Research Article

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

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Received 28 January 2011; Accepted 23 June 2011

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.
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 $\mu$m. 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.
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. During the production process, light gases ranging from C\(_2\) 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).

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

| Retention time | Compound name | Formula | Retention time | Compound name | Formula |
|----------------|---------------|---------|----------------|---------------|---------|
| 2.14           | Propane       | C\(_2\)H\(_6\) | 22.62          | Tetradecane   | C\(_{14}\)H\(_{30}\) |
| 2.23           | 3-butyn-1-ol  | C\(_4\)H\(_7\)O | 24.57          | 1,13-tetradecadiene | C\(_{14}\)H\(_{26}\) |
| 2.42           | 2-pentene     | C\(_5\)H\(_{10}\) | 24.76          | 1-pentadecene  | C\(_{15}\)H\(_{30}\) |
| 2.61           | 1,3-pentadiene| C\(_5\)H\(_8\)  | 24.91          | Pentadecane    | C\(_{15}\)H\(_{32}\) |
| 2.90           | Cyclohexane   | C\(_6\)H\(_{12}\) | 26.77          | 1,15-hexadecadiene | C\(_{16}\)H\(_{30}\) |
| 3.90           | 1,4-hexadiene | C\(_6\)H\(_{10}\) | 26.94          | 1-hexadecanol  | C\(_{16}\)H\(_{34}\)O |
| 4.05           | Cycloheptane  | C\(_7\)H\(_{14}\) | 27.08          | Hexadecane     | C\(_{16}\)H\(_{34}\) |
| 4.18           | Heptane       | C\(_7\)H\(_{16}\) | 28.86          | 11-hexadecen-1-ol, (Z)- | C\(_{16}\)H\(_{32}\)O |
| 4.66           | Cyclohexane, methyl- | C\(_7\)H\(_{14}\) | 29.00          | E-14-hexadecenal | C\(_{16}\)H\(_{30}\)O |
| 5.52           | 1,3,5-cycloheptatriene | C\(_8\)H\(_{18}\) | 29.13          | Heptadecane    | C\(_{17}\)H\(_{36}\) |
| 5.86           | 1,7-octadiene | C\(_8\)H\(_{16}\) | 30.83          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 6.08           | Cyclooctane   | C\(_8\)H\(_{16}\) | 30.98          | E-15-hexadecenal | C\(_{17}\)H\(_{32}\)O |
| 6.30           | Octane        | C\(_8\)H\(_{18}\) | 31.08          | Octadecane     | C\(_{18}\)H\(_{38}\) |
| 6.94           | 1,4-octadiene | C\(_8\)H\(_{16}\) | 32.71          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 8.53           | 1,8-nonadiene | C\(_9\)H\(_{18}\) | 32.83          | 1-nonadecene   | C\(_{19}\)H\(_{38}\) |
| 8.81           | 1-nonene      | C\(_9\)H\(_{18}\) | 32.93          | Nonadecane     | C\(_{19}\)H\(_{38}\) |
| 9.04           | Nonane        | C\(_9\)H\(_{20}\) | 34.49          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 9.37           | Cyclopentane, 1-methyl-2-(2-propenyl)-, trans- | C\(_8\)H\(_{16}\) | 34.62          | 1-nonadecene   | C\(_{19}\)H\(_{38}\) |
| 11.48          | 1,9-decadiene | C\(_9\)H\(_{18}\) | 34.71          | Eicosane       | C\(_{20}\)H\(_{32}\) |
| 11.77          | Cyclodecane   | C\(_9\)H\(_{20}\) | 36.21          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 11.99          | Decane        | C\(_9\)H\(_{22}\) | 36.31          | 1-docosene     | C\(_{22}\)H\(_{44}\) |
| 14.39          | 1,10-undecadiene | C\(_{10}\)H\(_{20}\) | 36.41          | Henecosane     | C\(_{21}\)H\(_{42}\) |
| 14.66          | Undecene      | C\(_{10}\)H\(_{22}\) | 37.85          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 14.88          | Undecene      | C\(_{10}\)H\(_{22}\) | 37.95          | 1-docosene     | C\(_{22}\)H\(_{44}\) |
| 17.16          | 1,11-dodecadiene | C\(_{11}\)H\(_{24}\) | 39.42          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 17.41          | 1-dodecene    | C\(_{11}\)H\(_{24}\) | 39.52          | 1-docosene     | C\(_{22}\)H\(_{44}\) |
| 17.61          | Dodecane      | C\(_{11}\)H\(_{26}\) | 40.94          | 1,19-eicosadiene | C\(_{20}\)H\(_{38}\) |
| 19.78          | 1,13-tetradecadiene | C\(_{12}\)H\(_{26}\) | 41.02          | 1-docosene     | C\(_{22}\)H\(_{44}\) |
| 20.00          | 1-tridecane   | C\(_{12}\)H\(_{26}\) | 42.48          | 1-docosene     | C\(_{22}\)H\(_{44}\) |
| 20.19          | Tridecane     | C\(_{12}\)H\(_{28}\) | 43.89          | 1-tetracosanol | C\(_{24}\)H\(_{50}\)O |
| 22.24          | 1,13-tetradecadiene | C\(_{13}\)H\(_{28}\) | 45.28          | 9-tricosene, (Z)- | C\(_{21}\)H\(_{46}\) |
| 22.45          | Cycloetradecane | C\(_{14}\)H\(_{30}\) | 46.76          | 17-pentatriacontene | C\(_{35}\)H\(_{70}\) |

