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# Design of a 1000 g Laboratory-Scale Plastic Pyrolyzer System for Converting Polyethylene Terephthalate (PET) to Derived Oil

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## ABSTRACT

This study presents the design and material selection of a $1000\ g$ pyrolysis system for converting waste Polyethylene Terephthalate (PET) bottles into diesel fuel. The volume, height, wall thickness, the flat-end thickness of the top of the pyrolysis reactor and the thickness of the insulation material were designed as $3376800\ mm^3$, $220\ mm$, $2.13\ mm$, $4.49\ mm$ and $3\ mm$ respectively. The system is designed to operate at a maximum temperature of $400℃$, based on the vaporization temperature of diesel is within 300 - 360 ℃. The material balance of the $1000\ g$ of PET plastic feedstock was based on $38.89\ wt\%$ liquid fuel, $52.13\ wt\%$ gas, and $8.91\ wt\%$ char yields, while the power rating of the heating element was designed as $682.6\ kJ$. The safety analysis associated with high-temperature processing, gas handling, and high pressure system, where accounted for in the design, and mitigated through the implementation of safety protocols. The reactor was designed to be operationally safe, with a total cost of fabrication and safety analysis estimated at four hundred and forty-five thousand naira (₦445,000) only. This pyrolysis system demonstrates a promising approach for the conversion of waste PET plastics to a valuable fuel, gas and char.

## 12. INTRODUCTION

Plastics are synthetic or semi-synthetic materials find extensive use in construction, packaging, sports safety gear, medical field, electrical, and electronics among others [1]. This wide applicability of plastics and plastic materials, results in the daily use of these materials in virtually all households. However, plastics are non-biodegradable [2]. Report has it that it takes over 500 years to completely biodegrade a plastic bag, which has made plastic waste become a major issue, both on land and water, leading to catastrophic effects on the ecosystem [3]. Not only has the landfills and seas become eyesore, plastics also release toxins and greenhouse gases into the earth and air during disposal, which are a tremendous threat to the environment [4].

The mass of waste plastics generated annually is on the rise, and is a persistent issue for the environment. One of the main wastes in many nations around the world, is used plastic. Spending huge amount of money on land filling to handle plastic garbage that might eventually endanger the environment is a costly endeavor. Plastic garbage is causing health problems for those who reside close to incinerator operations. Modern homes, offices, and companies generate large amounts of plastic waste, which is difficult to separate and recycle. Nevertheless, eliminating these enormous quantities and transforming waste plastic into applications that are in great demand, and also reducing the significant air pollution caused by the burning of plastic garbage, is of paramount interest.

Mainly, two types of plastics exist: thermoplastics and thermosetting plastic [5]. The application of enough heat can soften and melt thermoplastics repeatedly, and they solidify on cooling, therefore, can be formed into new plastic products. Examples of thermoplastics are Polystyrene (PS), Polyvinyl chloride (PVC), Polyethylene terephthalate (PET), High-density polyethylene (HDPE), Low-density polyethylene (LDPE), poly propylene (PP) etc. While thermosetting plastics are those plastics that melts and can be shaped only once, and after solidification, they remain in that solid state, e.g. epoxy resin, phenol formaldehyde and urea formaldehyde [5].

Polyethylene terephthalate (PET) is a great choice for plastic packaging of various products in food industries, mainly beverages, such as containers for mineral water, soft drinks and fruit juice [6]. This is due to its intrinsic properties such as, lightweight and pressure-resistant containers, suitability for large-capacity. Other utilizations of PET incorporate electrical protection, printing sheets, attractive tapes, X-ray and other photographic film [5]. Some of these PET properties and their values are represented in Table 1:

**Table 1 heat capacity, molecular weight and density of PET**

| Property | Value | Reference |
|---|---|---|
| Density | 1.18 g/cm$^3$ | [7] |
| Molecular weight | 8000 g/mol | [8] |
| Specific heat capacity | 1.8203 kJ/kg.K | [7] |

Several methods have been employed in plastic waste recycling, which include pyrolysis [1], chemical recycling [9], plastic combustion in incinerators [10] and gasification [11]. Among these plastic recycling techniques, pyrolysis stands out because it does not generate harmful pollutants and the by-products such as derived oil can be used as alternative fuel because of its high calorific value [12], while the char can be used as adsorbent [13].

Pyrolysis technique is most frequently used in the processing of organic materials. It is one of the methods used to char wood, and the temperature range for it is typically between 250 °C and 900 °C [14]. Specific temperature range has enormous effect on the products yield and makeup of the pyrolysis. If the gaseous product or char product is preferred, a higher temperature of over 500°C is required, and if liquid product is preferred, lower temperature in the range of 300 – 400°C is recommended, and this condition is applicable for all plastics [15]. Pressure is another significant factor which affects the products of pyrolysis of plastics. Mimura *et al.*, (2004) [16] studied the pyrolysis product of HDPE converted in a continuous stirred tank reactor at elevated temperature obtaining pressure of about 430℃ and 0.1- 0.8 MPa. The carbon content of the liquid product was affected by pressure, by producing carbon compounds of lower molecular weight at high pressure. Furthermore, the rate of formation of double bond compounds, decreases when pressure is increased, which suggests that the scission rate of $C - C$ links in polymer is directly affected by increase in pressure. Also, residence time is largely affected by pressure at low temperature, however, as the temperature increases to above 430℃, the effect of pressure on the residence time become negligible. Fakhrhoseini and Dastanian, (2013) [17] reported that the quantity of waste plastics converted to oil also depend on the reaction time. The higher the reaction time, the more effective and efficient the pyrolysis reaction will occur to achieve a more oil yield and high waste reduction.

