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Study design and implementation of a pyrolysis device for the production of fuel and gas from plastic waste

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Abstract

In this study, a local pyrolysis system was created to recover oil from used polypropylene (PP) plastic waste for the production of fuel and gas. The system was initially tested with two kilograms of waste plastic for three hours. This technique displays various sustainable development in terms of energy, using gas as the primary source of heat and using gas created throughout the process as a secondary or auxiliary source to hasten the decomposition process. The reactor chamber's original size could not support the pressure needed for the pyrolysis process. The second experiment was modified to have the following dimensions: height (30 cm), diameter (15 cm), and thickness (5 mm) resulting in a volume of 5301.44 cm3. A volume of one liter of liquid fuel, grease, and gas in various percentages of 80%, 10%, and 10%, respectively, was produced from one kilogram of type (PP) waste. Additionally, the heat pressure inside the chamber rises as the pyrolysis breakdown temperature grows. The research recommends utilizing catalysts in the pyrolysis of (PP) production to reduce the temperature necessary to break the bonds between hydrocarbon molecules. It is necessary to carry out an isolation process for plastic waste before the pyrolysis process. It is preferred to physically treat plastic waste, such as shredding and cutting it into little pieces before using it and depositing it in a pyrolysis device, while also adhering to occupational safety and security regulations.

Keywords: Fuel; Plastic waste; Polypropylene; Pyrolysis; Thermolysis; Useful energy

1 Introduction

The increasing demand and high price of energy sources are driving efforts to convert organic compounds into useful hydrocarbon fuels. Although most of this work is focused on biomass, there are strong benefits to deriving fuels from plastic waste.

Waste plastics are abundant and their disposal by traditional methods creates major problems for the environment. Plastic does not decompose in landfills, cannot be easily recycled and its quality decreases during the recycling process. It also produces ash, heavy metals, and potentially harmful gas emissions if it is burned at high temperatures. However, high-temperature thermal processes can be used to convert plastics into hydrocarbon fuels such as gasoline, diesel, and jet fuel, which have unlimited applications in the airline, helicopter, heavy transport, and electricity generation industries [1].

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2 The importance and objectives of the research work

The scientific and technical development in dealing with solid waste has led to reconsider the tons of waste that are produced daily by material civilization and to consider it as an alternative source of energy. There are a variety of products that use plastic materials. as a result of the increase in the level of private consumption of these plastic materials, a large amount of them are discharged into the environment. This trend makes pollution constantly increasing, as the environmental problems of waste accumulation extend beyond annoying odors and bad views to the leakage of toxicities, which create fertile environments for the spread of many diseases and epidemics. This is in addition to the increase in carbon dioxide emissions through burning fossil fuels during waste disposal processes or through direct emissions of methane, ammonia, and sulfur dioxide from waste, which contributes to the deepening of global warming.

For this, the initiative was to find solutions to manage these accumulated and unceasing quantities of plastic waste by sorting and studying its various components and understanding the extent to which some of these components can benefit, either through reuse and recycling or by treating some components to produce energy.

To turn waste from a source of ecosystem pollution into usable energy, the concept of energy generation from waste is based on the physical and chemical processing of solid waste to produce electrical or thermal energy [2]. This is because the waste volume has increased globally due to a rapid increase in population and a change in people's lifestyles.

3 Theoretical study

3.1 Elastic material (plastic)

Plastic is divided into many types that can be shortened into two main types: hard plastic and thin film plastic.

In the last four decades, the percentage of plastic materials in household waste has increased, especially after the discovery of polymeric materials such as polyolefin and polystyrene, which replaced other packaging materials (paper, metal sheets, and glass containers). This is due to the excellent specifications of polymers as typical packaging materials. It is suitable for packing all types of materials, resistant to weather conditions, resistant to irritating materials, and causing metal corrosion. It is a flexible plastic that does not break easily like glass. In addition, polyethylene (LDPE) is light-density, transparent and cheap. Recently, the concept of energy recovery from hard plastic solid waste has been a very important topic. It is also undesirable to landfill plastic waste due to poor biodegradation. An alternative strategy is chemical recycling known as feedstock recycling which has attracted a lot of attention recently to convert waste plastics into basic petrochemicals for use as chemicals or fuels for a variety of businesses [3, 4].

3.2 Classification of plastic

Plastics can be classified into two categories

- Thermoplastic can be easily recovered by melting. This category mainly includes light and high-density polyethylene used in the manufacture of milk containers, polyvinyl chloride (P.V.C) used in the manufacture of mineral oil and water bottles, and finally polystyrene.
- Most plastic materials contain between (100 - 20,000) units or more that are characterized by their formability at a temperature of (100 - 200) C°, moldability, and insulation [5].
- Non-thermal degradable plastic: This category includes the rest of the plastic materials that cannot be re-molded, as they consist of compounds with a network connection to each other in a solid form, meaning this category is not recoverable and must be isolated from thermoplastic [6].

