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Research Article

Abundant High-Density Polyethylene (HDPE-2) Turns into Fuel by Using of HZSM-5 Catalyst

Moinuddin Sarker, Mohammad Mamunor Rashid, and Mohammed Molla

Department of Research and Development, Natural State Research, Inc., 37 Brown House Road, Stamford, CT 06902, USA
Address correspondence to Moinuddin Sarker, msarker@naturalstateresearch.com

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Abstract The thermal degradation of high-density polyethylene (HDPE-2) was conducted in a fiber glass reactor system at a reaction temperature between 370 °C and 420 °C and a reaction time of 4 hours using HZSM-5 molecular sieves as catalyst to obtain hydrocarbon liquid fuel. Reactions in the reactor changed the polymer structures breaking down the long chain hydrocarbons to form shorter ones thus forming a hydrocarbon chain range between C_3 and C_{28}. The gas chromatography and mass spectrometer were used to determine the range of trace mass hydrocarbon present in the liquid fuel. The presence of the HZSM-5 catalyst accelerated the reaction rate and improved the quality of the liquid fuel produced. The experiment process produced gaseous products in the range of C_1–C_4. To obtain hydrocarbon fuel, gross heat of combustion is 123,845 BTU/gal, API gravity is 53.70 ° API and sulfur contains 3.05 ppm. The liquid hydrocarbon product is mainly alkane and some alkene groups which resemble aliphatic groups and also some aromatic groups are present.

Keywords HDPE-2; hydrocarbon; thermal degradation; GC/MS; fuel; catalyst

1 Introduction

Nowadays, the use of plastics is common in our society. These plastics come in many different forms such as water bottles, food containers and toys and they are used in almost every aspect of our daily lives. The increase in application leads to higher per capita consumption of raw plastics. Thus, increment rose from 96.6 kg in 2002 to 98.1 kg per capita in 2003 [3, 11]. Plastics have gained a vast popularity among all major sectors of the world due to their versatility. However, apart from thermoplastics which are used to make products with long time life span, the majority of the other waste plastics types such as, HDPE-2, LDPE-4, PP-5 and PS-6 are used to make products that have a very short life span and HDPE and LDPE (milk containers, plastic shopping bags) are the major components of the total plastic content of municipal solid waste. HDPE is used to make varieties of everyday usable goods. What is shown in Table 1 is the use of HDPE in various sectors and the amount generated to make everyday product each year. These municipal solid wastes are non-biodegradable, which means that they can occupy the landfill for a 1000-year period to breakdown completely and when these wastes end up in the ocean the marine habitants mistake them for food and are killed in vast numbers because of that.

HDPE-2 wastes are present in vast amounts in landfill, municipalities and in other sectors. As shown in Figure 1, out of all the waste plastics generated HDPE is 18% that occupies the total amount. This paper reports the utilization of a particular plastic type high-density polyethylene (HDPE-2) into liquid hydrocarbon like fuel in a closed steel reactor system in the presence of accelerated reaction catalyst HZSM-5 molecular sieves. The work of converting plastics into products is not new. Many studies and experiments have been done to convert plastics into fuel. Studies of converting plastics specifically HDPE into volatile, liquid and gas products have been reported using methods such as thermal degradation [1, 8, 10, 19, 20, 22, 24], catalytic cracking [2, 6, 13, 15, 16, 17, 21, 23, 25] and pyrolysis [4, 5, 7, 9, 12, 14, 18, 26, 27] to name a few of them. These methods are widely used and considered to be successful in de-polymerization of waste polymers into valuable

Product category	Estimated United States generation (ton)
Durable goods	450,000
Trash bags	230,000
All other non-durables	350,000
Soft drink bottle base cups	20,000
Milk and water bottles	650,000
Other plastics containers	670,000
Bags, sacks and wraps	520,000
Other plastics packaging	1,230,000
Total generated HDPE	4,120,000

Table 1: HDPE plastic generation in the USA per year.

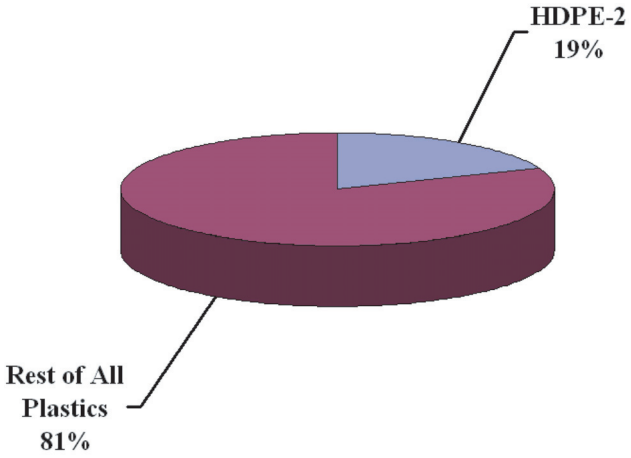

Figure 1: HDPE-2 waste plastic percentage from all types of plastic.

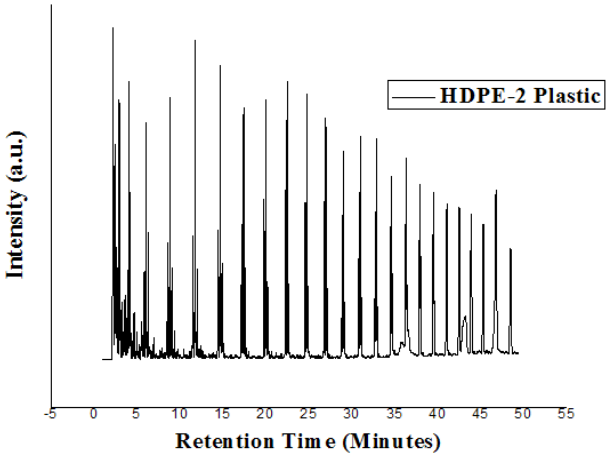

Figure 2: GC/MS chromatogram of HDPE-2 raw waste plastic.

products because plastics have a high calorific value that is, polyethylene 43 MJ/kg, polypropylene 44 MJ/kg.

The product obtained from pure thermal degradation of HDPE plastics show wide hydrocarbon numbers requiring further processing. The hydrocarbon chain ranges from C_3 to C_{28} when thermal degradation is applied. The experiment conducted in this particular report is using basic thermal degradation to convert HDPE-2 plastics into liquid hydrocarbon fuel like materials in the presence of HZSM-5 catalyst. The particle size of the HZSM-5 catalyst is 3.00–5.00 μm. The reaction rate with the presence of the HZSM-5 catalyst and without it is discussed further in this report.