When organic materials are pyrolyzed, volatile chemicals are produced and a solid residue rich in carbon called char, is left behind. Plastic pyrolysis is extensively used in the chemical sectors [18]. It was initially devised in the 1970s as a means of extracting valuable components and energy from waste plastics [12]. The expanding global issue of plastic trash, which is having adverse effect on both the health of human and the environment, has brought the procedure back into the spotlight in recent years. The use of traditional disposal techniques such as landfilling and cremation on persistent pollutant like plastic garbage becomes ineffective, and can have serious negative effects on the ecosystem [12].

The pyrolysis of plastic is a thermal decomposition of plastic that occurs in the absence of oxygen. This process breaks down plastic into smaller molecules such as oil, gas, and Char [14]. Thermal decomposition or degradation involves the application of heat to breakdown large molecules of polymers into smaller molecules. This process can lead to a range of products represented by equation (1), including monomers, oligomers, and various gases. The specific products depend on the type of polymer and the temperature of operation [19].

$$(CH_2CH_2)n \rightarrow CH_4+C_2H_4+C_2H_2+\ldots(CH_2CH_2)n \rightarrow CH_4+C_2H_4+C_2H_2+\ldots \qquad (1)$$

Thermal degradation of polyethylene for example, breaks down the polyethylene into smaller hydrocarbons, such as methane ($CH_4$), ethylene ($C_2H_4$), acetylene ($C_2H_2$), and other lower molecular weight hydrocarbons, as well as carbonaceous residue [20]. These bye products of plastics can be generally grouped as oil, gas and char [14].

A plastic pyrolysis reactor is a type of equipment used to convert plastic waste into useful products through a process called pyrolysis. It is a key part in the pyrolysis plant and it affects the lifetime, user experience and efficiency of the process. The reactor typically consists of several key features, such as, the sturdy and cylindrical chamber which can withstand high temperature and pressure: it is where the plastic waste is heated and converted into valuable end products [21].

The plastic pyrolysis reactor typically consists of a cylindrical chamber made of high-quality steel or other heat-resistant materials. The reactor is fitted with a heating device, a syngas recycling device, a feeding system, and a discharging system.

Nankwasa and Ogene (2023) [4], carried out design and fabrication of a pyrolysis batch reactor for converting plastic waste materials to oil. The research involves testing five batches of 1000 g LDPE plastics per batch, at 50 °C, 350 °C and 450°C and at pyrolysis time of 40, 50 and 60 minutes. The results showed that 250 mL of oil was produced at 450 °C, forming the highest, while the lowest quantity of oil produced was 132 mL at 250℃. The lowest quantity of char produced was 450 g while the highest was 600g at 450℃ and 250℃ respectively. At 350℃, the quantity of oil produced was 180 mL (138.78g), and 520g of char, but the detail of the reactor design was not reported. Lamido *et al*. (2023) [22] designed a fixed bed pyrolysis reactor of 0.21 m diameter, reactor height of 0.421 m with total capacity of 7.9 liters. The shell thickness of the reactor was 5 mm, with design temperature of 522℃. Mild steel was used as construction material, with shell and tube type of heat exchanger, designed to serve as cooling system for the pyrolysis reactor. Much attention was on the pyrolyzer operation and product analysis, but the design details were not included in their report. Aswan *et al.* (2020) [23] designed a pyrolysis reactor to process 5000 g of plastics at 350℃ with 20 liters capacity. The reactor height was 360 mm, diameter 310 mm, the length of condenser was 400 mm, condenser diameter 400 mm and a design temperature of 800℃. Nevertheless, the process and equipment design detail of the work, on how the design parameters were obtained was not reported. Jayswal *et al*. (2017) [24] worked on design, fabrication and testing of a pyrolyzer with a capacity of 91 liters, 476 mm height, 500 mm outer diameter, 494 mm inner diameter with wall thickness of 6 mm, while shell and tube heat exchanger was used for condensation. The design parameters of the reactor obviously show that the reactor capacity (91 liters) cannot be obtain with the configurations stated, indicating the need for the process and equipment design details to be clearly stated. Patel and Patel, (2019) [25] designed a plastic pyrolysis reactor with design temperature of 450℃, and the pyrolysis system consist of the reactor, heating system and condenser, but the design details and parameters were not included in the report.

In this work, emphasis is on the design details and the design parameters of a 1000 g laboratory-scale plastic pyrolyzer system employing a tubular heat exchanger for cooling the vapor to the derived oil.

### 1.1 Conservation of mass

Mass balance is a basic concept that helps to account for the materials input and output (mass) within the system in chemical and environmental engineering. This concept ensures that the total mass of materials entering a system, equals the total mass of materials leaving the system, plus any material accumulated or depleted within the system. The basis of process and equipment design is mass balance, and this will determine the quantity of raw materials required for the process and the products expected. Balances over individual process unit is determined from the process stream and their compositions. The general expression for the conservation of mass for any system can be written as:

$$Material\ out = Material\ in + Generation - Consumption - Accumulation \qquad (2)$$

When considering a steady-state system, the accumulation term will be eliminated. Except for nuclear processes, mass is neither created nor consumed; but if a chemical reaction is involved, a particular species may be created or consumed in the process. If there is no chemical reaction equation (2) reduces to:

$$Material\ out = Material\ in \qquad (3)$$

A balanced equation can be written for each species or element or compound or radical present, separately identified and for the total material.