The recovery of plastic materials is not only an economic issue because it also contributes to the preservation of raw materials and saves money spent to dispose of waste uselessly, and also contributes to protecting the environment. The first recycling that turns plastic waste into plastic results in products that have properties similar to the original plastic, and the second recycling results in products with lower quality (poor) physical and chemical properties than the original plastic.

Recycled plastics are globally prohibited from being used in food packing and packaging. Nevertheless, they can be used to manufacture shoe soles and others because of the pollutants that can be stuck in them. Plastic is a material composed mainly of polymers, which are large molecules made of units called monomers, as shown in Figure (1).

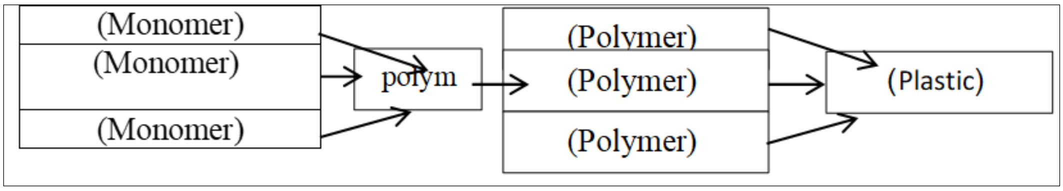


Figure 1 Plastic composition

3.3 Pyrolysis technology

Pyrolysis technology offers to turn different types of plastic waste into clean fuels with an ultra-low sulfur content that meets the most stringent international standards while not emitting toxic gases such as dioxins and other secondary pollutants.

3.4 Existing commercial pyrolysis technologies and processes

Plastic pyrolysis plants have been developed and built in many countries. The choice of pyrolysis technology depends on the characteristics of the raw materials and target products in general. Each pyrolysis technology consists of three parts feeding system, pyrolysis reactor, and separation system [4] (See Figure (2)).

3.4.1 Feeding system

In most commercial processes, the raw materials are first heated and melted in the feed system before flowing into the reactor. Air, moisture, and other solid materials can be separated from the raw plastic materials in the feeding system. Additionally, pretreatment may be required to crack the PVC at 250°C.

In some rotary kiln reactors, solid plastic particles of appropriate sizes can be extruded directly into the reactor. Most feed systems transfer highly viscous plastics to reactors by gravity or an extruder. However, the required temperature gradient from the feed to the pyrolyzer must be maintained although this may not be a problem for rotary kiln reactors, the required temperature gradient is to prevent plastic cracking before entering the pyrolyzer. A free-fall feeding system is widely applied in fixed and fluidized bed reactors [7].

3.4.2 Thermolysis

The continuous pyrolysis process is applied to most commercial plants with the ability to use catalysts in which the retention time of the plastic is relatively short.

Very few commercial plants use a high-pressure operating condition and most plants operate at atmospheric pressure or slightly above. Operating temperature in reactors varies greatly from 250°C (Mazda fixed bed catalyst process in Japan) up to 800°C (pressurized bed static pyrolysis in the UK) but most pyrolysis reactors operate between (400 - 550)°C percentage.

It should be noted that if the operating temperature is above 800°C, the process becomes gasification and the products are mainly short chain hydrocarbons which remain as gases under room temperature and atmospheric pressure. Using rapid pyrolysis, reactors can be operated in three technologies: stationary bed, fluidized bed, and rotary kiln.

3.4.3 Separation and collection of the product:

Plastic pyrolysis products are mainly flammable gases and liquids. Fluids can be burned for power generation or subjected to further refining to produce higher-quality fuels. The products of the diesel group can then be distilled as in the oil refining process. Non-condensable gases consist mainly of hydrocarbons and a small amount of hydrogen and carbon monoxide. The gases can be liquefied as fuel, or used as fuel to heat the pyrolysis reactor, or if the amount is not important, the non-condensable gases are sent to an incinerator burning with air.