2 Experimental process description

2.1 Sample preparation

The waste HDPE sample used in this experiment is obtained from local supermarkets and groceries. The sample is then sorted, cleaned of contamination using detergent, dried, grinded prior to putting it inside the reactor. The grounded sample size ranges from 14 mm–15 mm. The sample is pre-analyzed using GC/MS Gas chromatography and mass spectrometer Clarus 500, FT-IR Spectrum 100, TGA Thermogravemetric analyzer and EA 2400 Elemental analyzer.

2.2 Pre-sample instrumental analysis

The analysis in Figure 2 and Table 2 of the HDPE-2 raw plastics using the GC/MS shows that the raw sample contained mostly double bond compounds which are present in the raw HDPE-2 plastics. From GC/MS analysis, the raw HDPE plastic's hydrocarbon compound ranges from C_3 to C_{35}. When heat is applied during thermal degradation to the HDPE sample it is broken down into shorter chain hydrocarbon compounds.

The physical, mechanical properties and environmental impact of the raw HDPE-2 sample shown in Table 3 represent the capabilities of the sample and provide information on how it will affect the outcome of the final product.

Onset results:			
Onset	X1	50.42	°C
	Y1	100.430	%
	X2	406.98	°C
	Y2	70.224	%
	Onset X	394.09	°C
	Onset Y	100.036	%
Peak results:			
Area	X1	50.42	°C
	Y1	−0.026	%/min
	X2	793.72	°C
	Y2	−1.476	%/min
	Peak	406.98	°C
	Peak area	−41.613	%

The TGA analysis of the HDPE -2 sample as shown in Figure 3 states that by 406.98 °C the sample was completely incinerated and no amount of residue was leftover at that point.

Figure 4 and Table 4 demonstrate sample identification results obtained from FT-IR spectrum 100.

Retention time	Compound name	Formula	Retention time	Compound name	Formula
2.14	Propane	C_3H_8	22.62	Tetradecane	$C_{14}H_{30}$
2.23	3-butyn-1-ol	C_4H_6O	24.57	1,13-tetradecadiene	$C_{14}H_{26}$
2.42	2-pentene	C_5H_{10}	24.76	1-pentadecene	$C_{15}H_{30}$
2.61	1,3-pentadiene	C_5H_8	24.91	Pentadecane	$C_{15}H_{32}$
2.90	Cyclohexane	C_6H_{12}	26.77	1,15-hexadecadiene	$C_{16}H_{30}$
3.90	1,4-hexadiene	C_6H_{10}	26.94	1-hexadecanol	$C_{16}H_{34}O$
4.05	Cycloheptane	C_7H_{14}	27.08	Hexadecane	$C_{16}H_{34}$
4.18	Heptane	C_7H_{16}	28.86	11-hexadecen-1-ol, (Z)-	$C_{16}H_{32}O$
4.66	Cyclohexane, methyl-	C_7H_{14}	29.00	E-14-hexadecenal	$C_{16}H_{30}O$
5.52	1,3,5-cycloheptatriene	C_7H_8	29.13	Heptadecane	$C_{17}H_{36}$
5.86	1,7-octadiene	C_8H_{14}	30.83	1,19-eicosadiene	$C_{20}H_{38}$
6.08	Cyclooctane	C_8H_{16}	30.98	E-15-heptadecenal	$C_{17}H_{32}O$
6.30	Octane	C_8H_{18}	31.08	Octadecane	$C_{18}H_{38}$
6.94	1,4-octadiene	C_8H_{14}	32.71	1,19-eicosadiene	$C_{20}H_{38}$
8.53	1,8-nonadiene	C_9H_{16}	32.83	1-nonadecene	$C_{19}H_{38}$
8.81	1-nonene	C_9H_{18}	32.93	Nonadecane	$C_{19}H_{40}$
9.04	Nonane	C_9H_{20}	34.49	1,19-eicosadiene	$C_{20}H_{38}$
9.37	Cyclopentane, 1-methyl-2-(2-propenyl)-, trans-	C_9H_{16}	34.62	1-nonadecene	$C_{19}H_{38}$
11.48	1,9-decadiene	$C_{10}H_{18}$	34.71	Eicosane	$C_{20}H_{42}$
11.77	Cyclodecane	$C_{10}H_{20}$	36.21	1,19-eicosadiene	$C_{20}H_{38}$
11.99	Decane	$C_{10}H_{22}$	36.31	1-docosene	$C_{22}H_{44}$
14.39	1,10-undecadiene	$C_{11}H_{20}$	36.41	Heneicosane	$C_{21}H_{44}$
14.66	1-undecene	$C_{11}H_{22}$	37.85	1,19-eicosadiene	$C_{20}H_{38}$
14.88	Undecane	$C_{11}H_{24}$	37.95	1-docosene	$C_{22}H_{44}$
17.16	1,11-dodecadiene	$C_{12}H_{22}$	39.42	1,19-eicosadiene	$C_{20}H_{38}$
17.41	1-dodecene	$C_{12}H_{24}$	39.52	1-docosene	$C_{22}H_{44}$
17.61	Dodecane	$C_{12}H_{26}$	40.94	1,19-eicosadiene	$C_{20}H_{38}$
19.78	1,13-tetradecadiene	$C_{14}H_{26}$	41.02	1-docosene	$C_{22}H_{44}$
20.00	1-tridecene	$C_{13}H_{26}$	42.48	1-docosene	$C_{22}H_{44}$
20.19	Tridecane	$C_{13}H_{28}$	43.89	1-tetracosanol	$C_{24}H_{50}O$
22.24	1,13-tetradecadiene	$C_{14}H_{26}$	45.28	9-tricosene, (Z)-	$C_{23}H_{46}$
22.45	Cyclotetradecane	$C_{14}H_{28}$	46.76	17-pentatriacontene	$C_{35}H_{70}$

Table 2: GC/MS compound list of HDPE-2 waste plastic.

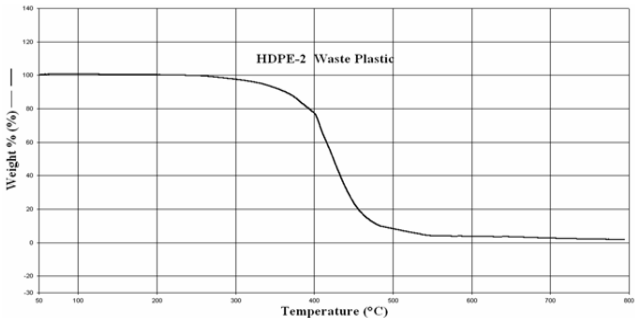

Figure 3: TGA graph of HDPE-2 raw waste plastic.

