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Design and Fabrication of a Fixed Bed Pyrolyser for the Pyrolysis of Waste Plastics (Pure-water Sachets)

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Abstract:

Plastics wastes continue to pose as a threat to the environment. Plastic wastes are major causes of environmental pollution, their non-biodegradability nature contributes to hazardous adverse effect they have on the environment. Polyethylene or polyethene is the most common type of plastic as well as plastic waste. As of 2017, over 100 million tons of polyethene resins was produced accounting for about 29% of the total plastics market in the world of which, only about 9% is recycled. Plastic wastes especially polyethylene accounts for one of the largest municipal solid wastes in Nigeria. In this research, the design and fabrication of plastics pyrolyser was carried-out. Polyethylene was pyrolysed in the locally fabricated fixed bed pyrolyser reactor to produce pyro oil as the main desired product. Waste polyethylene popularly known as pure-water sachet (PWS) was pyrolysed at 350- 450 ˚C for 4-5 hours to obtain liquid fuel oil, semi-solid residue and gases. The oil yield obtained from the reactor was found to be 41.1%. The pyro oil properties include: a viscosity of 1.208 cSt, density of 760 kg/m^3, ash content of 5.52 %, flash point of 57.6 ˚C, pour point of -12 ˚C, fire point of 64.7 ˚C and cetane number of 71.49.

Keywords **—Plastic Waste, Polyethylene, Pyrolyser, Pyrolysis, Recycling, Pure-Water Sachet**

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I. INTRODUCTION

The world is still suffering over energy crisis and without any reasonable doubt, the current shortage of energy affecting Nigeria will persevere. This challenge calls for the exploration of other sources of energy. Energy demand in Nigeria is at present far more than the supply, thereby negatively retarding the country's socio-economic and technological developments [1, 2]. In a survey conducted by USAID in 2018, the larger part of Nigerian population of around 60 % do not have access to adequate power supply [3]. Plastics have become an indispensable part in today's world, due to their light weight, durability, energy efficiency, coupled with a very fast rate of production and design flexibility [4, 5]. Plastics are employed in the entire gamut of industrial and domestic areas. Hence plastics have become an essential material and their applications in the industrial and domestic field are continually rising [6]. Plastics play a vital role in enhancing the standard lives of many human beings for more than 50 years. It is a key of innovation of many products in various sectors such as construction, healthcare, electronic, automotive, and packaging and others [7]. The demand for commodity plastics has been increased due to the rapid growth of the world population. The continuous rising of plastic demand led to the growing in waste accumulation every year. Consequently, waste plastic recycling, regenerating, and utilization have become a hot spot of research and have gradually formed a new industry [8]. Polyethylene or polyethene is the most common plastic. As of 2017, over 100 million tons of polythene resins are produced accounting for 29% of the total plastics market. Its primary use is in packaging (plastic bags, films, containers including water bottles and buckets etc). It can therefore be said that polythene is the major component of the total plastic content of Municipal Solid Waste [9]. The decomposition of these plastic wastes is very relevant and of interests to industries since plastics has become a major commodity. Plastics wastes are accumulated without decomposition and hence pose a threat to mother earth and humans at large.

Recycling is one of the three ways for utilizing and minimizing of the huge amount of waste. The others are land filling and incineration with or without energy recovery. Neither land filling of incineration can solve the growing problem of huge amount of plastic waste [10]. Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition and is irreversible. The word is coined from the Greek - derived elements pyro "fire" and lysis "separating". Pyrolysis is most commonly used in the treatment of organic materials. In general, pyrolysis of organic substances produces volatile products and leaves a solid residue enriched in carbon, char [11]. Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonization. The process is used heavily in the chemical industry, for example, to produce ethylene, many forms of carbon, and other chemicals from petroleum, coal, and even wood, to produce coke from coal. Aspirational applications of pyrolysis would convert biomass into syngas and biochar, waste plastics back into usable oil, or waste into safely disposable substances [12].

Pyrolysis of waste plastics however can solve the problem of plastic pollution and also alleviate the energy shortage to a certain extent. Plastic pyrolysis may serve as a standalone operation or preferably as a pre-treatment to yield a stream of to be blended into a refinery or a petrochemical feed stream. Plastic pyrolysis converts waste plastics into liquid fuel like gasoline or diesel etc. or a chemical raw material [13]. Pyrolysis is the most attractive technique for the recycling of polyethene. Pyrolysis process considers the thermal cracking of polyethene by heating it in the absence of oxygen, which results in the formation of a solid residue (char), liquid product and gas. The pyrolysis of polyethylene is usually conducted at temperatures between 400 – 600 ˚C [14]. Yield of products in the pyrolysis process depends on the pyrolysis temperature, the reactor type and the presence of catalysts [15]. As an advantage, pyrolysis can treat all the mixtures consisting of various types of plastics without separation or treatment. The produced oil is distributed to end users, typically as a cheaper substitute for heavy oil and it can be used in industrial boilers, burners and power generators [16].