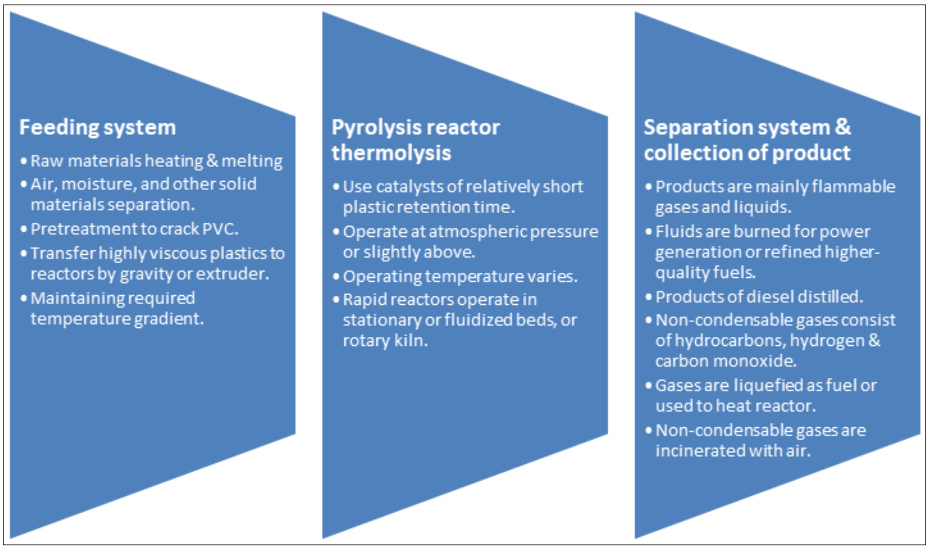


Figure 2 Pyrolysis technology parts

According to Bow and Pujiastuti's research, [8] higher heating temperatures in the reactor result in higher yield rates, liquid product densities, and volumes with higher specific gravities. In contrast, API Gravity, Heating Value, and Flash Point decrease with increasing temperature.

4 Research materials and methods

4.1 Devices used

A locally designed pyrolysis device was used, and it consists, as shown in Figure (3), of the following:

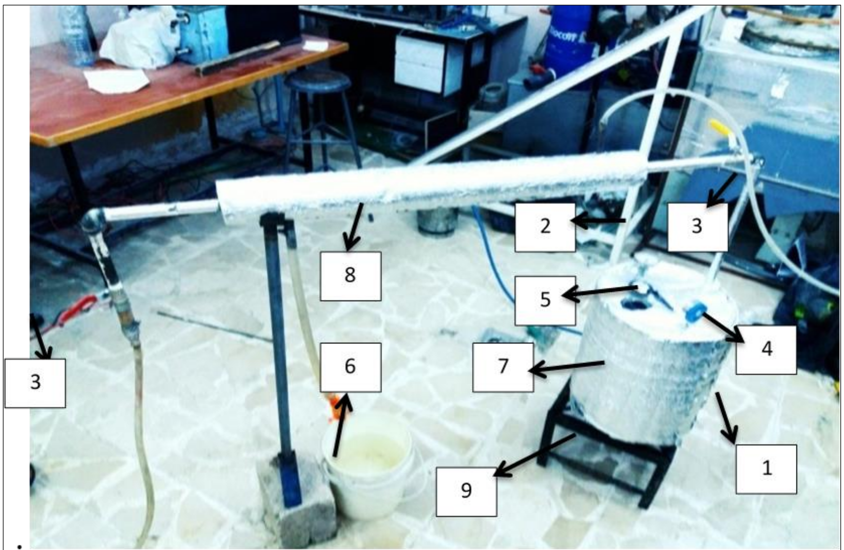


Fig. (3): The locally manufactured pyrolysis device

Key			
1) Combustion chamber (reactor)	2) Tubes for transporting gases	3) Shut-off and opening valves	4) Thermal clock
5) Pressure clock	6) Condensate liquid receiving chamber	7) Thermal insulation (glass wool	8) Condenser
9) The stove			

Figure 3 The locally manufactured pyrolysis device

The dimensions of the combustion chamber were chosen as follows: Height (50 cm), diameter (35 cm), and thickness (2 mm) to give a volume of 48105.64 cm^3.

The condenser (heat exchanger) was chosen: with the parallel flow, as the direction of the two fluids is in the same direction as in Figure (4).

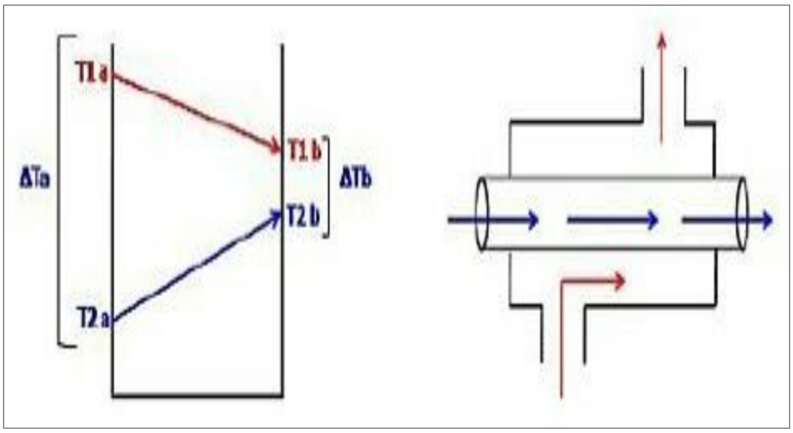


Figure 4 Parallel Flow Exchanger

The dimensions of the condenser were chosen as follows: Diameter of the inner tube of the condenser (gas carrier): 0.5 inches, and the length of the inner tube of the condenser (carrier of gas): 1.5 m.

