

PYROLYSIS OF WASTE PLASTIC TO FUEL CONVERSION FOR UTILIZATION IN INTERNAL COMBUSTION ENGINE

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Abstract. In the present study different plastic waste materials with various types of plastics such as low-density polyethylene and polypropylene with zinc oxide catalyst have been pyrolyzed in batch tubular reactor. Waste plastics were characterized by using TGA and DTG analysis and FTIR spectroscopy. The pyrolyzed products are analyzed by standard methods to determine various parameters.

Keyword: waste plastic, tubular reactor, fuel, thermogravimetric analysis, catalysis and kinetics, internal combustion.

1. Introduction

Pyrolysis is one of the efficient procedures of chemical recycling of plastic wastes. Municipal wastes contain high number of plastic wastes, which really creates problem like choking of sewage systems.¹ When pyrolyzed the waste material generates a fuel oil which may be used in Internal Combustion (IC) engines. From child safety seats to credit cards, telephones to thermal underwear, and cars to computers, the medical industry, with gloves, prosthetic limbs, sutures, and beyond the packaging industry that accounts for almost one third of plastic produced in every year. This growth has caused a huge amount of plastic waste production. In this situation, research has been carried out to contribute to the development of cost-effective program methodologies on plastic waste in the world and conversion of this waste into diesel fuel. In this way a good amount of foreign currency may also be saved as the import of crude petroleum may

be reduced. There are various methods to overcome this problem. Blending of plastic with virgin material to some extent solves the problem. However, blending reduces the quality of the material; articles made from blended plastics will never retain the same elasticity and strength as those prepared from virgin plastic.¹ The main difficulty to the operation of plastic waste recycling is the in homogeneity of plastic wastes. Maximum recycling methods require a relatively pure feedstock containing only goods derived from a single form of polymer, such as high-density polyethylene (HDPE) commonly used to make milk pouches, bottles of polyethylene terephthalate (PET). Incineration generates a lot of obnoxious gases which pollute the atmosphere. Pyrolysis of waste plastic materials in presence of a catalyst may be one of the useful solutions to this problem.² Plastics are long chain polymers of hydrocarbons mainly, derived from by-products of the petrochemical industry and are effectively a non-renewable fissile based resource.

In general, municipal solid waste consists of HDPE, LDPE, polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET).¹⁻³ Fossil fuels also are of great concern today due to its declining resources. So, if depolymerized efficiently they may produce smaller size hydrocarbons which can be used as fuels. At a temperature above the ceiling temperature the polymers generally decompose into smaller hydrocarbons. Addition of catalyst enhances the conversion and fuel quality catalytic hydrogenation of polystyrene in solution in an organic solvent was studied by Roberts *et al.* using an agitator to produce other polymers like poly (vinyl cyclohexane) having higher glass transition temperature.⁴ They also hydrogenated poly (bisphenol-A carbonate) poly (ethylene terephthalate), polybutadiene and copolymers thereof, polyisoprene, copolymers thereof and obtained different products. Xu and coauthors also showed the phase equilibrium characteristics for hydrogenation of polystyrene using a heterogeneous catalyst suspended in a solvent swollen by supercritical CO₂.⁵ Rate of hydrogenation of polystyrene was found to be higher in this case than pure

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solvent. Hydrogenation efficiency is higher with boric acid compared to copper ion, silver ion or ferrous ion. Almeida and Marques reported the pyrolysis of polypropylene and polyethylene with and without addition of niobium oxide as catalyst in a glass reactor inside a furnace and observed polypropylene cracking happens at a lower temperature than polyethylene cracking.⁶ Most recently, Kremer and coauthors also showed catalytic cracking of mixed polymeric wastes followed by subsequent kinetic study of liquid products.⁷ Thermal feedstock pyrolysis begins with a random initiation to produce polymer radicals, but solid catalyst-based catalytic pyrolysis is initiated by the abstraction of H^+ from the reactants to form anionic intermediates called carbon ion.⁸ The surface O^{2-} ions of metal oxides catalyst abstract H^+ ion and this metal cations stabilize the carbon ion. The anionic species formations indicate the existence of an electron or electron pair donating sites on the surface. In addition, the basic catalyzed pyrolysis reaction is a related process to thermal pyrolysis. The C-C bond break occurs at the C-C bond located beta to the carbon atom with the unpaired electron, according to the empirical β law. The catalyzed pyrolysis occurring based on metal oxides are formation of isomerization, addition, decomposition, alkylation, and esterification.⁹

As per the recent literatures availability in the field of waste plastics to diesel production using batch or continuous process.^{7,9-11} Therefore, in view of the importance of the rapid depletion of fossil fuel and the environmental concerns that have led to an intense search for alternative fuels for internal combustion engines, a research programme has been undertaken to investigate the following aspects. Develop a process methodology of recycle the polymeric waste to liquid fuel that can be used in furnaces, diesel generators and vehicles. Improvement of different catalytic activity for a particular product. The aims of the present research were to renovate catalytically waste plastic using solid catalysts at comparatively low liquid hydrocarbon temperatures, such as liquid derivation in the boiling variety of fuel oil for profitable use. The strong solid acid catalysts in this study (Zeolite) and other catalysts for catalytic pyrolysis have been identified.

The present study on the effect of catalyst on plastic degradation temperature by thermo gravimetric analysis (TGA), FTIR analysis. Analysis of the product- characterization and testing and kinetic study were measured.

