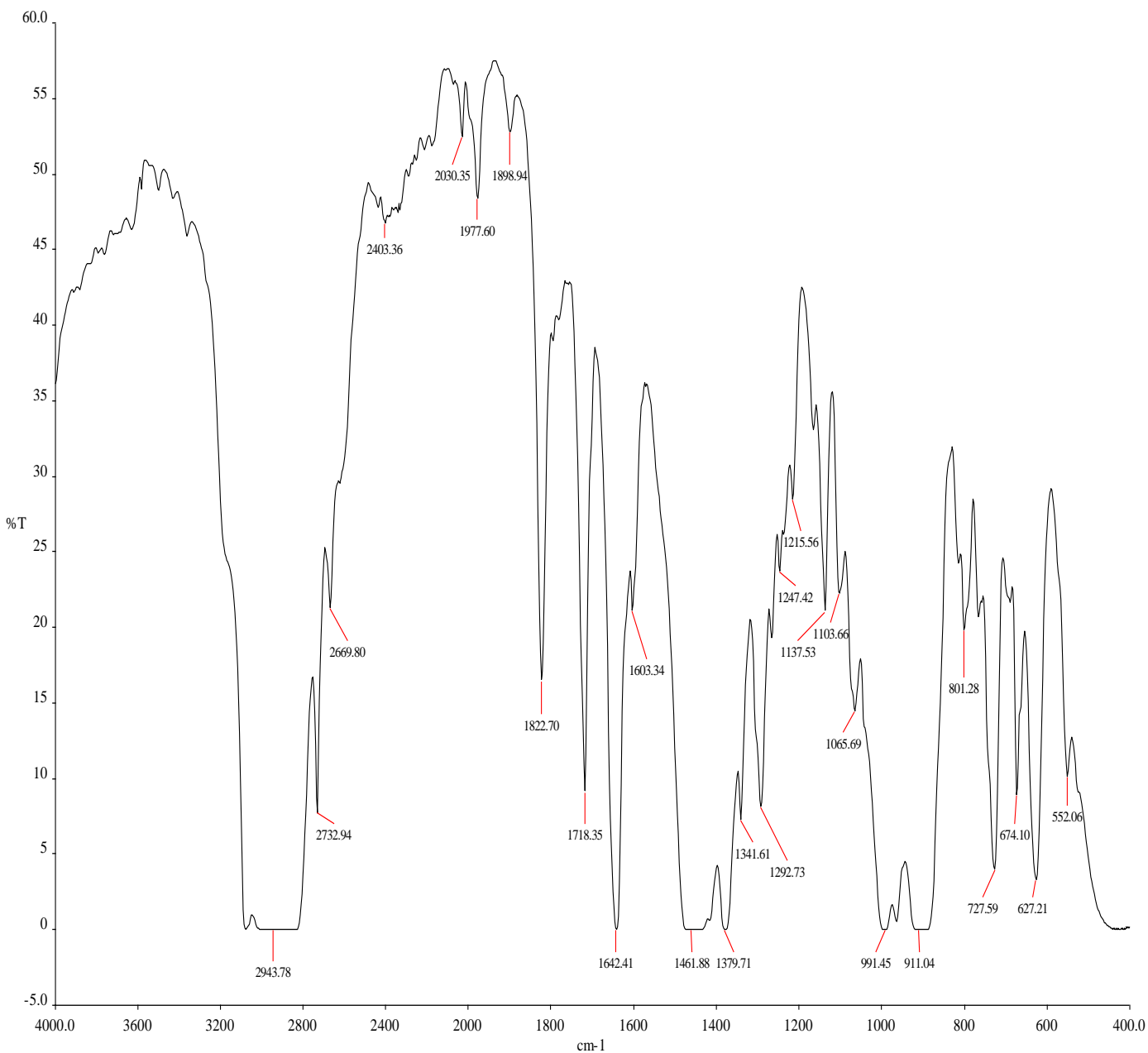


Fig. 5: FT-IR spectrum of HDPE fuel to 1st fractional fuel

Table 2: HDPE fuel to 1st Fractional Fuel Functional Group Name

Number of Wave	Wave Number (cm ⁻¹)	Functional Group	Number of Wave	Wave Number (cm ⁻¹)	Functional Group
1	2943.78	C-CH ₃	11	1603.34	Conjugated
2	2732.94	C-CH ₃	12	1461.88	CH ₂ / CH ₃
3	2669.80	C-CH ₃	13	1379.71	CH ₃
7	1898.94	Non-Conjugated	21	991.45	-CH=CH ₂
8	1822.70	Non-Conjugated	22	911.04	-CH=CH ₂
9	1718.35	Non-Conjugated	24	727.59	-CH=CH-(cis)

10

1642.41

Conjugated

25

674.10

-CH=CH-(cis)