2.3 Process description

A small-scale conversion process has been performed with the simplified process shown in Figure 5 using one type of waste plastic: high-density polyethylene (HDPE-2 mostly milk containers). The plastic is collected, optionally shorted, cleaned of contaminants. These plastics types were investigated singly. The plastics were grinded into small pieces in sizes of 13–14 mm. These small plastic pieces were analyzed by EA-2400 (elemental analyzer) in CHNS mode to find the compositions. The analysis presented as 86% being C, 12% being H, 0.9% being N and about 1.1% being S. The process of conversion involves heating the waste plastic to form a liquid slurry (thermal liquefaction in the range 370 °C to 420 °C), cooling of the slurry, distilling the slurry in the presence of cracking with HZSM-5 catalyst which helps breakdown the hydrocarbons into more shorter chain compounds than without it and accelerates the reaction time, condensing the liquid slurry with a distillate to recover the liquid hydrocarbon fuel materials which is termed NSR fuel. During the production process, light gases ranging from C_1 to C_4 are produced and about 5% residue is leftover from the production process. The residue is black colored and contains high BTU value. Production yield percentage is 90% liquid fuel, 5% light gas and 5% residue (see Figure 6).

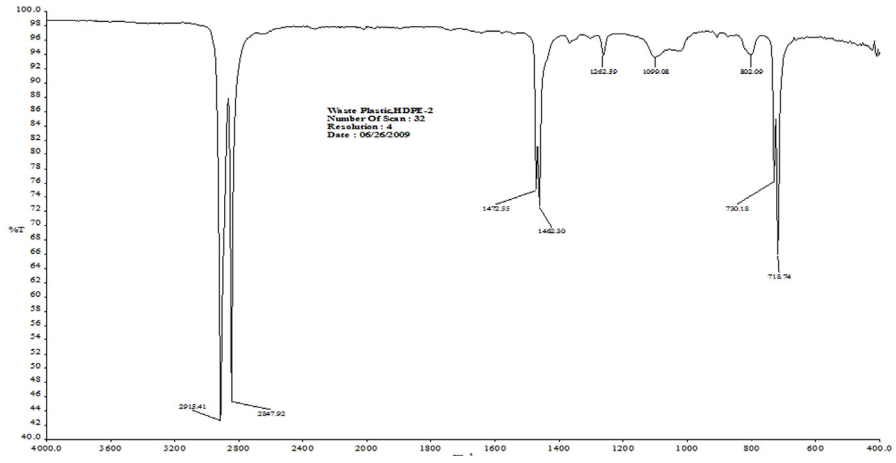

Figure 4: FTIR spectra of raw HDPE-2 plastic.

Mechanical properties		
Quantity	**Value**	**Units**
Young's modulus	600–1400	MPa
Shear modulus	700–800	MPa
Tensile strength	20–32	MPa
Elongation	180–1000	%
Fatigue	18–20	MPa
Bending strength	20–45	MPa
Impact strength	0.27–10.9	J/cm
Physical properties		
Quantity	**Value**	**Units**
Thermal expansion	110–130	e-6/K
Thermal conductivity	0.46–0.52	W/m.K
Specific heat	1800–2700	J/kg.K
Melting temperature	108–134	°C
Glass temperature	−110–−110	°C
Service temperature	−30–85	°C
Density	940–965	kg/m^3
Resistivity	5e+17–1e+21	Ohm.mm^2/m
Breakdown potential	17.7–19.7	kV/mm
Dielectric loss factor	0.0005–0.0008	
Friction coefficient	0.25–0.3	
Refraction index	1.52–1.53	
Shrinkage	2–4	%
Water absorption	0.01–0.01	%
Environmental data		
Quantity	**Value**	**Units**
Eco indicator 95	2.782	mPt
EPS	768	mELU
Ex (in)/Ex (out)	1.813	MJ/MJ
GER	75.74	MJ
Raw materials input	43.546	kg
Solid	0.004	kg
Eco indicator 99	0.339	Pt

Table 3: HDPE-2 raw plastic properties.

In the mini-scale process, the weight of a single batch of input plastic for the fuel production process ranges from 500 gm to 2 kg. A further fractional distillation process producing NSR fuel (1st distillation) went through another distillation process. The early 40% of the distillate (2nd distillation) was collected in the 1st collection tank which is termed as the "NSR double condensed fuel 1st collection" or "NSR-1" (gasoline category); 40–120 °C temperature was used to obtain it and 50% was collected in the 2nd collection tank and termed as the "NSR double condensed fuel 2nd collection" or "NSR-2" (Diesel category); 120–260 degree C temperature was used and the remaining 7% remains on the double condensed boiling chamber and it is termed "residual fuel" or "NSR- 3" and the rest 2–3% of light gas is also produced during the second fractional production process.

Band peak number	Wave number	Compound group number
1	2915.41	C-CH_3
2	2847.92	Non-conjugated
3	1472.55	
4	1462.30	
5	1262.59	CH_3
6	1099.08	CH_2
7	802.09	CH_3
8	730.18	
9	718.74	Acetates

Table 4: Raw HDPE-2 plastic FTIR spectra wave number and functional group name.

3 Results and discussion

The same analysis method was used to analyze the HDPE sample into fuel and the fractional fuels. The GC/MS method of analysis is as follows: initial GC temperature: 40 °C for 1.00 min, ramping rate: 10.0 °C/min, hold for 15.00 min. The total time to complete the analysis was 44.50 min to reach the final temp. of 325 °C. 0.5 μL sample was used for the GC analysis. Elite-5MS 30-meter long GC