2. Materials and Methods

2.1. Experimental Procedure

There are various methods of plastics recycling: mechanical recycling, chemical recycling, and thermal recovery (Incineration). When decomposition process is

carried out in the absence of air it is termed as pyrolysis. Direct heating of the grinded polymer waste at 700°C to 800°C in the absence of air in a reactor is called thermal pyrolysis. In catalytic pyrolysis, feedstock is mixed with catalyst and heated in the reactor at the temperature of 400°C to 450°C . The lower hydrocarbons obtained are distributed over a small range and the method is economical with respect to thermal pyrolysis. The catalytic pyrolysis reactions happening over metal oxides are usually isomerization, addition, decomposition, and alkylation.⁸ In present study, Polymer waste coming from the laboratory waste plastic from institute level was collected. Waste was grinded to increase its bulk density and its proper melting. The mixture has been taken in a reactor, which is a cylindrical stainless-steel shell fitted with a perforated removable cover. The reactor has been placed inside the furnace tube which is fitted with a thermocouple well band heater. The thermocouple sensor was used to measure the temperature by means of the temperature controller through the wall of the stainless-steel pyrolysis reactor. Every batch consists of 1kg of laboratory waste plastic and 1% ZnO mixed-together. Every batch is fed into the reactor for 6–7 hours at the temperature 400°C and 1 atmospheric pressure.¹² The Schematic diagram experimental setup is shown Fig. 1.

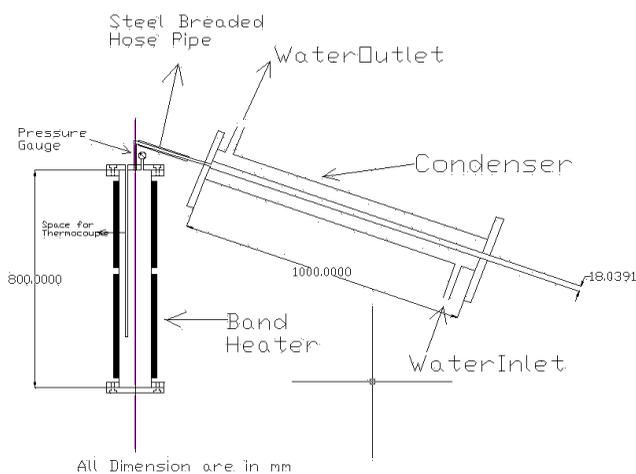


Fig. 1. Schematic diagram of plastic waste catalytic pyrolysis setup

The products coming out from the reactor have been cooled with the help of a condenser using ice-cold water. The condensed material has been collected in a storage tank by gravity settling. The oil type material left behind has been distilled under standard norms. The clean samples obtained after ASTM distillation have been analyzed to find out characteristics and the compositions. Tests have been performed with oil from plastic wastes along with diesel oil (in different proportions) in IC en-

gines under varying operating conditions to check its suitability. The experiments were repeated several times to ensure the reproducibility of the data. The waste solid as a wax material was collected from the reactor after finish of pyrolysis cycle. It can be use road making purpose substitute of bitumen. The nomenclatures of the different batch samples are shown in Table 1.

2.2. Kinetic Study

The TGA curves are compared to see the effect of catalyst in pyrolysis. Polymer and catalyst combinations were heated from room temperature to 400 °C at different heating rates of 3, 5, 10, and 20 °C/min in isothermally condition for two hours to blow unconverted fragments further by cracking with catalyst and/or thermal cracking.¹² The Ozawa method was used to estimate TGA data

from the experiments at 400 °C using various heating rates (3, 5, 10, and 20 °C/min). If it is assumed that a single n th-order response can model the reactions, the weight loss curve can be expressed as

$$\frac{-dw}{dt} = kW^n \quad (1)$$

It also results from the basic kinetics of the n th order used for collective isothermal tests with Arrhenius given in the following equation.

$$k = Ae^{-\frac{E}{RT}} \quad (2)$$

where k = reaction coefficient, E = activation energy, $\frac{-dw}{dt}$ = rate of reaction, w = weight fraction remaining at temperature T , n = order of the reaction.

Table 1. The nomenclature of the different batches of waste plastic samples

S.N.	Nomenclature	Details
1	B1	HDPE 1 kg waste+ 1% ZnO
2	B2	LLDPE 1 kg waste+ 1% ZnO
3	B3	PP 1 kg waste+ 1% ZnO
4	B4	HDPE+LLDPE+PP (1:1:1) 1 kg waste+ 1% ZnO
5	B5	HDPE+LLDPE+PS (9:10:5) 1 kg waste+ 1% ZnO
6	A1	LDPE 1 kg waste
7	A2	LDPE 1kg waste + 1% ZnO
8	A3	LDPE 1kg waste + 1% Alumina
9	A4	LDPE 1kg waste + 1% Zeolite based ZSM-5

2.3. Characterization

Thermo-Gravimetric Analysis (TGA) and Differential Thermo-gravimetric Analysis (DTG) were performed on a Shimadzu TGA/DTG analyzer (Shimadzu-DTG-60, Kyoto, Japan) analyzer in N₂ environment, at different heating rates of 3, 5, 10, and 20 °C/min at room temperature to 400 °C using platinum crucible. For each set of experimental runs, 10 mg of sample was used. Fourier Transform Infrared (FTIR) Spectrum of waste polymers/plastics was recorded in between 400-4000 per cm via Shimadzu (Corporation, Japan; IR-Prestige 21).

3. Results and Discussion

Materials used for this experiment are grinded HDPE, LLDPE, PP, and PS which are the waste of laboratory work. Different batches of feedstock are prepared by taking single and mixture of plastics. Three batches are prepared by taking individual plastic; batches 1, 2, and 3 are consisting of HDPE, LLDPE, and PP, respectively. Two batches of mix plastics are prepared. Batch 4 contains HDPE, LLDPE and PP in the ratio (1:1:1) and batch 5 contains HDPE, LLDPE, and PS in the ratio (9:10:5), respectively. The weight of each batch taken is 1kg and

amount of oil extracted in batch is shown in Table 2 and Fig. 2.