**Figure 3**: TGA graph of HDPE-2 raw waste plastic.
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     |
| 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/m³     |
| Resistivity           | 5.0×10⁻¹⁷–1.0×10⁻²¹ Ohm.mm²/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.

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\(_3\)H\(_8\) | 12.18               | Cyclopentane, hexyl- | C\(_{11}\)H\(_{22}\) |
| 1.66                | 2-butene, (E)-| C\(_2\)H\(_4\) | 12.92               | 1-dodecene     | C\(_{12}\)H\(_{24}\) |
| 1.68                | Butane        | C\(_3\)H\(_{10}\) | 13.05               | Dodecane       | C\(_{10}\)H\(_{21}\) |
| 1.96                | Cyclopropane, 1,2-dimethyl-, cis- | C\(_3\)H\(_{10}\) | 13.76               | Cyclooctadecane | C\(_{12}\)H\(_{24}\) |
| 2.00                | Pentane       | C\(_2\)H\(_{12}\) | 14.39               | 1-tridecane     | C\(_{12}\)H\(_{26}\) |
| 2.71                | 1-hexene      | C\(_3\)H\(_{12}\) | 14.51               | Tridecane       | C\(_{12}\)H\(_{28}\) |
| 2.80                | Hexane        | C\(_2\)H\(_{14}\) | 15.77               | 1-tetradecane   | C\(_{12}\)H\(_{28}\) |
| 3.19                | Cyclopentane, methyl- | C\(_3\)H\(_{12}\) | 15.88               | Tetradecane     | C\(_{12}\)H\(_{30}\) |
| 3.50                | Cyclopentene, 1-methyl- | C\(_3\)H\(_{10}\) | 17.08               | 1-pentadecane   | C\(_{13}\)H\(_{30}\) |
| 4.10                | 1-heptene     | C\(_2\)H\(_{14}\) | 17.18               | Pentadecane     | C\(_{13}\)H\(_{32}\) |
| 4.26                | Heptane       | C\(_2\)H\(_{16}\) | 18.31               | 1-hexadecane    | C\(_{14}\)H\(_{32}\) |
| 4.64                | Cyclopentane, 1-methyl-2-methylene- | C\(_3\)H\(_{12}\) | 18.40               | Hexadecane      | C\(_{16}\)H\(_{34}\) |
| 4.75                | Cyclohexane, methyl- | C\(_4\)H\(_{14}\) | 19.48               | E-14-hexadecenal | C\(_{16}\)H\(_{30}\)O |
| 5.28                | 1-ethylcyclohexane | C\(_2\)H\(_{12}\) | 19.56               | Heptadecane     | C\(_{17}\)H\(_{36}\) |
| 5.58                | Cyclohexene, 1-methyl- | C\(_2\)H\(_{12}\) | 20.58               | E-15-heptadecenal | C\(_{17}\)H\(_{32}\)O |
| 5.94                | 1-octene      | C\(_4\)H\(_{16}\) | 20.67               | Octadecane      | C\(_{18}\)H\(_{38}\) |
| 6.11                | Octane        | C\(_5\)H\(_{18}\) | 21.64               | 9-nonadecene    | C\(_{20}\)H\(_{46}\) |
| 6.61                | Cyclopentane, 1,2-dimethyl-3-methylene-, cis- | C\(_3\)H\(_{14}\) | 21.71               | Eicosane        | C\(_{20}\)H\(_{42}\) |
| 6.66                | 1-methyl-2-methylenehexane | C\(_4\)H\(_{14}\) | 22.64               | 5-eicosene, (E)- | C\(_{21}\)H\(_{40}\) |
| 6.78                | Cyclohexane, methyl- | C\(_4\)H\(_{16}\) | 22.71               | Eicosane        | C\(_{21}\)H\(_{42}\) |
| 6.85                | Cyclohexane, ethyl- | C\(_4\)H\(_{16}\) | 23.64               | 10-heneicosene (c.j) | C\(_{21}\)H\(_{42}\) |
| 7.01                | Cyclopentene, 1-propyl- | C\(_4\)H\(_{14}\) | 23.71               | Heneicosane     | C\(_{22}\)H\(_{44}\) |
| 7.48                | Cyclohexane, ethylidene- | C\(_4\)H\(_{14}\) | 24.80               | 1-docosene      | C\(_{22}\)H\(_{44}\) |
| 7.84                | 1-nonene      | C\(_5\)H\(_{18}\) | 24.87               | Heneicosane     | C\(_{23}\)H\(_{46}\) |
| 8.00                | Nonane        | C\(_5\)H\(_{20}\) | 26.21               | 1-docosene      | C\(_{23}\)H\(_{44}\) |
| 8.67                | Cyclohexane, propyl- | C\(_5\)H\(_{18}\) | 26.30               | Heneicosane     | C\(_{24}\)H\(_{46}\) |
| 9.65                | 1-decene      | C\(_6\)H\(_{20}\) | 27.98               | 1-docosene      | C\(_{24}\)H\(_{44}\) |
| 9.80                | Decane        | C\(_7\)H\(_{22}\) | 28.09               | Tetracosane     | C\(_{25}\)H\(_{50}\) |
| 11.35               | 1-undecene    | C\(_8\)H\(_{22}\) | 30.24               | 1-docosene      | C\(_{25}\)H\(_{52}\) |
| 11.49               | Undecane      | C\(_8\)H\(_{24}\) | 30.38               | Octacosane      | C\(_{26}\)H\(_{58}\) |