Retention time (min)	Compound name	Formula	Retention time (min)	Compound name	Formula
1.56	Propane	C_3H_8	12.18	Cyclopentane, hexyl-	$C_{11}H_{22}$
1.66	2-butene, (E)-	C_4H_8	12.92	1-dodecene	$C_{12}H_{24}$
1.68	Butane	C_4H_{10}	13.05	Dodecane	$C_{12}H_{26}$
1.96	Cyclopropane, 1,2-dimethyl-, cis-	C_5H_{10}	13.76	Cyclododecane	$C_{12}H_{24}$
2.00	Pentane	C_5H_{12}	14.39	1-tridecene	$C_{13}H_{26}$
2.71	1-hexene	C_6H_{12}	14.51	Tridecane	$C_{13}H_{28}$
2.80	Hexane	C_6H_{14}	15.77	1-tetradecene	$C_{14}H_{28}$
3.19	Cyclopentane, methyl-	C_6H_{12}	15.88	Tetradecane	$C_{14}H_{30}$
3.50	Cyclopentene, 1-methyl-	C_6H_{10}	17.08	1-pentadecene	$C_{15}H_{30}$
4.10	1-heptene	C_7H_{14}	17.18	Pentadecane	$C_{15}H_{32}$
4.26	Heptane	C_7H_{16}	18.31	1-hexadecene	$C_{16}H_{32}$
4.64	Cyclopentane, 1-methyl-2-methylene-	C_7H_{12}	18.40	Hexadecane	$C_{16}H_{34}$
4.75	Cyclohexane, methyl-	C_7H_{14}	19.48	E-14-hexadecenal	$C_{16}H_{30}O$
5.28	1-ethylcyclopentene	C_7H_{12}	19.56	Heptadecane	$C_{17}H_{36}$
5.58	Cyclohexene, 1-methyl-	C_7H_{12}	20.58	E-15-heptadecenal	$C_{17}H_{32}O$
5.94	1-octene	C_8H_{16}	20.67	Octadecane	$C_{18}H_{38}$
6.11	Octane	C_8H_{18}	21.64	9-nonadecene	$C_{19}H_{38}$
6.61	Cyclopentane, 1,2-dimethyl-3-methylene-, cis-	C_8H_{14}	21.71	Eicosane	$C_{20}H_{42}$
6.66	1-methyl-2-methylenecyclohexane	C_8H_{14}	22.64	5-eicosene, (E)-	$C_{20}H_{40}$
6.78	Cycloheptane, methyl-	C_8H_{16}	22.71	Eicosane	$C_{20}H_{42}$
6.85	Cyclohexane, ethyl-	C_8H_{16}	23.64	10-heneicosene (c,t)	$C_{21}H_{42}$
7.01	Cyclopentene, 1-propyl-	C_8H_{14}	23.71	Heneicosane	$C_{21}H_{44}$
7.48	Cyclohexane, ethylidene-	C_8H_{14}	24.80	1-docosene	$C_{22}H_{44}$
7.84	1-nonene	C_9H_{18}	24.87	Heneicosane	$C_{21}H_{44}$
8.00	Nonane	C_9H_{20}	26.21	1-docosene	$C_{22}H_{44}$
8.67	Cyclohexane, propyl-	C_9H_{18}	26.30	Heneicosane	$C_{21}H_{44}$
9.65	1-decene	$C_{10}H_{20}$	27.98	1-docosene	$C_{22}H_{44}$
9.80	Decane	$C_{10}H_{22}$	28.09	Tetracosane	$C_{24}H_{50}$
11.35	1-undecene	$C_{11}H_{22}$	30.24	1-docosene	$C_{22}H_{44}$
11.49	Undecane	$C_{11}H_{24}$	30.38	Octacosane	$C_{28}H_{58}$

Table 5: HDPE-2 fuel GCMS chromatogram compound list.

column was used to purge the sample in the GC, 0.25 mm ID, 0.5 μm df, max. program temp. 350 °C, min. bleed at 330 °C. The MS program setup for compound mass trace is as follows: ion mode – EI+, data format – centroid, start mass –35.00, end mass –528.00, scan time (s) – 0.25, interval scan (s) – 0.15 Helium (He) was used as a carrier gas for GC analysis.

The GC/MS analysis of the fuel showed (see Figure 7 and Table 5) that the fuel contains hydrocarbon chain range from C_3 to C_{28}. The analysis was used to trace only the high peak compounds in the fuel. The compounds were selected based on retention time and the boiling point of when the compound was detected in the fuel sample. Most of the compounds found are single bonds, which are alkane and some are double bond compounds like alkene. Some compounds were also aromatic. From lower boiling point compound C_3 to high boiling point compound C_{28} was traced by the GC/MS, where the lower compound C_3H_8 (at retention time 1.56) has a molecular weight of 44.00 and the highest compound $C_{28}H_{58}$ (at retention time 30.38) has a molecular weight of 394.00.

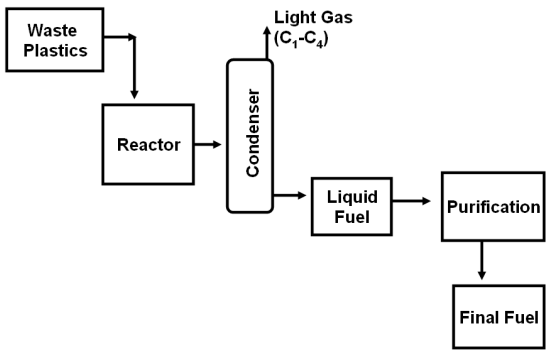

Figure 5: High density polyethylene (HDPE-2) to fuel production process.

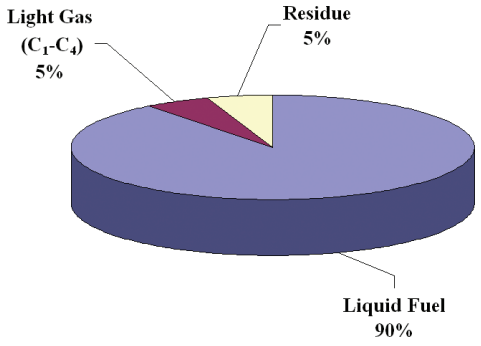

Figure 6: HDPE-2 waste plastic to fuel production yield percentage.

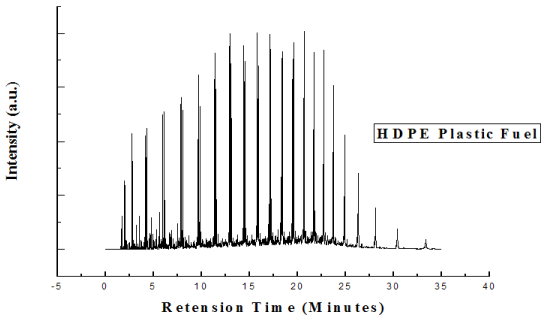

Figure 7: Gas chromatography and mass spectrometer of HDPE-2 to fuel.