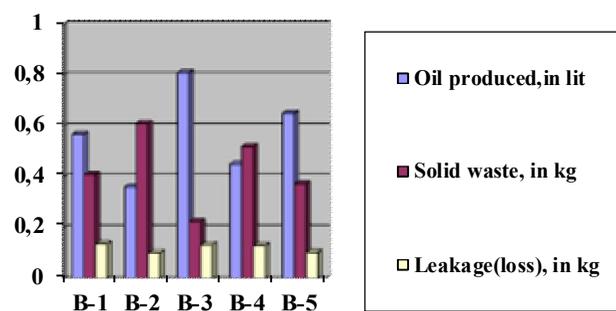


Fig. 2. Bar chart of products of various batches of oil prepared

These results indicate that the Batch B3 gives higher liquid product than other Batches. So, waste plastic of PP was better processing elements than other batch and its yield was higher. Similar study has been investigated by Shafferina *et al.*¹² Batch B2 has lower liquid contents and more solid waste formed. So, waste LLDPE produces lower yield than other batches experimentally observed by Shafferina *et al.*¹² Because LLDPE is not properly pyroly-

sis in same temperature than others and more waste solid produces. Gas lose are almost similar all the batches indicate smaller product of hydrocarbon generation are same.

3.1. Analysis of Waste Plastic Fuel

Various tests were performed using this fuel oil. The fuel properties of the oil ware are checked according to the

following methods and summarized in Table 3. All analyses were done using standard ASTM method and results obtained were compared with the existing commercial counterparts. The pyrolysis of waste plastic as a feed material in absence of oxygen and at around 250–300 °C has been reported.¹³ The enhancement in viscosity will typically influence the fluid to decrease the flow velocity.

Table 2. Amounts of oil extracted from different plastic waste samples

Parameters	B1	B2	B3	B4	B5
Initial mass (kg)	1	1	1	1	1
Liquid produced (L)	0.567	0.360	0.810	0.450	0.650
Solid waste (kg)	0.410	0.610	0.225	0.520	0.373
Gas leakage(loss) (kg)	0.137	0.102	0.134	0.130	0.103
Yield (L/kg)	0.567	0.360	0.810	0.450	0.650

Table 3. Various parameters of the oil product from waste plastic samples and others related studies

Samples	Required Values of Automotive Diesel fuel (IS 1460: 2017- Bharat stage VI)	B2	B1	B3	B4	B5	HDPE [19]	PP [19]	HDPE[16]	Sample
Tests										Test Method
Density at 37.8°C (g/cc)	0.810-845(at 15°C) [ASTM D 4052]	0.806	0.781	0.794	0.779	0.822	0.89	0.86	0.74	IP 131/57
Kinematic Viscosity at 37.8°C (cSt)	2.0-4.5(at 40°C) [ASTM D 7042]	1.59	1.30	1.52	1.23	1.49	5.08	4.09	1.98	ASTM D 445
Flash Point (°C)	35[ISO 3104]	12	12	12	9	9	48	30	15	ASTM D 93
Fire Point (°C)	–	17	17	17	15	15	–	–	20	ASTM D 93
Pour Point (°C)	3 °C-15 °C [ASTM D 97]	-2	-2	-2	-1	-1	-5	-9	<-15	ASTM D 97
Aniline Point (°C)	–	72	69	66	65	66	45	40	–	ASTM D611-12
API grav-ity	–	45.12	45.60	47.34	50.10	40.56	27.48	33.03	–	ASTM D 287-12
Ash Content (%)	0.01 [ASTM D 482]	0.02	0.03	0.04	0.02	0.02	0	0	0.03	ASTM D 48
Sulphur Content (wt. %)	0.01mg/kg [ASTM D 5453]	0.25	0.30	0.28	0.35	0.29	–	–	0.24	ASTM D 129-00
Carbon residue (wt. %)	0.30 [ASTM D 4530]	0.58	0.59	0.60	0.526	0.52	–	–	0.5	ASTM D189-65
ASTM Final Distillation Point	360 [ASTM D 7345]	268	270	266	249	262	–	–	–	ASTM
Calorific Value (Kcal/kg)	–	8502.9	8602.8	8500.1	8509.9	8688.0	9642.8	9714.2	9828.35	Bomb calorimeter 12/58

One of the significant characteristics of the fuel is the flashpoint, fire point, to avoid fire hazard during storage. Pour point is the temperature at which the tested oil ceases to flow. If the fuel has a lesser pour point, it has smaller paraffin composition but larger aromatic content.¹² The flash point of pyrolysis oil of all batches was very close to commercial diesel. Anantha Kumar and coauthors have studied the pyrolysis of waste plastics without atmospheric pressure.¹⁴ The ASTM distillation final boiling temperatures and physiochemical properties of the conventional diesel fuels are given in Table 3.