### 1.2 Conservation of energy

Energy balance is a thermodynamic concept used in energy analysis to account for energy entering and leaving the system. This ensures that the total amount of energy input to a system equals the total amount of energy output from the system, plus any energy accumulated or depleted within the system. This analysis is made to determine the energy requirement of the process, that is, the heating and cooling power required. The energy balance expression is given as follows:

$$Energy\ out = Energy\ in + generation - consumption - accumulation \qquad (4)$$

The relationship between the heat energy of the cooling system and the heat energy of the reactor is: Since the heat energy lost by the PET is equal to the heat energy gained by the water, we can set up the following equation

$$Q_{PET} = Q_{water} = mhC(T_i - T_o) \qquad (5)$$

Where $Q_{water}$ is the amount of heat absorbed by the cooling system, $Q_{reactor}$ is the amount of heat generated by the reactor. This means that the heat absorbed by the cooling system is equal to the heat generated by the reactor. In other words, the cooling system removed the heat generated by the reactor, allowing the reactor to maintain a stable temperature. This relationship is based on the principle that energy can neither be created or destroyed, but can be transformed from one form to another. In this case, the heat energy generated by the reactor is transferred to the cooling system, which removes it from the reactor. The cooling system is designed to match the heat energy generated by the reactor, ensuring that the reactor operates within a safe and stable temperature range. If the cooling system is unable to absorb enough heat, the reactor temperature may rise, potentially leading to unsafe conditions or reduced efficiency.

### 1.3 Equipment design of the pyrolysis system

a. Volume of the pyrolysis reactor

Mole balance on specie A (plastic), at any time t, can be expressed as follows:

Flow rate of A into the system $(mol/time)$ − flow rate of A out of the system $(mol/time)$ + Rate of disappearance of A $(mol/time)$ + Rate of accumulation of A $(mol/time)$ (6)

But in a batch reactor, flow input = 0; output = 0

Therefore,

$$0 = rate\ of\ disappearance + accumulation \qquad (7)$$

Rate of disappearance A = $r_A V$

Consequently, rate of disappearance = $\frac{moles\ of\ A\ reacting}{(time)(volume\ of\ fluid)}$ x volume of the plastic

$$= \frac{moles\ of\ A\ reacting}{(time)}$$

Rate of accumulation = $\frac{dN_A}{dt}$ (8)

$$But\ N_A = N_{A0}(1 - X_A)$$

$$\frac{dN_A}{dt} = \frac{d\,(N_{A0}(1 - X_A))}{dt} \qquad (9)$$

But $N_{A0}$ is the initial number of moles of the plastic fed into the reactor, therefore if $N_{AO}$ is constant with respect to time, equation (9) becomes

$$\frac{dN_A}{dt} = 0 - \frac{-N_{A0}dX_A}{dt}$$

$$= \frac{-N_{A0}dX_A}{dt} \qquad (10)$$

Substituting equations (8) and (10) into (7)

$$0 = -r_A V \frac{N_{A0}dX_A}{dt} \qquad (11)$$

This is the design equation for a batch reactor in differential form, where $-r_A$= rate of the reaction of reactant of the plastic (A), V = reactor volume and $X_A$= mass fraction of reactant A
Therefore, assuming a first order reaction, the volume of the pyrolyzer reactor is obtained as:

$$V = \frac{-N_{A0}dX_A}{-r_A dt}$$

$$V = \frac{N_{A0}X_A}{t\ k\ C_A} \qquad (12)$$

Where $-r_A = kC_A$

b. Reactor wall thickness

The reactor wall's thickness is crucial and need to be designed to withstand internal pressure buildup. It should also have mechanical provisions for pipe threading, safety valves, and pressure gauges, as well as a safety margin for corrosion [26]. A reactor must be designed in such a way that it can withstand the maximum internal pressure to which it is likely to be subjected during the operation [21]. The formula for the determination of the thickness of the cylindrical reactor is as obtained for ASME B31.3 code:

$$t_m = t_p + C$$

$$t_p = \frac{Pd}{2(S\ E - PY)}$$

Therefore,

$$t_m = \frac{Pd}{2(S\ E - PY)} + C \qquad (13)$$

Where $t_m$ is the maximum required thickness; $t_p$ is the design thickness pressure; C stand for the sum of mechanical allowances and corrosion allowances; P represent the internal design gauge pressure, $b/in^2 (or\ N/mm^2)$; d represent the pipe inner diameter; S is the basic allowance for stress pipe material, $b/in^2 (or\ N/mm^2)$; E represent the casting quality factor; Y is the temperature coefficient (0.6) [27].

c. Flat end of the reactor

The flat ends of any cylindrical reactor is closed by heads of various shapes. The principal types of these ends are the flat plates and formed flat heads, hemispherical, ellipsoidal and torispherical heads. But hemispherical, ellipsoidal, and torispherical heads are collectively referred to as domed heads [26]. They are formed by pressing or spinning, and large are diameters fabricated from the formed sections [27]. The flat ends of the reactor require special attention because it is where the top where the sensing devices are mounted [26]. Therefore, the design equations used for the flat plate thickness determination are based on their stress's analysis, as Table 3 shows various design stresses for plates [21]. The thickness required for flat ends is determined as follows.