The FT-IR 100 spectrum analysis of the final product was analyzed using a KRS-5 diamond plate. The scan time was 32 and resolution was 4 cm^{-1}. The analysis spectrum

Band peak number	Wave number (cm^{-1})	Functional group number
1	2956.38	C–CH_3
2	2921.84	C–CH_3
3	2853.19	CH_2
4	1641.69	Non-conjugated
5	1465.41	CH_3
6	1377.92	CH_3
7	991.76	–CH=CH_2
8	965.02	–CH=CH–(trans)
9	909.08	–CH=CH_2
10	721.39	–CH=CH–(cis)
11	667.88	–CH=CH–(cis)

Table 6: HDPE-2 fuel FTIR spectra wave number and compound group name.

is displayed in transmittance graph. The results indicate that some functional groups are single bond and some are double bond cis and trans groups and non-conjugated groups are also present. The wave number 2956.38 cm^{-1} indicates a single bonded C–CH_3 functional group and the energy content of the compound is 67.191231 $\times$ 10^{-38} joules/s. The wave number 991.76 cm^{-1} represents a double bond –CH=CH_2 which has an energy value of 18.9229643 $\times$ 10^{-39} j/s. These results indicate that as the functional groups get lower the energy value of the functional groups also decreases (see Tables 6 and Figure 8).

The Jade DSC (Perkin Elmer) measures the boiling point of the produced fuel. As shown in Figure 9, it is suggested that at 115.37 °C where the peak is at its highest, the percentage of compounds is higher at that stage. The onset temp. of the fuel product is 113.72 °C when the sample starts to boil.

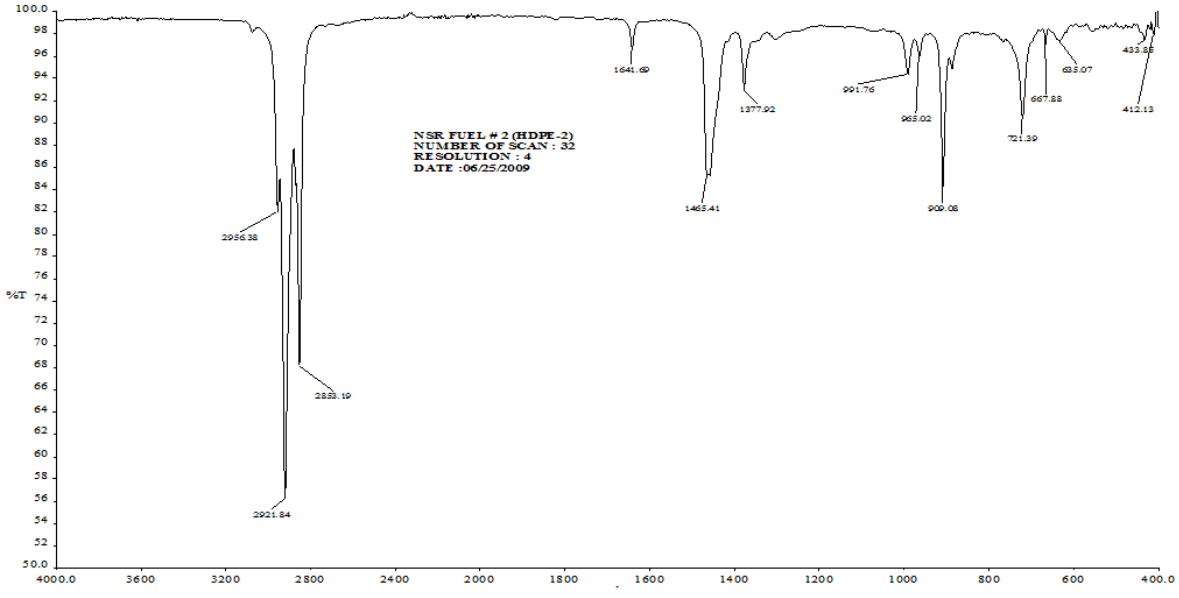

Figure 8: FTIR spectra of HDPE-2 to fuel.

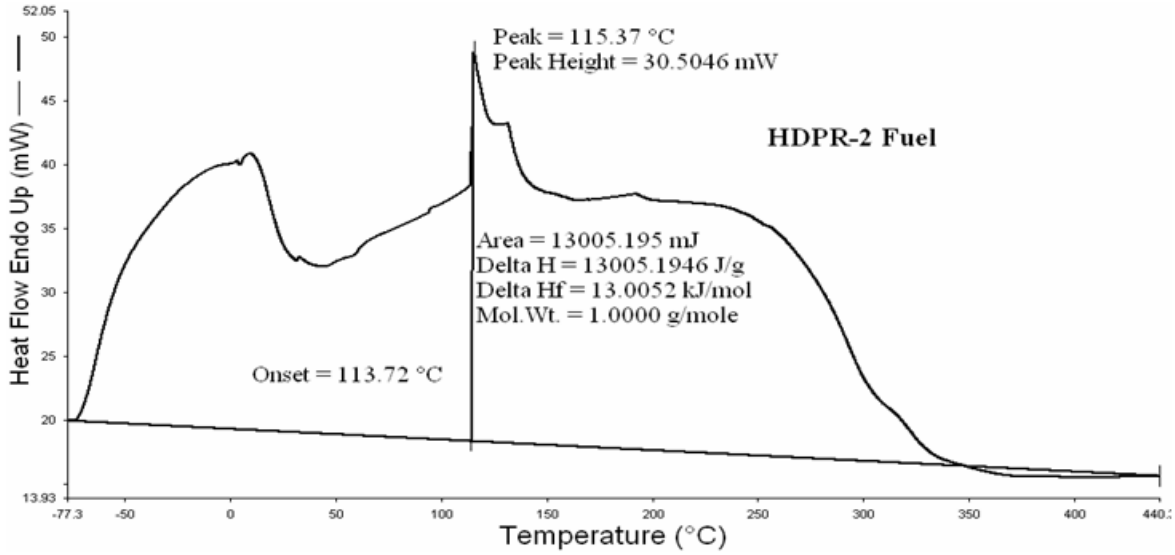

Figure 9: Differential scanning calorimeter (DSC) graph of HDPE-2 to fuel.

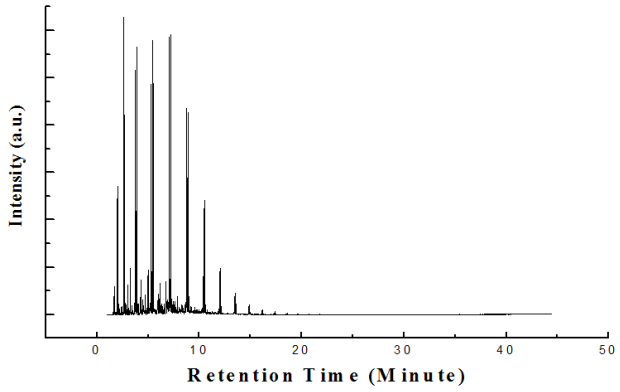

Figure 10: GC/MS chromatogram of HDPE-2 fuel to 1st fraction fuel (NSR-1).