Kumar and coauthors also investigated the performance and emission analysis of blends of catalytic pyrolysis waste plastic oil with diesel in a IC engine with changing loads and they reported the physico-chemical parameters of the tested fuels are as follows: fuel density (0.83 g/cm^3), viscosity ($2.58 \text{ mm}^2/\text{s}$), and gross calorific value (43.8 MJ/kg) of the diesel as control fuel, while those of waste plastic oil are density (0.79 g/cm^3), viscosity ($2.1 \text{ mm}^2/\text{s}$), and gross calorific value (40.18 MJ/kg), respectively.¹⁵ The calorific values, density, kinematic viscosity, aniline point of plastics oil is lower than diesel, so pyrolytic oil has lower aromatic content.¹² The Product obtained all batches flash point and fire point lower than results are obtained by Khan *et al.*,¹⁶ which indicates that these are not easy to handle, and the product has more volatile components. The product pore point is higher than the literature data, so it is suitability for oil for low temperature installation. The sulphur content in the product oil is slightly higher than pure diesel. So, more so_x emission that is an environmental issue and the ash contained of oil is non-combustible residue. The ash contained is slightly higher than pure diesel¹² as waste plastic contains some contamination. The carbon residue is slightly lower than pure diesel. So, it indicates the tendency of oil to depo-

sit a carbonaceous solid residue on oil injection nozzle in engine when its vaporizable constituents evaporate is lower than pure diesel. Density and viscosity of the present study oil is close to the density of pure diesel. Other researchers also showed the densities of liquid fuels product from HDPE, PS, and PP as 0.80 , 0.90 , and 0.81 g/cm^3 , respectively¹⁷ and also the kinematic viscosities of pyrolytic fuels product from HDPE, PS, and PP have been shown as 2.373 , 1.461 , and $2.115 \text{ mm}^2/\text{s}$, respectively.¹⁷ So, it may be replaced by plastic pyrolysis oil. In ASTM final boiling point (FBP) is slightly lower than diesel oil. So, in present study the oil in all batches has some lighter fraction of hydrocarbon present than diesel.¹² Calorific value is defined as the energy given out when unit mass of fuel burned entirely in air. Calorific value is also slightly lower than the literature data.

3.2 Thermo gravimetric (TGA) Analysis

TGA curves of PP and PP with 1 % ZnO of waste plastics are exposed in Fig. 3. The two plastic wastes are studied under dry condition with lesser weight loss of moisture in the early stage, therefore all the plastic waste TGA presented in Fig. 3 is certain form above $100 \text{ }^\circ\text{C}$. For polymer waste degradation is mixed with 1 % ZnO in HAAKE Rheocord 9000 mixture at $210 \text{ }^\circ\text{C}$ of 5 minutes.¹² Pure sample is also analyzed in TGA to see its degradation temperature with same condition.¹⁸ The TGA curves are compared to see the effect of catalyst in pyrolysis in the temperature range between 345 to $500 \text{ }^\circ\text{C}$, as shown in Fig. 3.

From Fig. 3 it can be easily seen that catalyst action in this pyrolysis is to decrease the degradation temperature and when we added the zinc oxide the degradation temperature decreases of waste plastics.¹⁹ It has been seen from data that ZnO decrease the degradation temperature from 375 to $345 \text{ }^\circ\text{C}$.

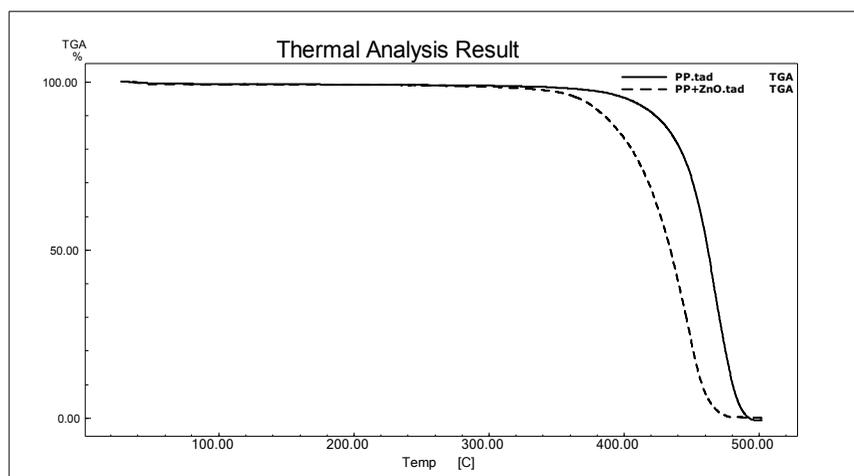


Fig. 3. TGA curve of PP and PP with catalyst of 1 % ZnO

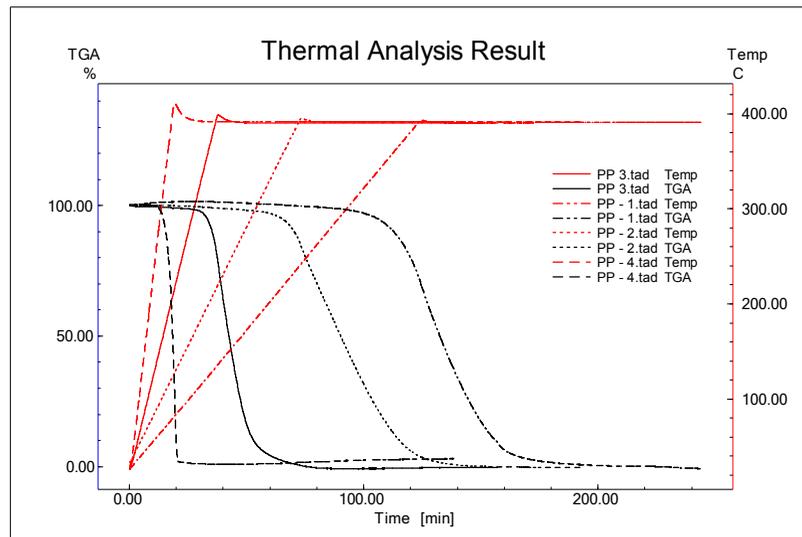


Fig. 4. TGA curve of PP at different heating rate

The thermal kinetics of PP waste plastics starting from room temperature to 400°C, with heating rate of 3, 5, 10, and 20°C/min using of TGA curves are shown in Fig. 4.