In Nigeria, plastics (polyethylene especially) also known as the Pure-Water Sachet (PWS) constitute a major percentage of environmental pollutants due to their non-biodegradable nature [17]. Plastics pollution has terrible effects on marine species, which can in turn lead to consequences for humans that eat fish and marine life for nutrients. The burning of plastics can also lead to the release of poisonous chemicals, thereby causing respiratory problems in humans [18]. The increase in petroleum and petrochemical prices opened the ways for industries to invest in the decomposition of plastic waste to useable oil.

II. METHODOLOGY

A. Collection of Waste Polythene (Pure-Water Sachet)

The collection of waste polythene is quite an easy task as compared to other wastes. Polythene wastes are abundant everywhere littering the environment and can be obtained in large quantities from households, road sides, hospitals, hotels, shops and markets. The collected waste PWS were washed thoroughly to remove dirt and were then sun dried.

B. Equipment Design and Specification

1.Pyrolyser Design and Specification

Table 1 shows the design parameters and specification of the pyrolyser equipment. The reactor is a fixed bed batch reactor which will be operated at 450^{o}C and can withstand a working pressure of 363.806 kPa. The pyrolyser reactor is of 0.210 m in diameter, 0.421 m in height and a total capacity of 0.0079 m^3.

2.Condenser Design and Specification

The condenser is the unit to cool the outlet gases for the collection of the product (pyro oil). Table 2 shows that the condenser is a shell and tube condenser. The condenser is designed to have a duty of 12815.136 kJ/batch and a total heat transfer area of 0.2744 m^2.

TABLE 1: SUMMARY OF PYROLYSER DESIGN SPECIFICTIONS

Parameters	**Specification**
Operation	Batch
Material Volume, m^3	0.0055
Design Volume, m^3	0.0079
Height to Diameter Ratio	2
Pyrolyser Diameter, m	0.210
Pyrolyser Height, m	0.421
Shell Thickness, mm	5
Internal Operating Pressure, kPa	101.3
Safe Working Pressure. kPa	363.806
Design Pressure, kPa	400.187
Operating Temperature, °C	450
Design Temperature, °C	522.315
Material of Construction	Mild Steel

TABLE 2: SUMMARY OF CONDENSER DESIGN

Parameters	**Specification**	
Duty, kJ/batch	12815.136	
Shell Side	Cooling Water	
Tube Side	Hydrocarbon Vapor	
	Tube side	Shell side
Inlet Temperature	450	25
Outlet Temperature	45	45
Number of Tube Pass	1	
LMTD, K	108.095	
Heat Transfer Area, m^2	0.2744	
Tube Length, m	0.80	
Tube OD, mm	25	
Tube ID, mm	21	
Number of Tube	4	
Tube side heat transfer Coefficient, W/m2K	99.973	
Tube Side Pressure Drop, kPa	0.002	
Shell Length, m	1.00	
Number of Baffles	2	
Shell Side Fluid Velocity, m/sec	0.0032	
Shell Side Fluid Density, kg/m^3	986	
Shell Side heat transfer Coefficient, W/m^2K	150.706	
Shell Side Pressure Drop, kPa	0.0001	
Overall heat transfer Coefficient, W/m^2K	52.672	
Shell Thickness, mm	3.5	
Safe Working Pressure. kPa	2923.009	
Design Pressure, kPa	3215.309	
Material of Construction	Carbon Steel	

III. WORKING DRAWINGS

A. *Pyrolyser Working Drawing*

Figure 1a and 1b shows the 2D and 3D models for the pyrolyser (reactor). The reactor is a fixed bedreactor of 1.203m in height and 0.203 m in diameter.

Figure 2a and 2b shows the 2D and 3D models for the condenser. The condenser is of the type shell and tube with a single pass and four (4) tubes. The height of the condenser is 0.8m and 0.21 m in diameter.