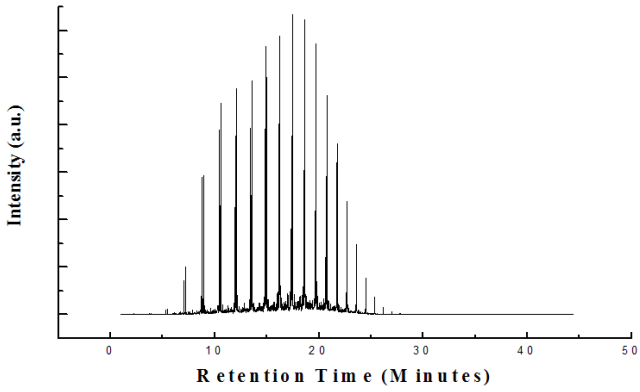

Figure 11: GC/MS chromatogram of HDPE-2 fuel to 2nd fraction fuel (NSR-2).

The enthalpy rate to reach peak of the sample is measured in delta H, which is 13005.1946 j/g and Delta Hf value of 13.0052 Kj/mol.

Figures 10 and 11 and Tables 7 and 8 demonstrate the GC/MS spectra and trace compound list of the HDPE fuel fractionated into two separate categories of (gasoline and diesel). The analysis methods were kept the same for these two samples as it was for the initial HDPE fuel sample. The fractionation of the initial HDPE fuel sample altered the hydrocarbon chain range between the 1st and the 2nd fractionation fuels. The 1st fraction fuel has a carbon chain range of C_4–C_{14} and the 2nd fraction fuel has a carbon chain range from C_8 to C_{27}. This separation occurred because a separate temperature profile was used to make the two different fuel types. The 1st fraction fuel contains higher octane-based compounds because all the hydrocarbons present in it are very light reason, as being compared to gasoline grade fuel; in contrast, all the heavy compounds end up in the 2nd fraction fuel making it close to diesel grade fuel.

The FT-IR analysis of the 1st and 2nd fractional fuel was conducted using an NaCl 0.050 mm cell.

Figure 12 and Table 9 show that the FT-IR spectra and functional groups of the HDPE-2 fuel to 1st collection fuel functional groups are H bonded NH, CH_2, C–CH_3, non-conjugated, CH_3, secondary cyclic alcohol, –CH=CH– (trans), –CH=CH_2, C=CH_2 and –CH=CH–(cis). The energy value of the first detected functional group H bonded NH at wave number 3078.39 cm^{-1} is 64.528150 $\times$ 10^{-38} j/s and –CH=CH-(trans) group at 965.09 cm^{-1} wave number has 20.582827 $\times$ 10^{-39}.

Retention time	Compound name	Formula	Molecular weight	Retention time	Compound name	Formula	Molecular weight
1.70	Butane	C_4H_{10}	58	6.72	Cyclohexanol, 1-ethynyl-, carbamate	$C_9H_{13}NO_2$	167
1.96	Cyclopropane, ethyl-	C_5H_{10}	70	7.05	1-nonene	C_9H_{18}	126
2.00	Pentane	C_5H_{12}	72	7.21	Nonane	C_9H_{20}	128
2.59	1-hexene	C_6H_{12}	84	7.83	Cyclopentane, butyl-	C_9H_{18}	126
2.66	Hexane	C_6H_{14}	86	8.77	1-decene	$C_{10}H_{20}$	140
3.00	Cyclopentane, methyl-	C_6H_{12}	84	8.93	Decane	$C_{10}H_{22}$	142
3.25	Cyclopentene, 3-methyl-	C_6H_{10}	82	10.42	1-undecene	$C_{11}H_{22}$	154
3.74	1-heptene	C_7H_{14}	98	10.56	Undecane	$C_{11}H_{24}$	156
3.87	Heptane	C_7H_{16}	100	11.97	3-dodecene, (E)-	$C_{12}H_{24}$	168
4.29	Cyclohexane, methyl-	C_7H_{14}	98	12.09	Dodecane	$C_{12}H_{26}$	170
5.00	Cyclohexene, 1-methyl-	C_7H_{12}	96	13.43	1-tridecene	$C_{13}H_{26}$	182
5.30	1-octene	C_8H_{16}	112	13.54	Tridecane	$C_{13}H_{28}$	184
5.46	Octane	C_8H_{18}	114	14.80	Cyclotetradecane	$C_{14}H_{28}$	196
6.14	Cyclohexane, ethyl-	C_8H_{16}	112	14.90	Tetradecane	$C_{14}H_{30}$	198

Table 7: GC/MS HDPE-2 fuel to 1st fraction fuel (NSR-1) compound list.

Retention time (min)	Compound name	Formula	Molecular weight	(min)	Compound name	Formula	Molecular weight
5.29	1-octene	C_8H_{16}	112	16.13	1-pentadecene	$C_{15}H_{30}$	210
5.44	Octane	C_8H_{18}	114	16.24	Pentadecane	$C_{15}H_{32}$	212
7.02	1-nonene	C_9H_{18}	126	17.36	1-hexadecene	$C_{16}H_{32}$	224
7.18	Nonane	C_9H_{20}	128	17.46	Hexadecane	$C_{16}H_{34}$	226
8.76	1-decene	$C_{10}H_{20}$	140	18.52	E-14-hexadecenal	$C_{16}H_{30}O$	238
8.91	Decane	$C_{10}H_{22}$	142	18.61	Heptadecane	$C_{17}H_{36}$	240
10.42	Cyclopropane, 1-heptyl-2-methyl-	$C_{11}H_{22}$	154	19.62	E-15-heptadecenal	$C_{17}H_{32}O$	252
10.56	Undecane	$C_{11}H_{24}$	156	19.71	Octadecane	$C_{18}H_{38}$	254
11.99	1-dodecene	$C_{12}H_{24}$	168	20.67	1-nonadecene	$C_{19}H_{38}$	266
12.11	Dodecane	$C_{12}H_{26}$	170	20.74	Nonadecane	$C_{19}H_{40}$	268
13.45	1-tridecene	$C_{13}H_{26}$	182	21.67	1-docosene	$C_{22}H_{44}$	308
13.57	Tridecane	$C_{13}H_{28}$	184	21.74	Eicosane	$C_{20}H_{42}$	282
14.83	1-tetradecene	$C_{14}H_{28}$	196	22.69	Heneicosane	$C_{21}H_{44}$	296
14.94	Tetradecane	$C_{14}H_{30}$	198	25.34	Tetracosane	$C_{24}H_{50}$	338
				26.17	Heptacosane	$C_{27}H_{56}$	380

Table 8: GC/MS HDPE-2 fuel to 2nd fraction fuel (NSR-2) compound list.