The sample was studied without moisture content with minute reduction of weight of moisture on the start, therefore all plastic waste material TGA exhibited in Fig. 4 are chosen from more than 100°C. It is usually accepted that the pyrolysis procedure PP includes three main levels. At starting level, the weight remains constant because of dry plastic wastes.¹⁸ Meanwhile the pyrolysis response is mainly volatile, and the volatile composition of PP is very less amount. The 2nd stage generally comprises varied burning of volatile and fixed carbon and amount reduction occurs rapidly. The plastic waste completely burns in the last level and the remainder is ash.¹⁸ At the transitional level, volatile and fixed carbon compositions in the main structure of PP began to burn in the range of 45–425 °C.²⁰ As the heating rate increase the time taken for pyrolysis decreases continuously.

3.3 Effect of Heating Rate

Combustion curves of PP and PP with 1 % ZnO of waste plastics are exposed in Fig. 5.

The waste plastic sample are studied with dry basis with minor weight reduction of moisture on the start, thus all TG-DTG curve seen in Fig. 5 are chosen from above 100 °C. The TG curves of PP and PP with ZnO have mutual performance, and the DTG of these plastic waste show single peak rate.²⁰ It is usually believed that the combustion procedure PP and PP with ZnO contains three major stages. At the first stage, the weight remains essentially unaffected and no humidity due to dry plastic wastes. Meanwhile the combustion response is mainly

volatile and the volatile composition of PP and PP with zinc oxide is less amount. The second phase mostly comprises mixed burning of volatile and fixed carbon and weight loss occurs rapidly. The plastic waste completely burns in the tertiary stage and the remainder is ash. Though the DTG representation of PP and PP with ZnO have sole peak rate, these DTG curves have a clear variance in the shape because of their structural variances.¹⁹ The peak of PP is high-pitched and elevated exothermicity, whereas the peak of PP with ZnO is widespread and less exothermicity in nature. In case of PP, first peak on 174.77 °C with heat is -0.477 KJ/gm, second peak on 467.48 °C with heat is -4.07 J/gm, respectively and in case of PP with 1 % zinc oxide, first peak on 168.27 °C with heat is -0.529 KJ/gm, second peak on 446.05°C with heat is -0.529 KJ/gm, respectively and both have exothermic reaction nature.²⁰ At the transitional stage, volatile and fixed carbon compositions in the main structure of PP and PP with ZnO started to burn in the range of 188–495 °C, and 179–475 °C, respectively.¹⁸ The initial peak appears (less than 100 °C) because of moisture removal, which indicates the endothermic progression.¹⁸ Observation of high temperature on waste plastics above 600°C could not become possible; though, TGA investigation established the fact that all the studied waste plastics were degraded under endothermic region.

3.5 Thermal Kinetics of Waste Plastic

Linear regression was utilized for simple, one-stage procedure, while multivariate nonlinear was utilized for complex, multi-stage procedure composed with statistical studies.

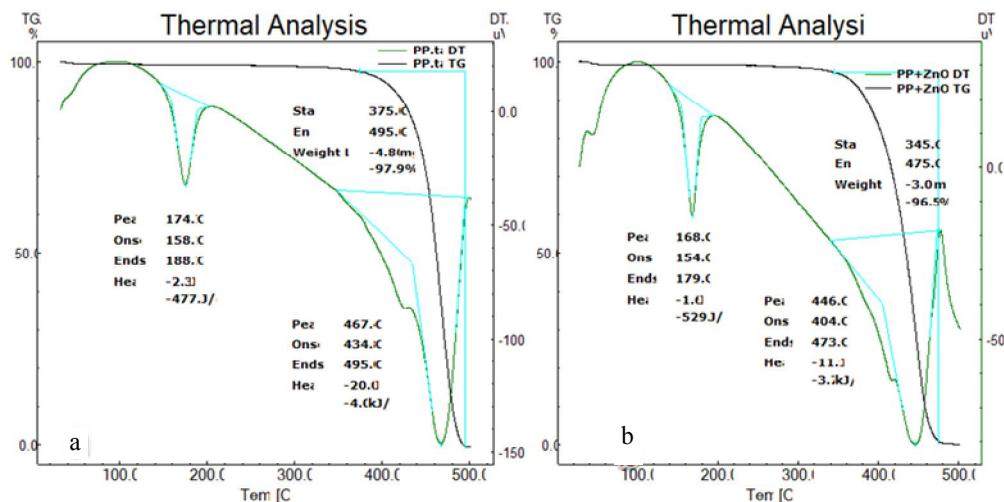


Fig. 5. TGA/DTA curve for (a) pure PP and (b) PP with catalyst of ZnO (1 %)