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

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\(_3\)H\(_8\) (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.
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 is displayed in a 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.

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

| 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)            |
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 \(6.528150 \times 10^{-38}\) J/s and –CH=CH-(trans) group at 965.09 cm\(^{-1}\) wave number has \(20.582827 \times 10^{-39}\).
### Table 7: GC/MS HDPE-2 fuel to 1st fraction fuel (NSR-1) compound list.

| Retention time (min) | Compound name | Formula | Molecular weight | Retention time (min) | Compound name | Formula | Molecular weight |
|----------------------|---------------|---------|------------------|----------------------|---------------|---------|------------------|
| 1.70                 | Butane        | C₄H₁₀  | 58               | 6.72                 | Cyclohexanol, 1-ethenyl-, carbamate | C₉H₁₈NO₂ | 167              |
| 1.96                 | Cyclopropane, ethyl- | C₅H₁₀ | 70               | 7.05                 | 1-nonene | C₉H₁₈ | 126              |
| 2.00                 | Pentane       | C₅H₁₂  | 72               | 7.21                 | Nonane | C₅H₁₀ | 128              |
| 2.59                 | 1-hexene      | C₆H₁₂  | 84               | 7.83                 | Cyclohexanate, butyl- | C₁₀H₂₀ | 126              |
| 2.66                 | Hexane        | C₆H₁₄  | 86               | 8.77                 | 1-decane | C₁₀H₂₀ | 140              |
| 3.00                 | Cyclopentane, methyl- | C₆H₁₂ | 84               | 8.93                 | Decane | C₁₀H₂₂ | 142              |
| 3.25                 | Cyclopentene, 3-methyl-1-heptene | C₆H₁₀ | 82               | 10.42                | Undecane | C₁₁H₂₄ | 156              |
| 3.74                 | Heptane       | C₇H₁₆  | 100              | 11.97                | 3-dodecene, (E)- | C₁₂H₂₄ | 168              |
| 4.29                 | Cyclohexane, methyl- | C₇H₁₄ | 98               | 12.09                | Dodecane | C₁₂H₂₆ | 170              |
| 5.00                 | Cyclohexene, 1-methyl-1-octene | C₇H₁₂ | 96               | 13.43                | 1-tridecane | C₁₃H₂₆ | 182              |
| 5.30                 | 1-octene      | C₈H₁₆  | 112              | 13.54                | Tridecane | C₁₃H₂₈ | 184              |
| 5.46                 | Octane        | C₈H₁₈  | 114              | 14.80                | Cyclooctadecane | C₁₄H₂₈ | 196              |
| 6.14                 | Cyclohexane, ethyl- | C₇H₁₆ | 112              | 14.90                | Tetradecane | C₁₄H₃₀ | 198              |