$$t_m = C_P D_e \sqrt{\frac{Pi}{f}} \qquad (14)$$

For hemispherical head, we have;

$$t = \frac{P_i D_i}{4SE - .4P_i} \qquad (15)$$

For ellipsoidal heads;

$$t = \frac{P_i D_i}{2SE - .2P_i} \qquad (16)$$

For Torispherical heads;

$$t = \frac{.885 P_i R_c}{SE - .1 P_i} \tag{17}$$

Any consistent unit can be used for equation, where $C_P$ is the design constant, $P_i$ is the internal pressure, $D_e$ is the internal plate diameter, f represent the design stress, $R_c$ is crown radius[27].

d. Insulation material

These are used to insulate the reactor and retain heat. Materials such as refractory bricks, constables, and glass fibers are common choices. They are designed to withstand high temperatures without degrading. Glass fiber is a popular insulation material for batch reactors. Glass fiber is made from a combination of silica sand, soda ash, and limestone, which are melted and formed into thin strands [28]. It is an insulation material produced from the fibers of glass and arranged into a texture similar to wool using a binder. Glass fiber has a high thermal insulation resistance (R-value) and low thermal conductivity (k-value).

It can withstand high temperatures (up to 1000°F/538°C) and is resistant to acidic and alkaline environments [28]. It is also non-corrosive and non-reactive with most process materials. Glass fiber insulation is a reliable and efficient material for batch reactors, offering excellent thermal insulation, chemical resistance, and durability. Its various forms and ease of installation make it a popular choice for many industrial applications [28]. Glass fiber insulation will be used in this design, due to its high fire resistance, heat resistance, resistance to most chemicals, low thermal conductivity and its availability in a variety of presentations [26]. Table 2 shows the thermal conductivity and density of different types of fiberglass as reported by Zaid, (2020) [29].

**Table 2. Thermal conductivity and density of glass fiber values at 0°C**

| Type | Density ($kg/m^3$) | Thermal conductivity (W/m°C) |
|---|---|---|
| Glass fiber | 64 – 144 | 0.036 |
| Type I | 10 – 18 | 0.044 |
| Type II | 19 – 30 | 0.037 |
| Type III | 31 – 45 | 0.034 |
| Type IV | 46 – 65 | 0.033 |
| Type V | 66 – 90 | 0.033 |
| Type VI | 91 | 0.036 |

Since the reactor has a cylindrical pipe shape, the heat conduction in the system is in the radial direction, and the area normal to the flow varies with distance [30]. Applying Fourier's law:

$$Q = \frac{-2\pi L k (\Delta T)}{In \frac{r_0}{r_i}} \tag{18}$$

Where Q represent the rate of heat loss, L represent the height of the cylinder, $\Delta T$ represent the temperature difference, while $r_o$ and $r_i$ are the outer and inner radii respectively. Moreover, considering a cylindrical system with insulation, equation (18) will become:

$$Q = \frac{-2\pi L (\Delta T)}{\frac{1}{k_1} In \frac{r_2}{r_1} + \frac{1}{k_2} In \frac{r_3}{r_2}} \tag{19}$$

Where $r_1$ and $r_2$ represent the inner and outer radii of the cylinder, $r_3$ represent the radius of the insulator, $k_1$ represent the heat coefficient of the cylinder, $k_2$ represent the thermal conductivity of the insulator.

e. Heat Exchanger

A heat exchanger is a device which transfer heat between two or more fluids [28]. The hot and cold fluids can be separated by a solid wall or in some cases they may be in direct contact [31]. Various types of heat exchanger devices in use are the Shell and tube type of heat exchanger, Plate, Regenerative, Air cooled and Tubular heat exchangers. The tubular type of heat exchanger is the type with tubes in a shell and it is a very common device in industries where heat recovery from gas or liquids is the focus [32; 33]. The tubular heat exchanger is extremely reliable, and is a piece of equipment usually made of stainless steel to withstand extreme temperatures and high pressures, and can operate with different types of fluids and can be adapted to different applications [32].

i. Mode of flow in a heat exchanger

The mode of flow in a heat exchanger refers to its operational characteristics or configuration, which determine how heat is transferred between the hot and cold fluids [32]. Here are some common modes of fluid flow in heat exchangers; parallel Flow (both fluids flow in same direction), Counter flow (both fluids flow in opposite direction), Crossflow (one fluid flow perpendicularly to the other), Regenerative (heat is absorbed by the system and released to the hot or cold fluid as it comes in contact), Direct contact (the two fluids come into direct contact, allowing for efficient heat transfer), Indirect contact (the two fluids are separated by solid barrier, preventing them from mixing), and regenerative combustion (this involves using the heat from combustion of gases to preheat incoming air or fuel in industrial furnaces or boilers) [32].

ii. Logarithmic Mean Temperature Difference

The Logarithmic Mean Temperature Difference (LMTD) is a key parameter used in the design and analysis of heat exchangers. It is a measure of the temperature difference between the hot and cold fluids at each end of the heat exchanger [32]. The LMTD is commonly used in calculating the heat transfer rate in counter flow and parallel flow heat exchangers [33]. The LMTD is defined as represented in equation (20):

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{In\frac{\Delta T_1}{\Delta T_2}} \quad (20)$$

Where $\Delta T_1$ represent the temperature difference between the hot and cold fluids temperature at the inlet, for a concurrent flow, while $\Delta T_2$ represents the temperature difference between the hot and cold fluids at the outlet of the flow, and ln is natural logarithm.