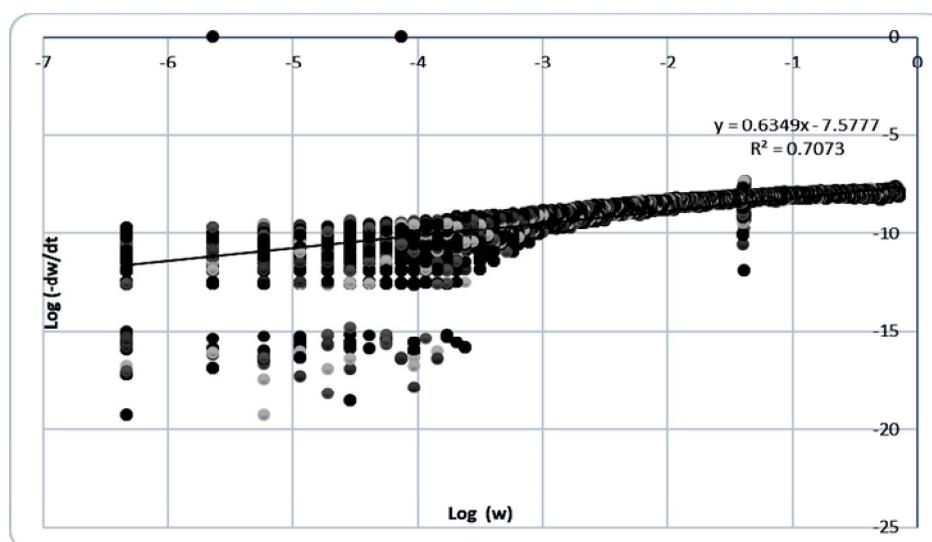


Fig. 6. Plot of $\log(-dw/dt)$ vs. $\log(w)$ for sample heated at the heating rate $5^\circ\text{C}/\text{min}$ up to 400°C

From Fig. 6 are using for the order of reaction are to be $n=0.7572$ and other case obtained $n=0.6482$, $n=0.6349$, $n=0.875$, and it is observed that with change in heating rate there is a change in order of reaction but the order of reaction has not deviated much far at lower heating rates of $3^\circ\text{C}/\text{min}$, $5^\circ\text{C}/\text{min}$, but there is noticeable increase in the order of reaction at the heating rate of $10^\circ\text{C}/\text{min}$ and $20^\circ\text{C}/\text{min}$ although the order of reaction in all the cases should have come approximately equal since the data recorded to determine the order of reaction was taken at $400 \pm 10^\circ\text{C}$.²⁰ Assuming this approximation we can determine an average order of reaction, which is found to be 0.7288 . Similar trend has been observed by Kremer *et al.*⁷

3.6 Analysis of the Distillation Curve

Distillation is the method of separating a liquid mixture according to its volatility into its components. The preliminary boiling point (PBP, $^\circ\text{C}$) is calculated in this process to create the first distillation drops of oil in which the temperature appears. The final boiling point (FBP, $^\circ\text{C}$) is that temperature at which the distillation chamber's entire oil sample disappears.¹²

The ASTM distillation curves plotted (Fig. 7) according to the experiments carried out on the oil obtained from the pyrolysis of the various batches as mentioned before and commercially available fuel oils like diesel and kerosene are shown above. It can be clearly observed that the distillation curves of the oil obtained from the polymer

wastes lie below the distillation curve for diesel, and the distillation curve for kerosene passes intersecting all the curves for the oils obtained from polymer waste. To separate the lighter hydrocarbon and the heavier hydrocarbon fraction present in waste plastic liquid fuel, distillation is performed. In this operation IBP of all batches is lower than pure diesel and kerosene. The product obtained from pyro-

lysis of waste plastic more has volatile component.^{16,21} But final boiling point of all batches are more than pure kerosene and less than pure diesel. Hence, the product is more suitable to blend with diesel and heavier hydrocarbon fraction present in all batches of waste plastic liquid fuel lower than pure diesel. Mostly all the product same as diesel oil are shown in Table 4.

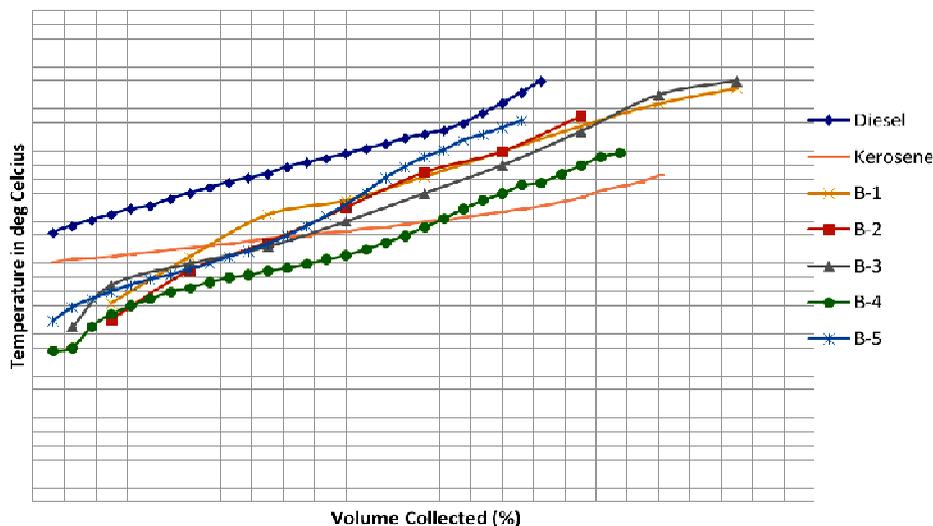


Fig. 7. ASTM distillation curve for the oil collected from the pyrolysis of plastic waste

Table 4. Liquid fuel collected from the pyrolysis from plastic waste

Batch	Oil content with higher boiling fraction than kerosene in percentage	Oil content with higher boiling fraction than diesel in percentage
B-1	77.5	0
B-2	67.5	0
B-3	70.0	0
B-4	47.5	0
B-5	67.5	0

Table 5. Analysis of the product using different catalyst and different oil samples

Parameters	A1	A2	A3	A4
Initial mass (kg)	1	1	1	1
Liquid Produced (Lit)	0.430	0.470	0.450	0.520
Solid waste (kg)	0.430	0.388	0.408	0.339
Gas Leakage(loss) (kg)	0.140	0.142	0.142	0.141
Yield (%)	43	47	45	52
Test of oil result of different sample using different catalyst				
Density at 37.8°C (g/cc)	0.8064	0.781	0.794	0.7792
Kinematic Viscosity at 37.8° C (cSt)	1.59	1.30	1.23	1.61
Aniline Point (°C)	72.0	69.0	66.0	65.0
API	43.97	49.67	46.7	40.22
Pour point (°C)	-2.0	-2.0	-2.0	-3.0
Calorific Value (kcal/kg)	8505.9	8630.0	8750.7	9009.79

These outcomes show that the larger percentage of hydrocarbon present in the pyrolysis liquid oil than kerosene and lesser than diesel. So, the conservative fuel like diesel oil may be replaced by plastic pyrolysis oil in all Batches.