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

| Retention (min) | Compound name | Formula | Molecular weight | Retention (min) | Compound name | Formula | Molecular weight |
|-----------------|---------------|---------|------------------|-----------------|---------------|---------|------------------|
| 5.29            | 1-octene      | C₈H₁₆  | 112              | 16.13           | 1-pentadecane | C₁₅H₃₀ | 210              |
| 5.44            | Octane        | C₈H₁₈  | 114              | 16.24           | Pentadecane   | C₁₅H₃₂ | 212              |
| 7.02            | 1-nonene      | C₈H₁₈  | 126              | 17.36           | 1-hexadecene | C₁₆H₃₂ | 224              |
| 7.18            | Nonane        | C₈H₂₀  | 128              | 17.46           | Hexadecane    | C₁₆H₃₄ | 226              |
| 8.76            | 1-decane      | C₁₀H₂₀  | 140              | 18.52           | E-14-hexadecanol | C₁₆H₃₆O | 238             |
| 8.91            | Decane        | C₁₀H₂₂  | 142              | 18.61           | Heptadecane   | C₁₇H₃₆ | 240              |
| 10.42           | Cyclopropane, 1-heptyl-2-methyl- | C₁₁H₂₂ | 154              | 19.62           | E-15-heptadecanol | C₁₇H₃₂O | 252             |
| 10.56           | Undecane      | C₁₁H₂₄  | 156              | 19.71           | Octadecane    | C₁₈H₃₈ | 254              |
| 11.99           | 1-dodecane    | C₁₂H₂₄  | 168              | 20.67           | 1-nonadecane | C₁₉H₃₈ | 266              |
| 12.11           | Dodecane      | C₁₂H₂₆  | 170              | 20.74           | Nonadecane    | C₁₉H₄₀ | 268              |
| 13.45           | 1-tridecane   | C₁₃H₂₆  | 182              | 21.67           | 1-docosene    | C₂₀H₄₄ | 308              |
| 13.57           | Tridecane     | C₁₃H₂₈  | 184              | 21.74           | Eicosane      | C₂₀H₄₂ | 282              |
| 14.83           | 1-tetradecane | C₁₄H₂₈  | 196              | 22.69           | Henicosane    | C₂₁H₴₄ | 296              |
| 14.94           | Tetradecane   | C₁₄H₃₀  | 198              | 25.34           | Tetracosane   | C₂₄H₅₀ | 338              |
|                 |               |         |                  |                 | Heptacosane   | C₂₇H₅₆ | 380              |

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

| 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     | CH₂                | 14                 | 1299.42     |                    |
| 3                  | 2731.76     | C–CH₃              | 15                 | 1139.24     |                    |
| 4                  | 2669.61     | C–CH₃              | 16                 | 992.26      | Secondary cyclic alcohol |
| 5                  | 2343.20     |                    | 17                 | 965.09      | –CH=CH–(trans)     |
| 6                  | 2028.03     |                    | 18                 | 910.43      | –CH=CH₂            |
| 7                  | 1977.08     |                    | 19                 | 888.28      | C=CH₂              |
| 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     | CH₃                | 23                 | 695.42      | –CH=CH–(cis)       |
| 12                 | 1378.16     | CH₃                | 24                 | 674.57      | –CH=CH–(cis)       |
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            | CH₃                      |
| 2                  | 2937.70            | C–CH₃              | 12                 | 1302.50            |                          |
| 3                  | 2730.80            | C–CH₃              | 13                 | 1075.98            |                          |
| 4                  | 2672.56            | C–CH₃              | 14                 | 991.77             | Secondary cyclic alcohol |
| 5                  | 2333.98            |                   | 15                 | 965.02             | –CH=CH–(trans)          |
| 6                  | 2026.45            |                   | 16                 | 909.30             | –CH=CH₂                  |
| 7                  | 1821.41            | Non-conjugated     | 17                 | 887.97             | C=CH₂                    |
| 8                  | 1717.07            | Non-conjugated     | 18                 | 811.73             |                          |
| 9                  | 1641.57            | Conjugated         | 19                 | 721.53             | –CH=CH–(cis)            |
| 10                 | 1467.30            | CH₃                | 20                 | 632.65             |                          |

Table 10: FTIR spectrum fractional 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–CH₃, non-conjugated, conjugated, CH₃, secondary cyclic alcohol, –CH=CH–(trans), –CH=CH₂, C=CH₂ 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 × 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).
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 C₁ to C₁₄ and the 2nd fraction fuels carbon ranges from C₆ to C₂₇. The gaseous product that forms in traceable amount during the production process contains C₁–C₄ 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.

Acknowledgments

The author acknowledges the support of Dr. Karin Kaufman, the founder and sole owner of Natural State Research, Inc. (NSR). The authors also acknowledge the valuable contributions of NSR laboratory team members during the preparation of this manuscript.

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