The LMTD is used in the heat transfer equation to calculate the heat transfer area (A) required for a heat exchanger:

$$Q = U \times A \times LMTD \quad (21)$$

Where Q represent the rate of heat transfer, U represent the overall heat transfer coefficient, and A represent the heat transfer area.

### 1.4 Materials for Construction

The construction of a plastic pyrolyzer requires careful selection of materials to ensure durability, efficiency, and safety. The choice of materials depends on the specific application, that is the process conditions including the type of feedstock, the operating temperature and pressure and the desired products. The design stress (presented Table 3) is determined by considering various factors such as safety factor, material properties, plate geometry (width, thickness and length) reported by Sinnott, (2005) [27]. These design stresses are used to determine the required thickness, width, and material properties of the plate to ensure that it can withstand the expected loads and stresses without failing or deforming excessively.

**Table 3. Typical design stress values for selected common materials**

| | Tensile Strength (N/mm$^2$) | Design stresses at temperature $^o$C (N/mm$^2$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
| Carbon steel | 360 | 135 | 125 | 115 | 105 | 95 | 85 | 80 | 70 | | |
| Carbon-manganese | 460 | 180 | 170 | 150 | 140 | 130 | 115 | 105 | 100 | | |
| Carbon-Molybd | 460 | 180 | 170 | 145 | 140 | 130 | 120 | 110 | 110 | | |
| Low alloy steel | 550 | 240 | 240 | 240 | 240 | 240 | 235 | 230 | 220 | 190 | 170 |
| Stainless steel (304) | 510 | 165 | 145 | 130 | 115 | 110 | 105 | 100 | 100 | 95 | 90 |
| Stainless steel (321) | 540 | 165 | 150 | 140 | 135 | 130 | 130 | 125 | 125 | 120 | 115 |
| Stainless steel (316) | 520 | 175 | 150 | 135 | 120 | 115 | 110 | 105 | 105 | 100 | 95 |

## 13. MATERIALS AND METHODS

The materials used in this design are waste Polyethylene terephthalate (PET), stainless steel 316, glass fiber and water, while the methods are process design, equipment design, safety analysis and costing

### 2.1 Process design

This involves the material and energy balances carried out on the reactor. The plastic waste is usually sorted and prepared for the pyrolysis operation. This may involve removing labels, sorting by type, and shredding the plastic into smaller pieces in the pretreatment segment. The pre-treated plastic waste is loaded into the reactor for pyrolysis. The heating system raises the temperature inside the reactor, causing the plastic waste to undergo pyrolysis and release pyrolysis gases. The pyrolysis gases are cooled by condensation in the cooling system, resulting in the production of liquid fuel, the uncondensed gases are collected as synthetic gas, while the residue in the reactor, are removed as char. These products and the energy used need to be properly accounted for.

### 2.1.1 Material balance around the reactor

The material balance around the plastic pyrolysis reactor was carried out according to the percentage fractions of the products obtained by Fakhrhoseini and Dastanian (2013) [17]. The liquid product yield 38.89 wt%, gas product yield 52.12 wt% and the solid residue (char) yield 8.98 wt%.
Basis: 1000g feed PET plastic
Only the plastic stream enters the reactor, while the gas, oil and char streams are the streams leaving the reactor, therefore, at steady state condition, accumulation is zero, using equation (3),
Material input = material output
Feed input (g) = gas (g) + char (g) + oil (g)

$$1000g = 388.9g + 89.8g + 521.3\ g$$

### 2.1.2 Energy balance on the reactor

This is the amount of energy required by the reactor for the plastic pyrolysis reaction is given by equation (5).

$$Q = mcp\Delta\theta$$

Where m is mass of the PET plastic, = 1000g (1kg), cp is specific heat capacity of plastic = $1.8203\frac{KJ}{Kg^0C}$, θ is change in operational temperature with ambient temperature.

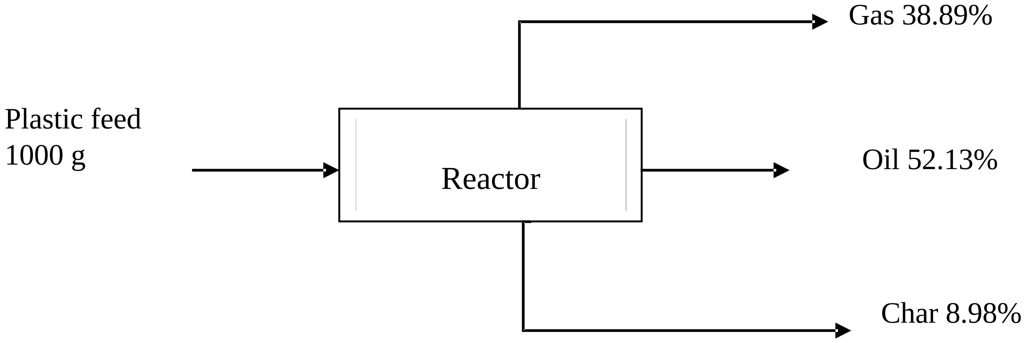

Figure 1 Material Balance Block Diagram

Therefore;
$Q$= 677.2 kJ
Operating under 1 hour (3600 secs)
Q = 188.1 Watts
The operational heat required for the pyrolysis is 188.1 W but the design heat requires safety factor of 10% operational heat [21].
Therefore;
$Q= 206.92\ W$
For 60 min operational period,