3.7. Catalyst Activity of Product

Many researchers have used the catalyst for enhancement of the quality of product to improve the hydrocarbon supply to make the pyrolysis of waste plastic a substitute of conventional fuel such as diesel. Material used for this experiment is LDPE which is waste of laboratory and processes are same as before. Different batches of feedstock are prepared by taking single of plastics and different catalyst. Four batches are prepared by taking individual plastic and different catalyst, batches A1, A2, A3 and A4. Batch A1 is thermal cracking without catalyst at 550–600 °C and at atmospheric pressure.¹² Analysis of all products obtained are shown in Table 5 and Its oil characterization was achieved as shown in Table 5 and test method are similar as before.

Zeolite based oil has higher calorific value and much more liquid forms than for other catalyst. The major pyrolysis catalyst like Zeolite, SiO₂, CaO, and Al₂O₃ are used because of dropping the temperature and are necessary to complete the reaction and enhance the reaction speed.²² In this study, Batch A2 to A4, each case 1 kg LDPE and different catalyst was used. These results indicate that the Batch A4 gives higher liquid product than

other Batches. So, Zeolite based ZSM-5 gives better liquid product than ZnO and Al₂O₃ catalyst.⁹ Garfoth *et al.* also studied the effective pyrolysis of HDPE with different catalysts such as HZSM-5, HUSY and HMOR with polymer and it was found that HZSM-5 had higher catalytic activity than HUSY and HMOR.²³ It proves that the different selectivity and similar trends was observed by Lin and Yen on PP pyrolysis using the HZSM-5 and HUSY.²⁴ Batch A1 has lower liquid contents and more solid waste formed than other batches. As, it is only thermal cracking occur. Comparing the results, catalytic pyrolysis is better than thermal pyrolysis and the calorific value of plastic pyrolysis oil based on Zeolite based ZSM-5 catalyst is higher than other catalyst that is ZnO and Al₂O₃ catalyst. Similar study has been conducted by Wong *et al.*⁹ Density, viscosity, pour point are comparatively similar.^{16,21} It can be suitable for replacing the conventional diesel oil for IC engine test.

3.8. Fourier Transform Infrared (FTIR) Analysis

FTIR is an important analysis technique that detects various characteristic functional groups present in oil obtains ZSM-5 catalyst (A4) was shown in Fig. 8.

The peak at 1639 cm⁻¹ can be assigned to physisorbed water. The following peaks at 1373 cm⁻¹ and 1303 cm⁻¹ can be observed due to water deformation vibrations (–OH). The different functional groups with various wavenumbers are shown in Table 6.

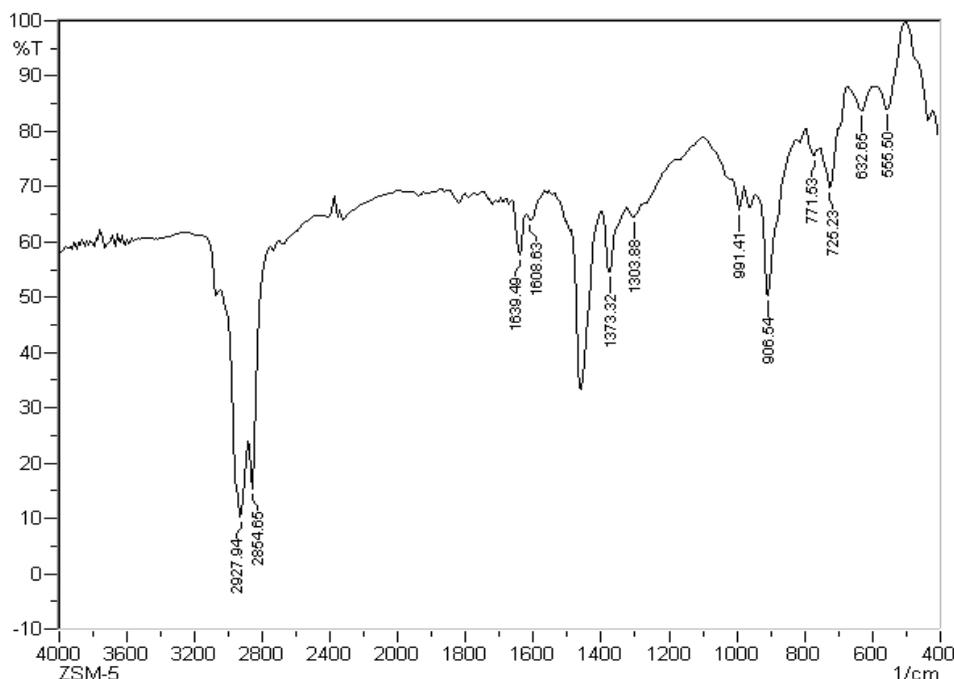


Fig. 8. FTIR spectra for fuel obtained with ZSM-5 catalyst (A4)

Table 6. Various functional groups corresponding wavenumber in waste plastic samples