4.2 Research Methods

Polypropylene (PP) was used as a raw material (waste plastic) to extract fuel through the pyrolysis process.

Where fuel is produced based on the following stages (See Figure 5):

First stage: pretreatment and pellet production. The pretreatment includes coarse shredding and removal of non-combustible materials such as metals and chlorine-containing plastics.

The second stage: is the pyrolysis process, which is the conversion of plastic to liquid fuel (pyrolysis at 150-300 ° C, using an inert gas such as nitrogen) and the condensation of the resulting hydrocarbons.

The third stage: is gas condensation, where the resulting oil (a mixture of liquid hydrocarbons) is continuously distilled once the plastic waste is decomposed inside the reactor. The boiling point of the produced oil is controlled by the operating conditions of the reactor and condenser. After the hydrocarbons are distilled from the reactor, hydrocarbons with high boiling points such as diesel, kerosene, and gasoline are condensed in a water-cooled condenser. The liquid hydrocarbons are collected in a storage tank.

- Gaseous hydrocarbons such as methane, ethanopropylene, and butane cannot be condensed. Thus, they are burned for use as a heat energy source for the reactor or collected in collection tanks for utilization. These stacks are necessary when the volume of exhaust gas emitted from the reactor is large.
- Fourth stage: filtration and purification the fuel collected in the assembly chamber, such as wax and grease, which is not clean, contains impurities. Therefore, to remove the impurities, the following processes were carried out: gravity separation, and filter paper filtration.
- Gravity separation: the liquid is poured into a vessel whose bottom is like a funnel. Therefore, when the liquid is poured, the denser liquid probably settles below where the waxy and grayish substance that was pale greenish yellow was found just above the water. Finally, most of the polypropylene oil appears above the upper layer. Then by opening the valve at the bottom all unwanted substances are removed.
- In the filtering process: Substances that are in a colloidal state can be removed as the filter paper allows particles that are smaller than its pores to pass through. Thus, the small pores of the filter paper used will give a cleaner fuel.

The fifth stage (gas collection): The resulting non-condensable gases are collected during the operation of the reactor. Likewise, gases can also be used instead of being collected for the pyrolysis process as a substitute for fuel.

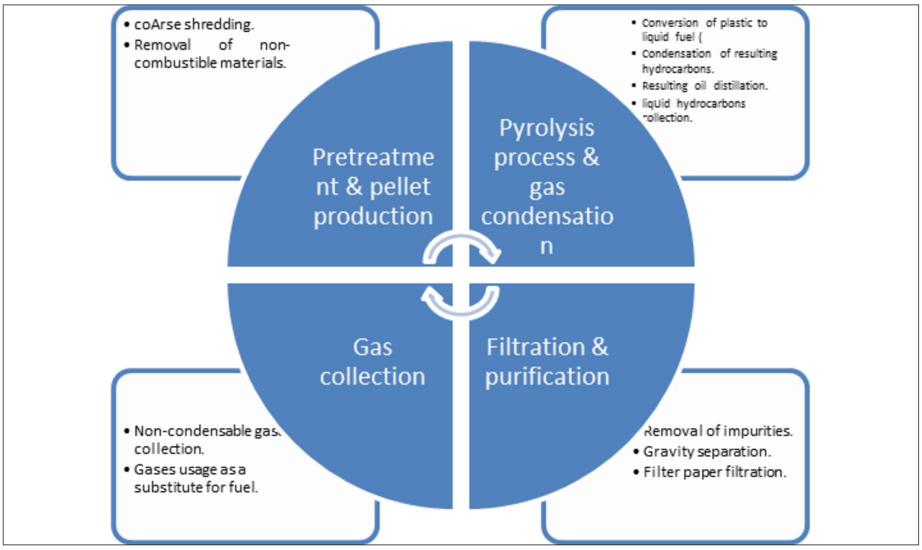


Figure 5 Stages of fuel production

5 Results and discussion

PP plastic waste was used in an amount of 2 kg, and the experiment took a thermal decomposition time of 3 hours. a heat source was used in the experiment and the proportions of the products of the polyethylene pyrolysis process were: a) Gas as a primary source for the thermal decomposition process and b) The gas produced from the thermal decomposition process is complementary or auxiliary to the decomposition process, meaning that this technique is characterized by sustainable development in terms of energy, where the resulting gas is used as an alternative to butane gas as a source of decomposition energy. The amount of liquid fuel obtained using the previous reactor chamber is V= 0 ml, and the amount of gas produced as a percentage is M=100%. This is consistent with Syamsiro's [9] findings that municipal plastic trash has better heating value solid products than biomass and low-rank coal.