Band serial number	Wave number	Functional group	Band serial number	Wave number	Functional group
1	3078.39	H bonded NH	13	1341.63	
2	2933.54	CH_2	14	1299.42	
3	2731.76	C–CH_3	15	1139.24	
4	2669.61	C–CH_3	16	992.26	Secondary cyclic alcohol
5	2343.20		17	965.09	–CH=CH–(trans)
6	2028.03		18	910.43	–CH=CH_2
7	1977.08		19	888.28	C=CH_2
8	1822.04	Non-conjugated	20	795.30	
9	1716.91	Non-conjugated	21	768.10	
10	1641.80	Non-conjugated	22	724.21	–CH=CH–(cis)
11	1452.14	CH_3	23	695.42	–CH=CH–(cis)
12	1378.16	CH_3	24	674.57	–CH=CH–(cis)

Table 9: FTIR spectrum factional group compound list of HDPE-2 fuel to 1st collection fuel (NSR-1).

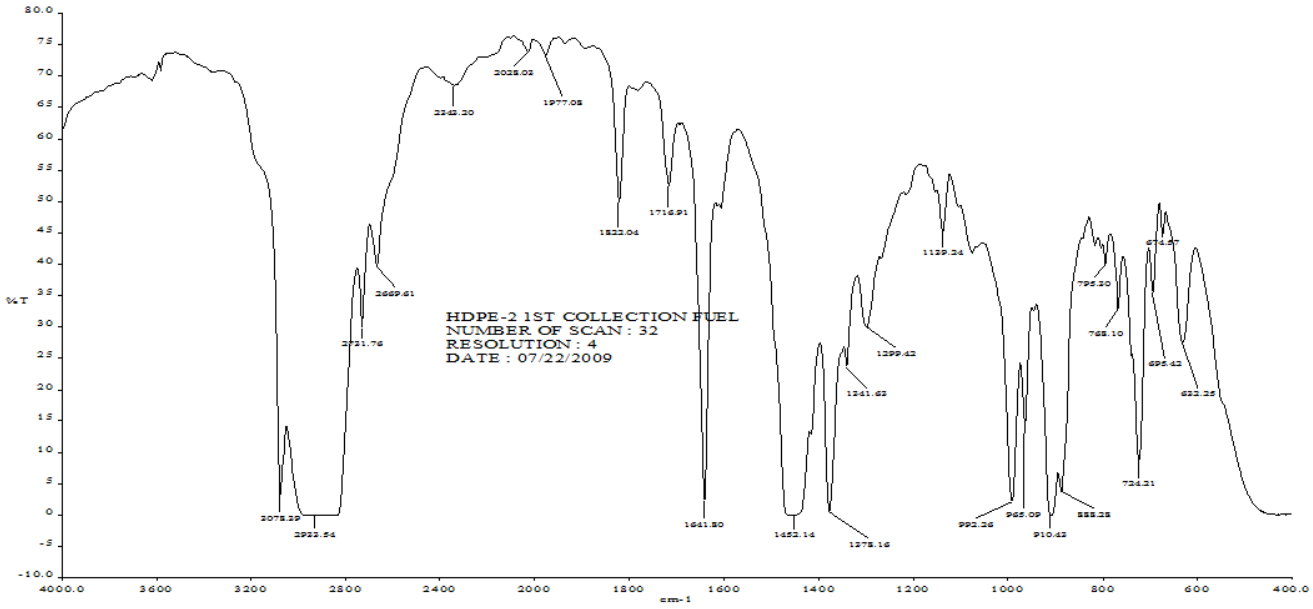

Figure 12: FTIR spectrum of HDPE-2 fuel to 1st collection fuel (NSR-1).

Band serial number	Wave number (cm^{-1})	Functional group	Band serial number	Wave number (cm^{-1})	Functional group
1	3077.44	H bonded NH	11	1377.72	CH_3
2	2937.70	C–CH_3	12	1302.50	
3	2730.80	C–CH_3	13	1075.98	
4	2672.56	C–CH_3	14	991.77	Secondary cyclic alcohol
5	2333.98		15	965.02	–CH=CH–(trans)
6	2026.45		16	909.30	–CH=CH_2
7	1821.41	Non-conjugated	17	887.97	C=CH_2
8	1717.07	Non-conjugated	18	811.73	
9	1641.57	Conjugated	19	721.53	–CH=CH–(cis)
10	1467.30	CH_3	20	632.65	

Table 10: FTIR spectrum factional group compound list of HDPE-2 fuel to 2nd collection fuel (NSR-2).

Figure 13 and Table 10 show that the FT-IR spectra and functional groups of the HDPE-2 fuel to 2nd collection fuel functional groups are H bonded NH, C–CH_3, non-conjugated, conjugated, CH_3, secondary cyclic alcohol, –CH=CH–(trans), –CH=CH_2, C=CH_2 and –CH=CH–(cis). The energy value of the first detected functional group H bonded NH at wave number 3077.44 cm^{-1} is 64.54807×10^{-38} j/s and group secondary cyclic alcohol at 991.77 cm^{-1} wave number has $20.029121 \times 10^{-39}$.

Figures 14 and 15 indicate the results obtained from Jade DSC of the 1st and 2nd fraction fuels boiling point, enthalpy value and onset temperature. The onset of the 1st fractional fuel of 47.76 °C indicates that lower boiling point compounds are present. The highest peak is at 126.48 °C which indicates that higher percentage compounds are present there. The enthalpy rate is 12619.99 j/g to reach the peak temp. The 2nd fraction fuel has a significant higher onset temp. of 178.77 °C because it contains heavier hydrocarbon compounds. Also the peak point is at 232.05 °C because of the heavier compounds, although the enthalpy value is lower than 1st fraction fuel because the 2nd fraction fuel has long straight chain compounds compared to branch-like hydrocarbon compounds.

4 ASTM test results

Tables 11, 12 and 13 are ASTM tests conducted rigorously from third party INTERTEK laboratory, NJ, USA.