SN	Wavenumber (per cm)	Functional groups
1	2927.94	C-CH ₃
2	2854.65	
3	1639.5	Conjugated
4	1639.63	
5	1373.32	CH ₃
6	1303.88	
7	991.41	-CH=CH ₂
8	906.54	
9	771.53	-CH=CH-(cis)
10	725.23	
11	632.65	

Table 7. The fuel product from HDPE (B1) in various compositions with the diesel oil

Brake power (Watts)	Input Thermal Power (Watts)	Thermal Efficiency (η_{th}) %	Brake-specific fuel consumption, BSFC (g/s · 10 ⁻⁴)
Engine characteristics with 100 % diesel			
794.225	5285.51	15.03	1.48
1588.45	6490.98	24.47	0.94
2223.83	7115.11	31.25	0.74
2859.21	9249.64	33.94	0.66
3494.6	10571.03	33.06	0.7
Engine characteristics with 90 % diesel & 10 % fuel oil from plastic			
794.225	4741.13	16.59	1.39
1588.45	6187.57	25.43	0.91
2223.83	7301.34	30.16	0.77
2859.21	8489.93	33.36	0.70
3494.6	10140.75	34.13	0.68
Engine characteristics with 60 % diesel & 40 % fuel oil from plastic			
794.225	4865.41	15.69	1.46
1588.45	6255.53	24.41	0.94
2223.83	7453.40	28.68	0.80
2859.21	8544.14	32.17	0.72
3494.6	10303.23	32.61	0.7
Engine characteristics with 75 % diesel & 25 % fuel oil from plastic			
794.225	4769.18	16.25	1.42
1588.45	6167.04	25.14	0.92
2223.83	7451.84	29.13	0.79
2859.21	8492.21	31.21	0.74
3494.6	10520.25	32.42	0.71

Different absorption peaks in waste plastics such as 2927 and 2854 cm⁻¹ are the C-CH₃ energy functional groups, 1639 and 1639 cm⁻¹ are the conjugated, 1373 and 1303 cm⁻¹ are the CH₃ functional groups, 991 and 906 cm⁻¹ are the -CH=CH₂ functional groups, 771 and 725 cm⁻¹ are the -CH=CH-(cis) functional groups, respectively.

3.9. IC Engine Test for Obtained Liquid Fuel

The fuel was obtained from HDPE (B1) plastic waste feeding in tubular reactor with catalyst 1 weight percentage zinc oxide at temperature of 350-400°C for 6 hours at atmospheric pressure. In this procedure, the dif-

ferent amount of liquid fuel and tested consuming it in the IC machine. Diesel IC machine have been tested for a four stroke, single cylinders and air-cooled.¹² The physicochemical properties of tested liquid fuels are as shown in Table 3. The fuel obtained from B1 is defined as quantity of fuel spent to create a unit break power for one hour. Mani *et al.* have found the liquid fuel by using waste plastics with 1 weight percentage catalyst and 10 weight percentage coals at 300-400°C for 3-4 hours.²⁵ In present study, it is observed from trial of pure diesel blends that specific fuel consumption for 90 % diesel and 10 % fuel oil from plastic, with 60 % diesel and 40 % fuel oil from plastic, and with 75 % diesel and 25 % fuel oil from plastic (Table 7).

Oil can be used as an alternative of diesel fuel oil. Blending of waste plastic recycle oil at different percentage with pure diesel have similar thermal efficiency in same power input (range: 794.26 to 3494.60) of IC engine. In comparison with other blending with 90 % pure diesel and 10 % fuel oil from plastic have more thermal efficiency and lower specific fuel consumption. The specific fuel consumption of the diesel engine must be lower to attain high performance.¹² All these data show that the fuel oil obtained from waste plastic is suitable for diesel engines having characteristics not much different from diesel oil. It is easily noted that diesel has more fuel consumption in its sole form than the blended form. So, for the automobile vehicles, blend of 10% fuel oil from plastic with 90 % diesel is recommended for IC engine.

4. Conclusions

Successful catalytic pyrolysis has been carried out with different types of waste plastic in batch tubular reactor. From FTIR analysis technique that detects various characteristic functional groups present in fuel obtained *via* (A4) catalyst were seen peak at 1639 cm⁻¹ can be assigned to physisorbed water, peaks at 1373 cm⁻¹ and 1303 cm⁻¹ can be observed due to water deformation vibrations (-OH). Yield of the fuel obtained from catalytic pyrolysis of PP based waste plastic (B3) was around 81 %; it has reasonably high calorific value (8500 kcal/kg) in comparison to other plastic waste materials, while yield of fuel obtained from LDPE based waste plastic (A4) was around 52 %, which is greater than others and it has higher calorific value (9009.8 kcal/kg) in comparison to other metal oxide catalyst. Oil obtained using Zeolite based ZSM-5 catalyst has higher calorific value. Finest result is obtained by blending this oil with diesel and 10 % blending of this oil with diesel is the best for IC engine.

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ПІРОЛІЗ ПЛАСТИКОВИХ ВІДХОДІВ З ПЕРЕТВОРЕННЯМ НА ПАЛИВО ДЛЯ ВИКОРИСТАННЯ В ДВИГУНАХ ВНУТРІШНЬОГО ЗГОРЯННЯ

Анотація. У цьому дослідженні різні пластикові відходи різноманітних типів пластмас, таких як поліетилен низької густини та поліпропілен, піддано піролізу в трубчастому реакторі періодичної дії з каталізатором оксидом цинку. Пластикові відходи охарактеризовано за допомогою ТГА та ДТГ аналізу, а також ІЧ-спектроскопії. Продукти піролізу аналізували стандартними методами для визначення різних параметрів.

Ключові слова: пластикові відходи, паливо, термогравіметричний аналіз, каталіз і кінетика, внутрішнє згоряння.