5.1 Summary of the previous chamber pyrolysis process:

The reactor chamber used did not help to withstand the pressure necessary for the pyrolysis process to produce liquid fuel. Thus, it was modified in terms of dimensions in the second experiment, such that the height became (30 cm), the diameter (15 cm), and the thickness (5 mm), giving a volume of 5301.44 cm^3.

In the pyrolysis process, after adjusting the dimensions of the combustion chamber, 1 Kg of plastic (PP) waste was used.

5.2 Effect of decomposition time on the amount of fuel

It is observed through the (time-fuel quantity) curve that the amount of fuel produced has been increased by increasing the time of the thermal decomposition process inside the chamber.

When the device was started with a time of 30 min, the process of dissociating the bonds between the hydrocarbon molecules did not take place and thus the condensation process did not take place.

Then, at a time of 60 min, it is noticed from the curve that the particles began to disintegrate and move towards the condense Thus, the process of forming the hydrocarbon liquid with a volume of v = 10 ml began. Then with the increase of time, the amount of formed liquid increased, reaching v = 1000 ml at a time of 120 min. Nonetheless, with the increase of time, the amount of liquid formed did not increase. Thus, there are no longer any condensable gases inside the device, and therefore the thermal decomposition process has ended inside the device.

Figure (6) shows the relationship between time and the amount of fuel.

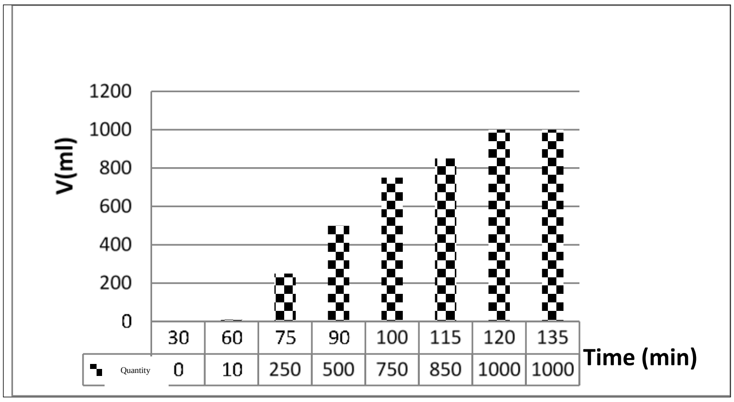


Figure 6 The relationship between time and the amount of fuel

From the previous curve, it is noticed that the pyrolysis process took 120 min to produce the liquid fuel.

5.3 The effect of temperature on the amount of fuel

Figure (7) shows the relationship between temperature and fuel quantity.

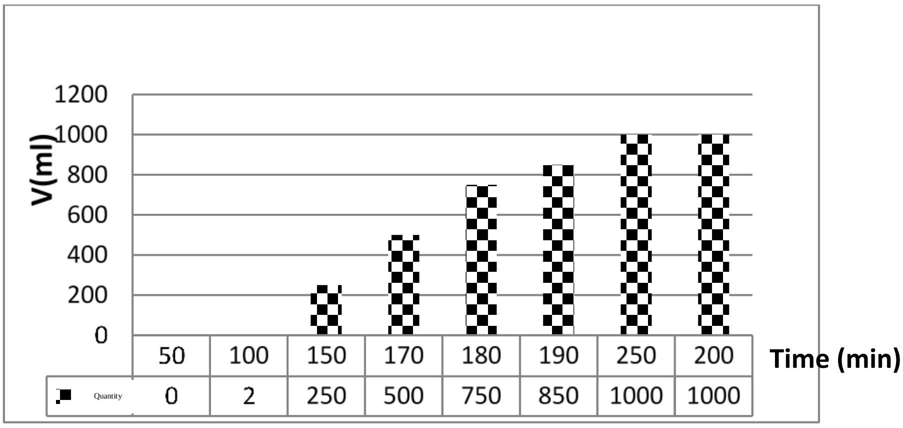


Figure 7 The relationship between temperature and the amount of fuel

It is observed from Figure (7), which shows the relationship between (temperatures - the amount of fuel) that when the temperature in the pyrolysis chamber increases, the amount of fuel produced increases.