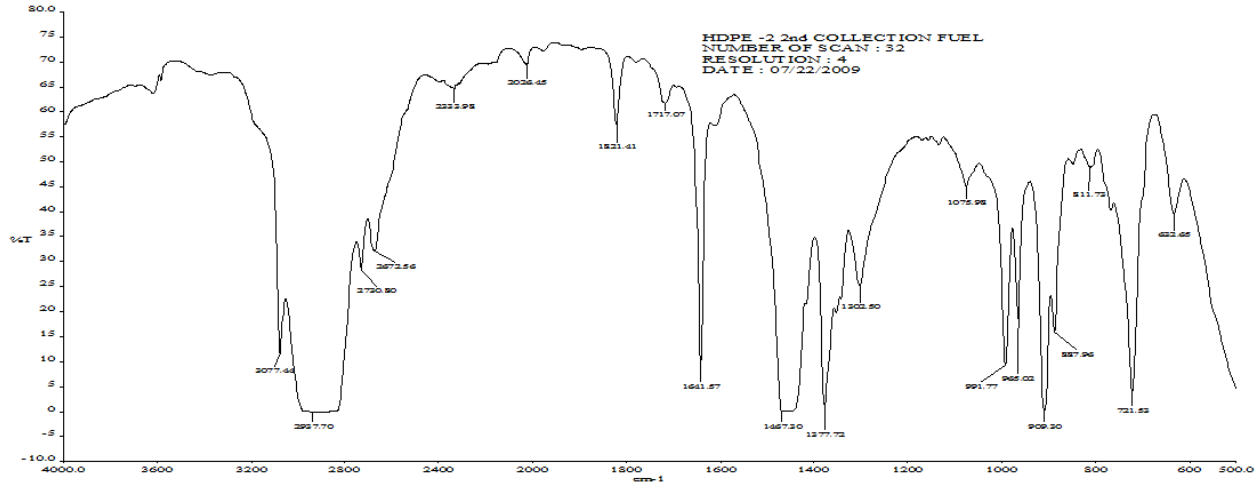

Figure 13: FTIR spectrum of HDPE-2 fuel to 2nd collection fuel (NSR-2).

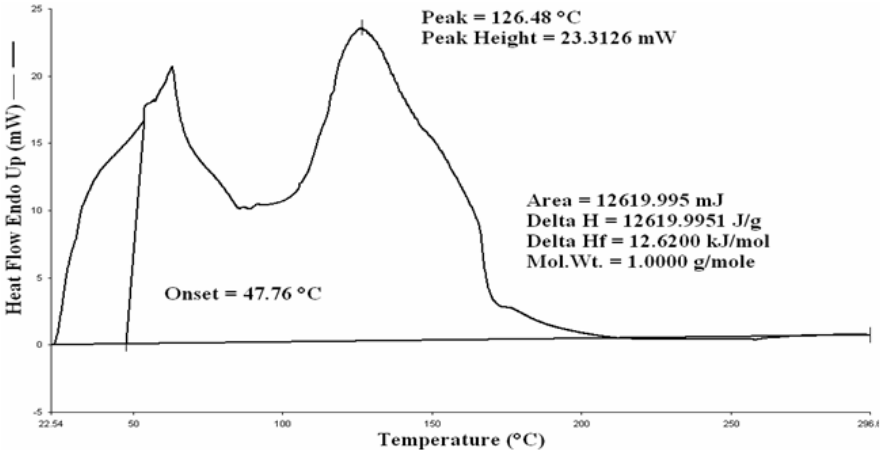

Figure 14: DSC graph of HDPE-2 fuel to 1st collection fuel (NSR-1).

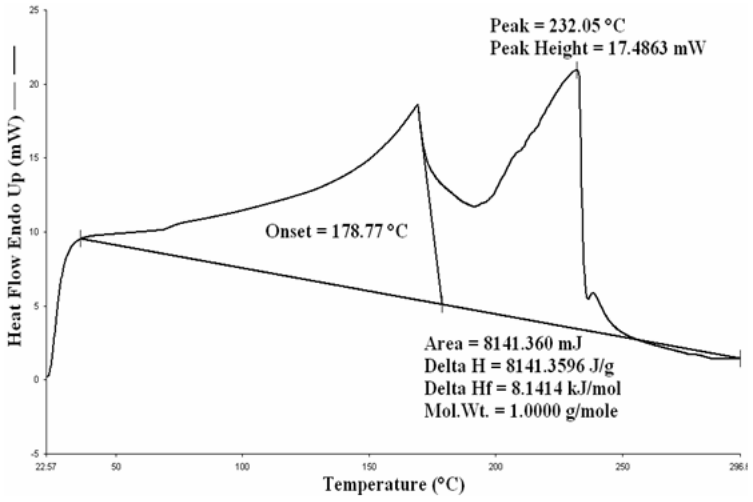

Figure 15: DSC graph of HDPE-2 fuel to 2nd collection fuel (NSR-2).

Method	Test	Results	Units
D240	Gross heat of combustion	123,845	BTU/gal
D4052	API gravity @ 60 °F	53.70	°API
D5453	Sulfur	3.05	ppm

Table 11: HDPE-2 plastic to fuel (ASTM test results).

Method	Test	Results	Units
D4052	API gravity @ 60 °F	61.2	°API
D5453	Sulfur	4.1	ppm
D240	Gross heat of combustion	18,236	BTU/ib
D240	Gross heat of combustion	111,477	BTU/gal

Table 12: HDPE-2 fuel to 1st fraction fuel (NSR-1) (ASTM test results).

Method	Test	Results	Units
D4052	API gravity @ 60 °F	61.2	°API
D5453	Sulfur	4.1	ppm
D240	Gross heat of combustion	18,236	BTU/ib
D240	Gross heat of combustion	111,477	BTU/gal

Table 13: HDPE-2 fuel to 2nd fraction fuel (NSR-2) (ASTM test results).

5 Conclusion

The thermal degradation of HDPE plastic to convert it into liquid hydrocarbon products (initial fuel) after being fractionated has competitive similarities with already available commercial fuels such as gasoline and diesel. The 1st fraction fuel's carbon chain ranges from C_4 to C_{14} and the 2nd fraction fuels carbon ranges from C_8 to C_{27}. The gaseous product that forms in traceable amount during the production process contains C_1–C_4 compounds. These carbons represent natural gases such as methane, ethane, butane and propane. The residue leftover from the production process is a high energy value compound which closely resembles coals and its immense BTU value.

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