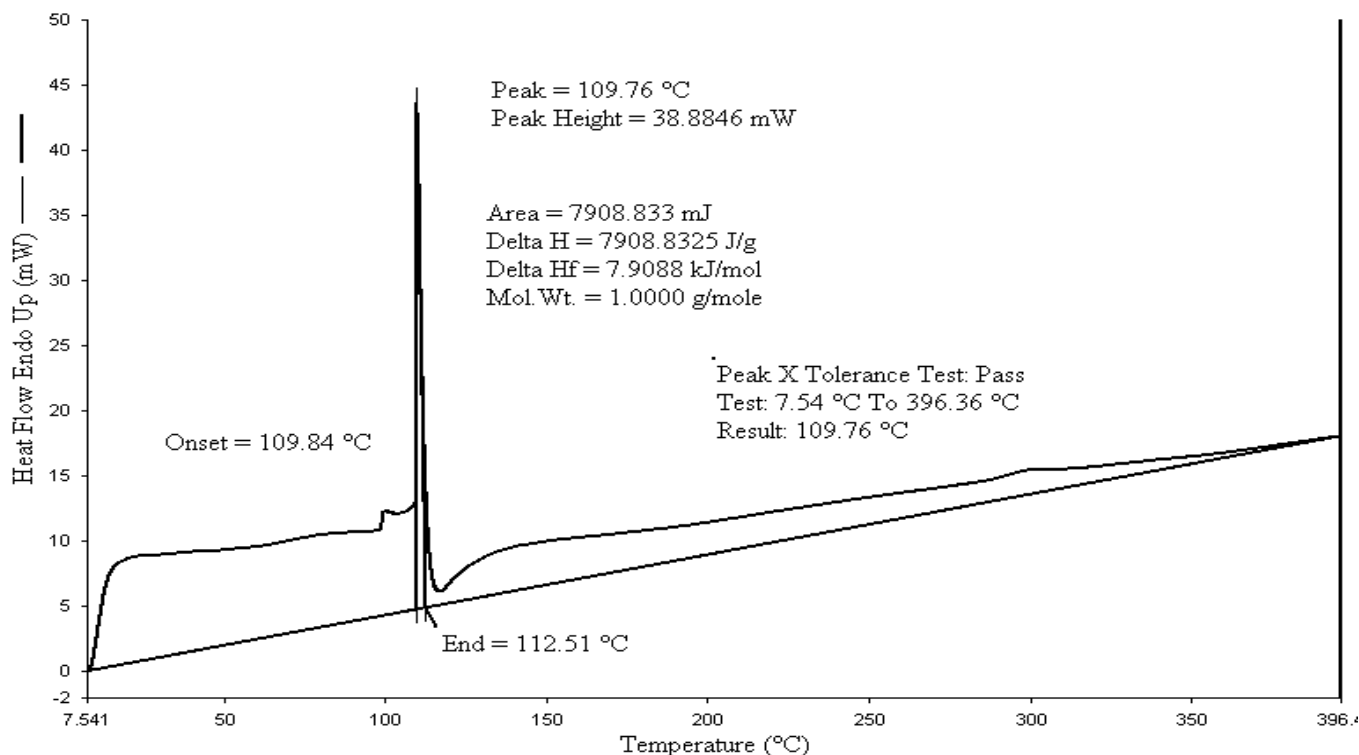


Fig. 6: DSC graph of HDPE fuel to 1st fractional fuel

Differential Scanning Calorimeter (DSC) is used for HDPE 1st fractional fuel (seen fig. 6) heating and freezing point analysis. Program setup of DSC is based on fuel category. The temperature range for DSC analysis is 5 - 400 °C and ramping temperature range 10 °C per minutes was maintained for all the analysis. Nitrogen at 20 ml/m is used as carrier gas. Aluminum pan used for sample holding and sample amount is 50 micro liters. From DSC analysis we found HDPE 1st fraction fuel temperature is 109.84 °C, peak 109.76 °C from set temperature and peak height 38.8846 mW. Peak height represents heat flow Endo up from 100 to 45%. DSC analysis shows the peak area 7908.833 mJ and heat enthalpy value Delta H is 7908.8325 J/g. From this fuel analysis we found the fuel boiling point. HDPE 1st fractional fuel is a light fraction fuel, its fraction temperature range is lower because obtained peak temperature is 109.76 °C.

HDPE fuel to 1st fraction fuel was analysis by 3rd party ASTM test procedure Intertek laboratory, New Jersey, USA. API gravity @ 60 °F (ASTM D4052), dry vapor pressure equivalent (ASTM D5191 EPA), gross heat of combustion BTU/gal/lb (ASTM D240), freezing point °C/°F (ASTM D5972), calculated cetane index (ASTM D4737), cloud point °C/°F (ASTM D2500), Research octane number (ASTM D 2699), MTBE (ASTM D4815), total aromatic (ASTM D5769) ethanol (ASTM D4815), initial boiling point (ASTM D86) etc.

4. Conclusion