At a temperature of 50 degrees Celsius, there was no process of dissociation of the bonds between the hydrocarbon molecules, and no hydrocarbon liquid (fuel) was formed. Then when the temperature was increased to 100 degrees Celsius, the bonds between the hydrocarbon molecules began to disintegrate and the condensable molecules were released towards the condenser and the production of liquid fuel began at a volume of V = 2 (ml). Then when the temperature is increased to 150 degrees Celsius, the amount of fuel formed through the pyrolysis process becomes V = 250 (ml). With the increase in temperature, the amount of fuel formed through the pyrolysis process increased. When the temperature is increased to 250 ° C, the amount of fuel formed through the pyrolysis process became V = 1000 (ml), then the temperature began to drop to 200 ° C and the amount of fuel remained constant at V = 1000 (ml). Thus, there are no longer any condensable particles in the device and the pyrolysis process of waste plastic inside the device came to an end.

5.4 The effect of pressure on the amount of fuel

Figure (8) shows the relationship between pressure and quantity of fuel.

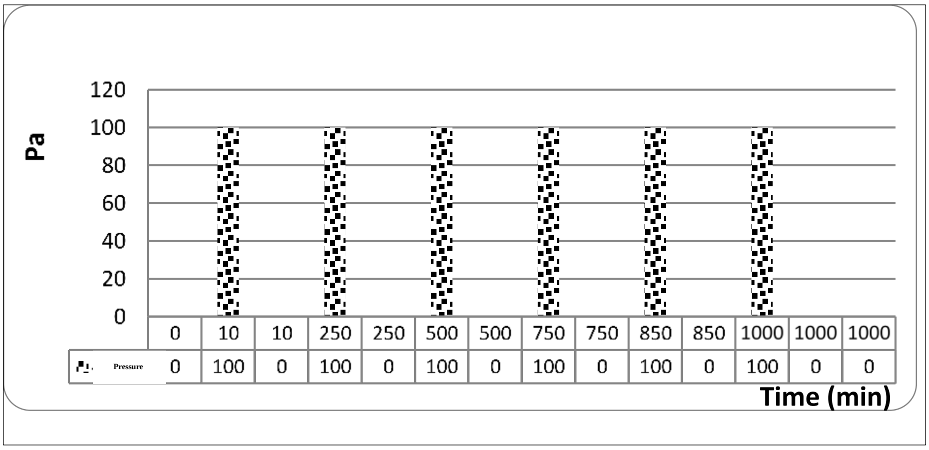


Figure 8 The relationship between pressure and quantity of fuel

It is noticed from Figure (8) that the higher the pressure in the pyrolysis chamber, the greater the amount of fuel produced. At the beginning of the decomposition process, the pressure is equal to zero P = 0 (Pa), meaning that there are no condensable gas molecules in the device. Then the pressure starts after a certain period to rise until it reaches the set value of the valve, which is P = 100 (Pa). Then the valve opens and the hydrocarbon liquid (fuel) comes out with a volume of v = 10 (ml), at which it is observed a decrease in pressure to the value P = 0 (Pa).

Then the pressure inside the device rises again until it reaches the value P = 100 (Pa), thence the valve opens and the hydrocarbon liquid comes out from the condenser (fuel with a volume of V = 250 (ML).

Thus, the process of decreasing pressure continues to P = 0 (Pa) and its rise to P = 100 (Pa) till the pressure in the device remains equal to the value P = 0 (Pa), thence it shows that there are no condensable particles left in the device. At this stage, it is concluded that the process of thermal decomposition of plastic waste in the device is over.

5.5 Effect of time on pressure:

Figure (9) shows the relationship between time and pressure.

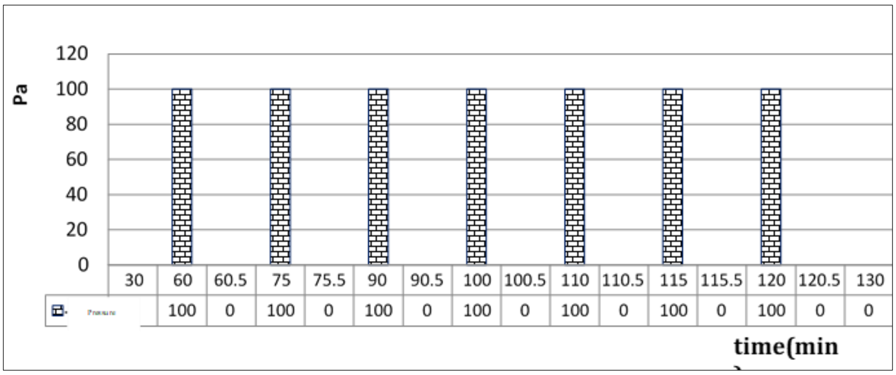


Figure 9 The relationship between time and pressure

From Figure (9) of the relationship between time and pressure, it is noticed that the longer the residence time of the dissociated hydrocarbon molecules in the pyrolysis chamber increases, the more pressure in the chamber. After running the device with a time of T = 30 min, the pressure in the device is equal to P = 0 (Pa). The pressure value remains constant until a time of T = 60 min. The pressure value in the device rises and becomes P = 100 (Pa), so the valve is opened and the hydrocarbon liquid is passed from the condenser. We note that at the time T = 60 min the bonds between the hydrocarbon molecules began to disintegrate and move towards the condenser. When the valve is opened, the hydrocarbon liquid passes and exits from the condenser, and the pressure drops to the value P = 0 (Pa) at the time T = 60.5 min. Then at the time T = 75 min, the pressure rises to the value of P = 100 (Pa), whence the valve is opened and the hydrocarbon liquid (fuel) is passed from the condenser. The pressure in the device drops to P = 0 (Pa), at a time T =

75.5 min, and this rise and fall in the value of the pressure continues until the end of the pyrolysis process of plastic waste, that is, at a time of T = 135 min.