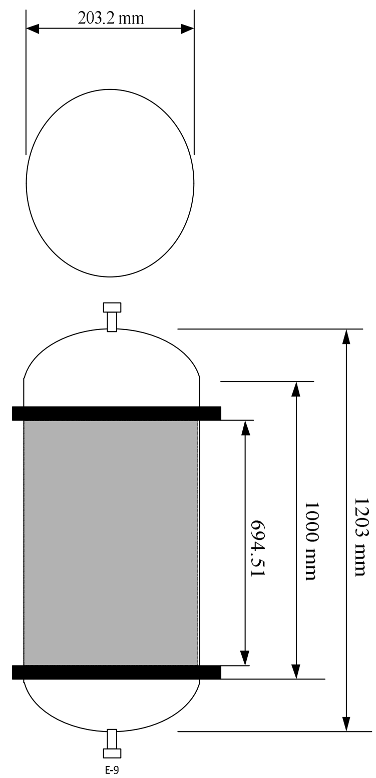

Figure1a:Schematic diagram of Pyrolyzer(Reactor)

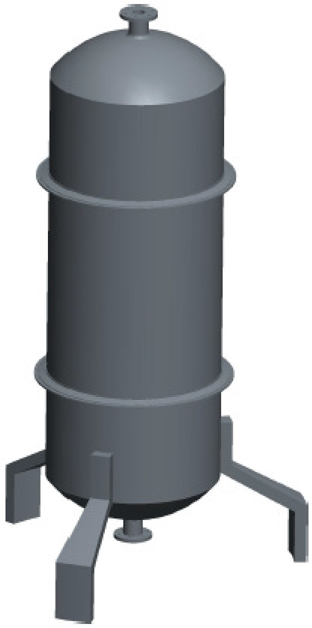

Figure 1b:3D Model of Pyrolyzer (Reactor)

B. *Condenser Working Drawing*

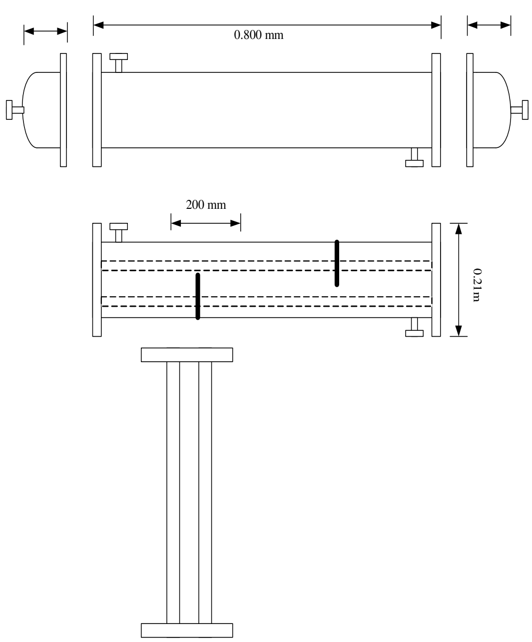

Figure 2a: Schematic diagram of Condenser

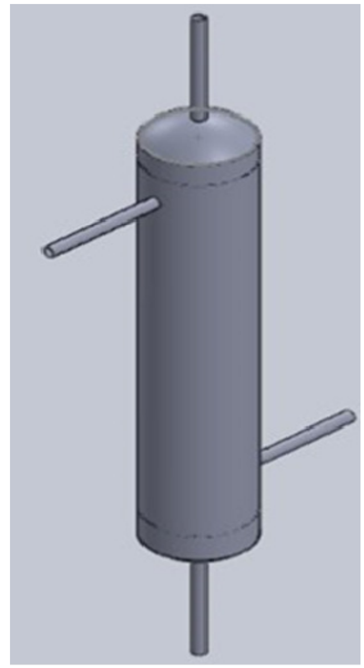

Figure 2b: Schematic diagram of Condenser

Figure 3:Fabricated Pyrolysis Unit

IV. FABRICATED PYROLYSIS UNIT

The pyrolysis set up depicted in Figure 3 consists of two main parts, which are the reactor (pyrolyzer) and the condensing unit. The reactor has an inner cylinder and an outer cylinder which are made concentric on a base plate. Pyrolysis reactor and the condenser are both made of mild steel, Fibre glass was used as the insulating medium so as to reduce heat losses due to conduction and convection.

V. PRODUCED PYROLYSIS OIL

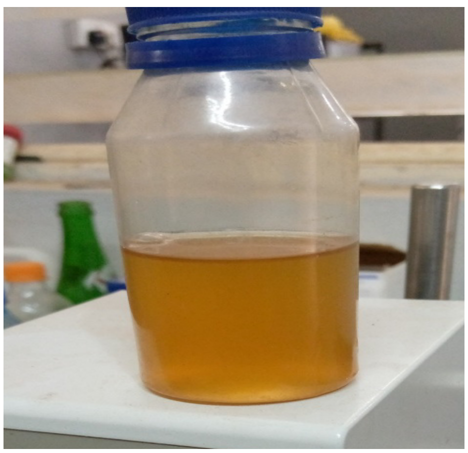

Figure 4: Pyrolysis Oil

Figure 5: Residue from the pyrolysis Process

Figure 4 shows the pyrolysis oil gotten from the thermal decomposition of waste polyethylene (waste pure water sachet). The dark thick residue shown in Figure 5 was collected at the bottom of the reactor after a batch operation.