The thermal degradation process of high-density polyethylene (HDPE) waste plastics were studied individually. The thermal degradation process reactions were carried out in stainless steel reactor at around 100–420 °C under atmosphere of without any carrier gas and without any catalyst or any extra chemical. The result indicated that HDPE individual plastic provides the best results in the form of conversion and further fractional distillation process for 1st fraction light hydrocarbon fuel. GC/MS identified some very important chemical compounds present in the liquid products obtained from the thermal of HDPE fuel to 1st fractional fuel, boiling point measured by DSC and FT-IR analysis shows different functional group present into 1st fractional light hydrocarbon fuel. These compounds are of great importance to the industry and environment as well. Thermal process of individual plastics converted into

useful liquid fuel and chemical feed stocks. The results obtained from this study show useful and feasibility of the 2 step thermal process of the each plastic as an alternative approach to feedstock refinery.

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References

- [1] Prakash K. Ramdoss and Arthur R. Tarrer*High-temperature liquefaction of waste plastics, Department of Chemical Engineering, Auburn University, Auburn AL 36849-5128, USA (Received 14 March 1997; revised 15 July 1997).
- [2] Ng, S. H., Seoud, H., Stanciulescu, M. and Sugimoto, Y., Energy & Fuels, 1995, 9, 735.
- [3] Songip, A. R., Masuda, T., Kuwahara, H. and Hashimoto, K., Energy & Fuels, 1994, 8, 131.
- [4] Taghiei, M. M., Feng, Z., Huggins, F. E. and Huffman, G. P., Energy & Fuels, 1994, 8, 1228.
- [5] Kastner, H. and Kaminsky, W., Hydrocarbon Processing, 1995, 74(5), 109.
- [6] Feng, Z., Zhao, J., Rockwell, J., Bailey, D. and Huffman, G., Fuel Processing Technology, 1996, 49, 17.