The type of heat source that was used in the decomposition process:

- Gas (butane gas) is a primary source for the pyrolysis process.
- The gas produced from the thermal decomposition process is complementary or auxiliary to the decomposition process.

5.6 Fuel testing and analysis

Purified fuel should be tested for its properties. To interpret the quality and properties of the fuel, various tests were carried out in the laboratory under different test conditions. Table (1) shows the result of the tests that were carried out. The analysis included color, density, viscosity, calorific value, flash point, ash content, cloudy point, casting point, Fourier Transform Infrared Radiation (FTIR) test, and GC / MS test of the hydrocarbon liquid and its comparison with diesel. Figure (10) shows the "Fourier" device for converting infrared spectroscopy (FTIR), and Figure (11) presents the GC/MS chromatograph.

Figure 10 Fourier Infrared spectrum converter

Figure 11 GC/MS. chromatography

Table 1 The result of analyzing the hydrocarbon liquid and comparing it with diesel

Contents	**Diesel**	**Hydrocarbon liquid**
Color	Bright yellow	Reddish orange
Density	830 Kg/m3	711 Kg/m3
Bright spot	38ºC	23ºC
Cloud point	-40ºC	-37.7ºC
Casting point	5.6ºC	-43.8ºC
Ash ratio	<0.01	none

Viscosity	2.4cm2/sec	6.723cm2/sec
Calorific value	45000 KJ/Kg	49163 KJ/Kg

Table (02) shows a comparison of the carbon content of the liquid produced from polypropylene with other petroleum products

Table 2 Comparison of the liquid carbon content of polypropylene with other petroleum products

Fuel	**Liquefied petroleum gas**	**Benzene**	**Kerosene**	**Diesel**	**Hydrocarbon liquid**	**Heavy fuel oil**
Hydrocarbons	C3 to C4	C4 to CI2	C12 to CI5	C12 to C24	C3 to C30	C12 to C70

The gas produced from the pyrolysis device has been examined, and the results appeared as shown in Figure (12).

CH_4 : 100% vol, CO_2 : 0 % vol, H2S : 302 ppm

These results for the gas produced are very good from an environmental and energy point of view. This result supports Gao's [10] assertion that the pyrolysis process is environmentally beneficial and has a very high energy profit. The oil produced is of very high quality and is comparable to commercial liquid fuels sourced from petroleum.

Pyrolysis device gas test results

Pyrolysis device gas test

Figure 12 Pyrolysis device

The proportions of the polypropylene pyrolysis process products were as shown in Figure (13).

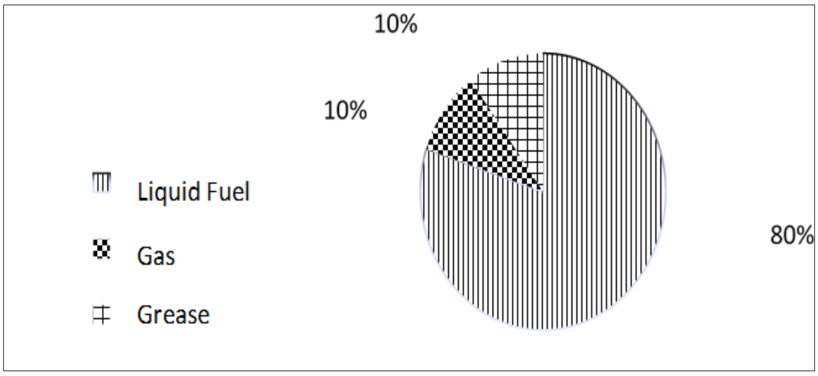
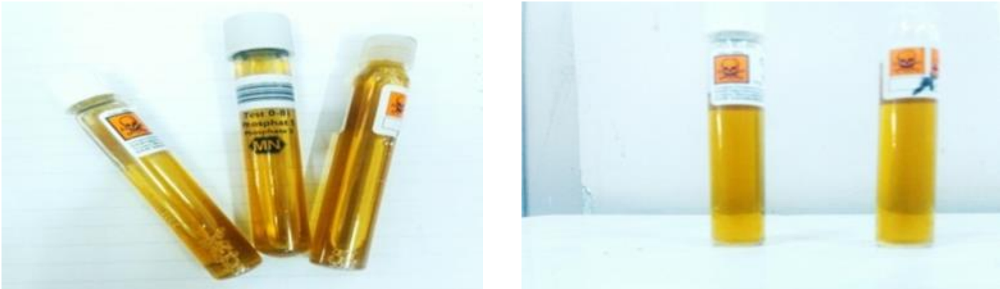
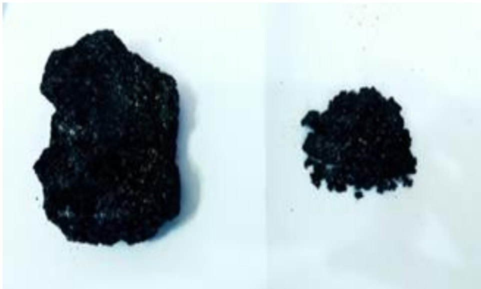