$= 12{,}415.2\ J/s$

## 2.2 Equipment Design

The reactor which is where the burning of the plastic takes place in the absence of oxygen is therefore designed as follows;

a. Volume of the reactor

$$N_A = \frac{1\ \text{g of the PET plastic x mole fraction of PET}(X_A)}{\text{Molecular weight of PET plastic}}$$

$N_A = 0.125\text{mole}$

$$C_A = \frac{\text{mass of plastic(PET) x mole fraction of oil in PET}(X_A)}{\text{Volume of the PET used}}$$

Substituting the above in equation (12) we have,

$$V = \frac{N_{A0}\, X_A}{tKC_A}$$

Where t = 60mins; k = rate constant of plastic (PET) = $0.00699\ \text{min}^{-1}$

V = 2,020.7 $\text{cm}^3$

Computation of safety factor of 20% for the reactor, yield a total volume, V as:

$V = 2424.8\ \text{cm}^3$

But for the volume of the reactor, equation of the volume of cylinder will be applied for the evaluation of its height, because of its similarity, $V = \pi r^2 h$ [34, 35]. Assuming internal diameter of 14 cm or 140 mm, radius = 7 cm or 70 mm.

Where r represent the radius of the reactor and h represent the height of the reactor, V = volume of the reactor $\simeq 2.5\ litre$

Therefore;

$h = 15.8cm$

$\simeq 16\ cm$ or 160 mm

b. Wall thickness of the reactor

The minimum wall thickness of the reactor was calculated using equation (13),

$$\text{tm} = \frac{\text{Pd}}{2(\text{SE} - \text{PY})} + \text{C}$$

Where P represent the design gauge pressure $= \frac{1\ .833\text{N}}{\text{mm}^2}$, $\text{d} = \text{pipe inner diameter } 14\text{cm} = 140\text{mm}$ S is the allowable stress of pipe material $= \frac{359.87\text{N}}{\text{mm}^2}$, E is the Casting quality factor = 1, Y represent the temperature coefficient (0.4), C = 0 mm

$tm$ = 2.13 mm

c. Design of the flat end

The flat end of the reactor that will be able to withstand the internal pressure is design using equation (14)

$$F_{end} = C_P\, D_e \sqrt{\frac{Pi}{f}}$$

Where $F_{end}$ = Flat end of the reactor, $C_P$ = 0.1, $D_e$ =internal plate diameter = 140mm, Pi = Internal design stress pressure of 316 steel at $400^0$C = 105N/$\text{mm}^2$

Pi = Internal design gauge pressure = 10.833N/$\text{mm}^2$

$$F_{end} = 0.1 \text{ x } 140\text{mm x } \sqrt{\frac{1\ .8333\frac{\text{N}}{\text{mm}^2}}{\frac{105N}{\text{mm}^2}}}$$

$= 4.49\ mm \approx 5$ mm

d. Insulation of the reactor

Glass fiber was chosen for the insulation of the reactor because of its effectiveness to prevent heat losses to the environment, and the thickness of the glass fiber was calculated using equation (19)

$$Q = \frac{-2\pi L(\Delta T)}{\frac{1}{k_1} In\frac{r_2}{r_1} + \frac{1}{k_2} In\frac{r_3}{r_2}}$$

Where Q represent the rate of heat loss from the reactor, L represent the length or height of the reactor, ΔT is the temperature difference, $r_1$ and $r_2$ are the inner and outer radii of the cylinder reactor respectively. $k_1$ represent the heat coefficient of the reactor, which is 16 $W/m^\circ C$ for stainless steel 316 as reported by Iyagba, (2008) [30], $k_2$ is the thermal conductivity of insulator, $r_3$ is the outer radius or thickness of the insulating material.

$$Q = \frac{-2\pi L(\Delta T)}{\frac{1}{k_1} In\frac{r_2}{r_1} + \frac{1}{k_2} In\frac{r_3}{r_2}}$$

$$Q \left[\frac{1}{K_1} In \left(\frac{r_2}{r_1}\right) + \frac{1}{K_2} In \left(\frac{r_3}{r_2}\right)\right] = -2\pi L(\Delta T)$$

$$\frac{1}{K_1} In \left(\frac{r_2}{r_1}\right) + \frac{1}{K_2} In \left(\frac{r_3}{r_2}\right) = \frac{-2\pi L(\Delta T)}{Q}$$

$$\frac{1}{K_2} In \left(\frac{r_3}{r_2}\right) = \frac{-2\pi L(\Delta T)}{Q} - \frac{1}{K_1} In \left(\frac{r_2}{r_1}\right)$$

$$In \left(\frac{r_3}{r_2}\right) = K_2 \left[\frac{-2\pi L(\Delta T)}{Q} - \frac{1}{K_1} In \left(\frac{r_2}{r_1}\right)\right]$$

$$\frac{r_3}{r_2} = \exp \left[K_2 \left(\frac{-2\pi L(\Delta T)}{Q}\right) - \frac{1}{K_1} In \left(\frac{r_2}{r_1}\right)\right]$$

$$r_3 = r_2 \exp. \left[K_2 \left(\frac{-2\pi L(\Delta T)}{Q}\right) - \frac{1}{K_1} In \left(\frac{r_2}{r_1}\right)\right]$$