VI. RESULT OF PRODUCT (PYROLYSIS OIL) ANALYSIS

TABLE 3: PROPERTIES OF PYROLYSIS OIL

1) S/No	Properties	Pyrolysis Oil	Diesel Fuel
2) 1	Density(kg/m^3)	760	820-845
3) 2	Viscosity (cSt)	1.208	2 – 4.5
4) 3	Ash Content (%)	5.52	0.1
5) 4	Flash Point (˚C)	37.6	> 55
6) 5	Pour Point (˚C)	-12.6	-19
7) 6	Fire Point (˚C)	44.7	62
8) 7	Cetane Number	61.49	40-55

Density is an important property of a fuel oil as it's directly related to API gravity of crude oil or fuels. From Table 3, the density of the waste plastic pyrolysis oil was found to be 760 kg/m^3 which is less than that of diesel, kerosene and gasoline which are 820, 810 and 780 kg/m^3 respectively.

The API gravity is a measure for the classification of fuels as light, medium, heavy, or extra heavy. Thus, Light oil have the ^{o}API> 31.1, Medium oil are of ^{o}API between 22.3 and 31.1, Heavy oil are of ^{o}API< 22.3 and Extra Heavy oil are of the ^{o}API< 10.0. Based on the classification, the pyrolysis oil can be classified as light oil with ^{o}API of 54.

The viscosity of pyrolysis oil depends on feedstock, temperature and other variables. The viscosity of the pyro-oil at 40^{o}C was found to be 1.208cSt which is below that of diesel.

The ash content of oil is the non-combustible inorganic residue that remains after combustion in air at a specific temperature. The ash content of the waste plastic pyrolysis oil was measured using a furnace. The ash content as gotten from the test was 5.52%. This result shows that the ash content of the waste polyethene pyrolysis oil is high compared to that of diesel.

Flash point is the lowest temperature at which a fuel can vaporize to form an ignitable mixture in air.

Flash point is used to characterize the fire hazards of fuels. The flash point of the waste plastic pyrolysis oil was measured according to ASTM method. The flash point of the waste plastic pyrolysis oil was 37.6 ˚C. The flash point is less than that of diesel which is usually greater than 55 ^{o}C. Thus, the pyro oil indicates little presence of highly volatile materials in the fuel. The oil will be easy to handle and transported and is not of much serious safety concern.

The pour point is the temperature at which oil will cease to flow when cooled at a standard rate in a standard apparatus. Pour point determines the suitability of the oil for low temperatureinstallations. The pour point was measured using afridge and an infrared thermometer. The pour point was -12.6 ˚C. The low pour point value of the waste polyethene pyrolysis oil indicates that it is not suitable in cold temperature applications or cold weather countries.

Fire point of a fuel is the temperature at which it will continue to burn for at least five seconds after ignition with an open flame. The fire point is used to access the risk of the materials ability to support combustion. Generally, the fire point of any liquid oil is considered to be 10 to 20 ˚C higher than its flash point. The fire point of the waste polythene pyrolysis oil was found to be 64.7 ˚C.

Cetane number or cetane rating is a measurement of the quality and performance of diesel fuel. The higher the cetane number, the better fuel burns within the engine of a vehicle. The cetane number of the waste polyethene pyrolysis oil was calculated using Equation (1):

$$CN = 46.3 + \frac{5488}{SN} - (0.225\ x\ IV) \qquad (1)$$

Where CN = Cetane Number, SN = Saponification Number, IV = Iodine Value

The cetane number of the pyro oil produced was calculated to be 61.49 which is higher than 55 for diesel fuel.

VII. CONCLUSIONS

The design and fabrication of a low cost pyrolyser for the pyrolysis of waste polyethene (pure water sachets) was successfully carried out. The pyrolyser will go a long way in tacking the pollution problem of pure water sachet in Nigeria.

The two sections of the pyrolysis plant were successfully fabricated. The Fixed Bed Reactor (0.0079 m^3 volume, height of 0.421 m and 0.210 m diameter) and the shell and tube condenser (0.2744 m^2 heat transfer area and overall heat transfer coefficient of 52.672 W/m^2K)

The fabricated unit was installed and test-run to produce pyrolysis oil from waste water sachet made from low density polythene (PE). The produced hydrocarbon fuel oil has some of its properties similar to that of petrodiesel. Some properties of the pyrolysis oil include: density of 760 kg/m^3, flash point of 57.6 ˚C, pour point of -12 ˚C, cetane number of 71.49 and ^{o}API gravity of 54.

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