Figure 13 Proportions of the products of the pyrolysis process of polypropylene

Figure (14) shows the products of the polypropylene pyrolysis process.



Product No. 1 (Liquid Fuel)



Product No. 3 (grease) Product No. 2 (Coke)

Figure 14 Products of the polypropylene pyrolysis process

6 Conclusion

Through the study, the following conclusions emerged

- Every 1 kg of polypropylene (PP) plastic gives a volume, V of one liter of liquid fuel.
- Every 1 kg of plastic waste of the type (PP) can be converted into liquid fuel, grease, and gas in varying percentages of 80%, 10%, and 10%, respectively.
- With the increase in the pyrolysis temperature, the pressure in the pyrolysis chamber will increase.
- With the increase in pressure and temperature, there will be a process of gasification of the hydrocarbon molecules.
- With the increase in the residence time of the hydrocarbon molecules in the decomposition chamber, the pressure and temperature will rise faster.
- Polypropylene oil is reddish-orange and has a density of 711 kg/m3, which is lower than that of diesel and benzene.
- The fuel is flammable at room temperature, which according to the test was 23 degrees Celsius. The high combustibility of the fuel means that it can have a much lower flash point than that is already found. However, the flash point of benzene is much lower.
- The cloud point and casting point are as low as -37.7°C and -43.8°C respectively. As a result, this fuel can be used in extremely cold conditions easily.
- The above fuel has no ash content compared to diesel which has an ash content of less than 0.01.
- The calorific value of the fuel reaches 49,163 kJ/kg, which is better than both diesel and petroleum and therefore can be used for heavy diesel engines.
- From the above GC/MS test, the fuel contains a large hydrocarbon range of C7-C30 similar to the hydrocarbon range of diesel. As such, this fuel has more properties than diesel.
- The result of the FTIR test shows the presence of polypropylene on a large scale. Therefore, as a result of this secondary and tertiary pyrolysis can be carried out, and more products similar to commercial benzene can be obtained.
- This technology produces light fuel oil with competitive specifications.
- Better combustion efficiency with a cetane index of 61.2 is much better than that of a typical petrochemical diesel cetane index.

- Pyrolysis fuel does not emit any black smoke at all. This is due to the higher cetane count (better combustion efficiency) and low carbon residue which is about 1/4 of the fossil fuel isotope.
- This technology takes special care and produces a renewable oil with only 10 ppm sulfur content.
- This technology used is environmentally friendly and does not generate any pollutants to the soil and groundwater. Burning plastic usually produces toxic substances such as dioxins, but under the oxygen starvation state of this technology, dioxins are not produced at all.
- Through the pyrolysis device used, the majority (80%-85%) of plastic waste is converted into light fuel oil.

Recommendations

The study recommends the following:

- The use of catalysts in the process of fuel production through the pyrolysis of plastic waste reduces the temperature needed to break the bonds between hydrocarbon molecules.
- It is necessary to carry out an isolation process for plastic waste before the pyrolysis process.
- Ensure that plastic waste is clean and free of contaminants before using it in the thermal decomposition process so as not to affect the pyrolysis product.
- It is preferable to carry out a physical treatment process for plastic waste such as shredding and cutting it into small pieces before using it and placing it in a pyrolysis device to obtain a better and faster thermal decomposition process. This is because cutting increases the surface area of contact of plastic waste with heat.
- Follow the rules of occupational safety and security during implementation

Compliance with ethical standards

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Disclosure of conflict of interest

We, the authors, certify that there are no potential conflicts of interest or competing interests for the publishing of the manuscript or concerning a company or product that is referenced in the manuscript and/or crucial to the conclusion of the study that is being presented. In a similar vein, we writers certify that there is no competing interest in any of the products mentioned in our paper.

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