Where $r_1 = 0.07m$, $r_2 = 0.07213m$, $k_2 = \frac{.44W}{m}{}^0C$
$k_1 = \frac{16W}{m}{}^0C$, L = $0.16m$, $\Delta T = 375^0C$, $Q = 206.92\ W$
$r_3 = 0.078\ m$ or $78\ mm$

e. Design of the condenser

The condenser of the system is a tubular heat exchanger, with the hot gas flowing through the inner pipe and water flowing through the outer pipe. Therefore, let the mass of water required for the cooling during 60 min = 0.115kg

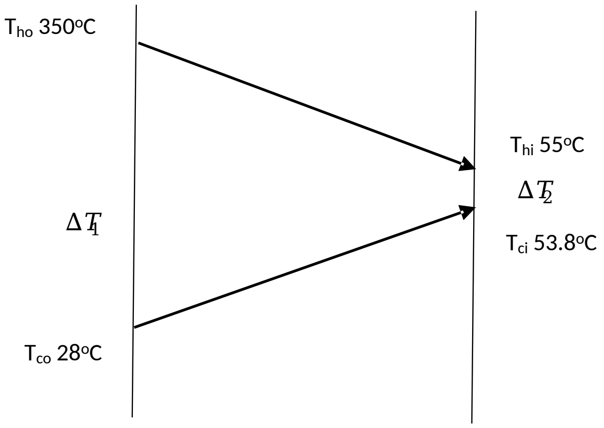

**Figure 2. Flow pattern of the heat exchanger**

Quantity of heat produced from the reactor Q, = $m\ 4178\ (T_{co} - 28)$
Therefore, $T_{co}$ = 53.8°C

Log mean temperature difference $\Delta T_m$ is evaluated using equations (20) and (21), and the flow pattern of the heat exchanger can be represented with Figure 2:
$\Delta T_1$ = 350 – 28 = 322°C
$\Delta T_2$ = 55 – 53.8 = 1.2°C
$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}}$
= 57.4°C

Calculation of the length of tubular heat exchanger is carried out using equation (21)

$Q = U_o A \, \Delta T_{lm}$

$= U_o x \; 2 \; \pi_o r L \; \Delta T_m$

Where $U_o$ is the thermal conductivity of stainless steel. Let the radius of the outer pipe = 1.5 cm

Quantity heat Q, flowing through per minute

Q = 206.92 W

Therefore, length of the pipe L,

$L = \frac{Q}{U_o \, 2 \, \pi \, r_o \Delta T_m}$

= 0.319 m or 319 mm

### 2.3 Safety and environment

The plastic pyrolysis reactor designed, requires strong emphasis on safety (free from danger or injuries) of the equipment, personnel and environment. The selection of stainless steel (316) was made because of its high tensile strength and yield stress for the pipes as well as strong anti-corrosion tendency of the reactor and fittings in order to prevent material cracking under high pressures and avoid accident. The flat end of reactor design is capable of withstanding pressures up to 10.8N/mm$^2$, ensuring there is no risk of explosions in cases of pressure rise. In this design, the vaporized noncombustible gases were condensed and recovered. In order to prevent their leakage into the environment which may cause fire, proper sealing, appropriate materials and fittings was used to prevent such. Glass fiber was used to insulate the reactor against heat loss to the surrounding, as well as preventing the reactor from hurting the operating personnel. This design provides closed system where no content is released till the end of the processing line after condensation. Also, after the condensation of the pyrolysis liquid, the acidic content of the oil should be neutralized, to protect the workers from acid burnt when they handle the finished products.

### 2.4 Costing

Adopting present market reality as at August, 2024, the cost of the following items presented in Table 1 were evaluated. The Cost evaluation on safety include, cost of seal of the reactor which comprises of high-temperature gaskets and sealants for flanges and fittings, cost of the safety features on the reactor such as temperature sensors, pressure sensors, emergency shutdown and system fire suppression system.

**Table 4 Bill of Engineering Measurement and Evaluation**

| **Item** | Quantity | Price (₦) |
|---|---|---|
| Temperature controller | 1 | 65,000 |
| Pressure gauge | 1 | 45,000 |
| Pressure valve | 1 | 3000 |
| Thermocouple | 1 | 9500 |
| Control box | 1 | 25,000 |
| Power relay | 1 | 19500 |
| Switch | 1 | 2500 |
| Heating element | 1 | 28,500 |
| Stainless steel plate | 1 | 160,000 |
| Fiberglass material | 3mm thick (1m x 1m) | 25,000 |
| Stainless steel electrode | 1 pack | 23,000 |
| Stainless steel screw | 12 | 2000 |
| Stainless steel rectangle pipe | 2 | 17,000 |
| Production cost | (Mechanical & Electrical) | 30,000 |
| Miscellaneous | - | 30,000 |
| Safety features | 1 | 120,000 |
| Seal | 1 | 35,000 |
| Total | | 445,000 |

## 3. RESULTS AND DISCUSSION

Reactor Design geometry is cylindrical with a diameter of $140\ mm$ and height of $160\ mm$ with a capacity of 2.5 liters, providing a sufficient volume for processing $1000\ g$ of plastic. A heat-resistant material of stainless steel (316) was used in the design to withstand the high temperatures and corrosive environment. Electrical heating element supplies heat to the reactor, and is designed not exceed a maximum temperature of $400°C$, since the vaporization temperature of diesel is within 300 – 360°C

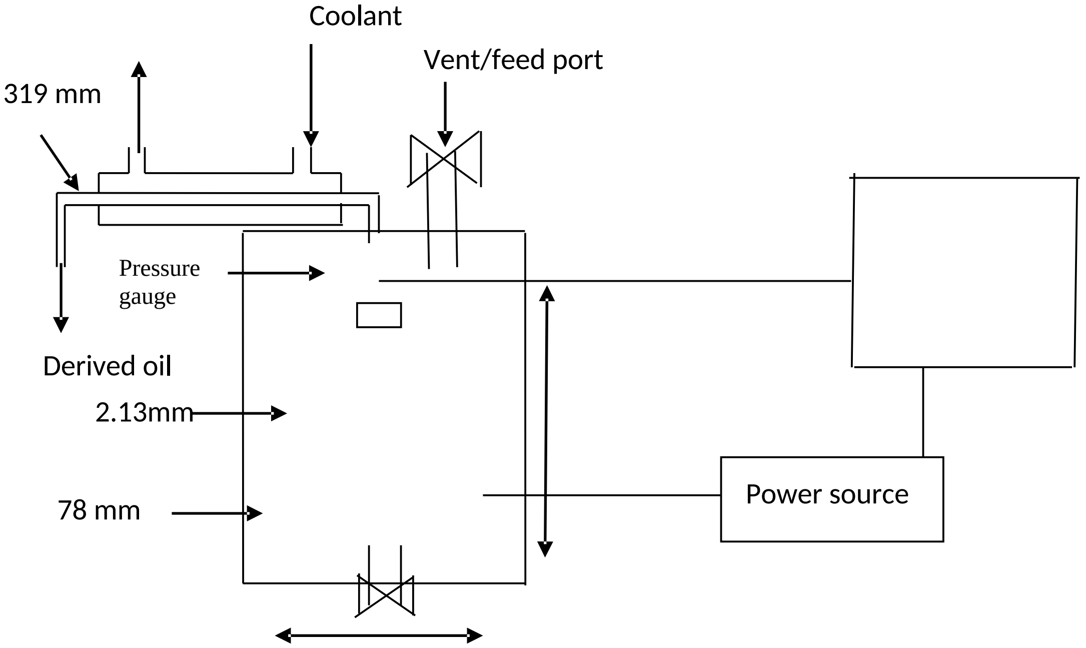

**Figure 3: Pyrolysis reactor system**

The temperature sensor control, continuously monitors and regulates the temperature, ensuring a consistent and safe operating condition, allowing for optimal pyrolysis reactions. The wall thickness the reactor which was designed as $3\ mm$, ensures the structural integrity while minimizing heat loss. This is similar to 6 mm Rominiyi *et al.* (2023) [35] obtained, when the internal pressure is evaluated with 51 bars which they used. The flat-top end thickness of $5\ mm$, provides additional strength and stability to the reactor at the top end, to withstand the operational pressure. Furthermore, the thickness of the reactor insulation was designed as $78\ mm$, using glass fiber to maintain consistent internal temperature and reducing heat loss. However, none of the researchers whose work was cited in this article, reported the details of the design of the insulation material they used for their reactor. The condenser length was designed as $319\ mm$, with $3\ mm$ diameter, to cool off the vaporized liquid before collection.

The materials balance was carried out using the results obtained by Fakhrhoseini and Dastanian, $(2023)$ [17]. The energy balance of the reactor was carried out by using the specific heat capacity of PET at $400°C$. Therefore, the result of the heating element power rating is calculated to be $682.6kJ$, which is higher than the $608\ kJ$ obtained by Rominiyi *et al.* (2023) [35], for the pyrolysis of 5kg of mixed plastic.

The equipment design of the reactor involves the design of the volume, height, wall thickness, the thickness of the glass fiber on the refractory covering the electrical heating element and the length of the condenser. The reactor volume was designed as about 2.5 liter (2425$cm^3$), which is less than the value reported by Aswan *et al.* (2020) [23] but agrees with the report of Lamido *et al.* (2023) [22]. The height of the reactor was designed as $160\ mm$ with internal diameter of $140\ mm$, but is less than the reports of Lamido *et al.* (2023) [22] and Aswan *et al.* (2020) [23].

However, safety factors were put into consideration during the design of the reactor and the insulation.

The vaporized gas will pass through the tubular heat exchanger as shown in the pyrolysis system in Figure 3, where the gas will be condensed into liquid, while the condenser is designed to use water as coolant.

The cost of the design, material selection and fabrication of this reactor as presented in Table 4, is estimated at Four Hundred and Forty-Five Thousand Naira (N445,000) only. Nevertheless, most of the researchers referenced in this article did show the detailed design of the reactor used and its cost estimation.

Pyrolysis reactions can be highly exothermic, and the presence of flammable gases and vapors increases the risk of fire and explosion, this should therefore be avoided when the system is in use. Also, a vacuum pump will ensure the elimination of air from the system, while regular maintenance of the reactor, condenser and electrical system will prevent failures when in use.

## 4. CONCLUSION

Plastic pyrolysis is an attractive technology which can serve as an alternative source for the production of diesel. Therefore, this design of a laboratory-scale pyrolysis reactor is of great importance. The design data from this work has enlarged the body of knowledge in diesel production from waste plastic. The $2.13\ mm$ thick batch reactor is designed to operate under safe condition with minimum design heat requirement of 208.56W, using electrical heating device, insulated with fiberglass of 3mm thickness. The temperature sensor was designed to measure a maximum temperature of about $400°C$ inside the reactor. The flat end of the reactor of 4.49mm is designed to be able to withstand the internal pressure of about $25\ bar$

The cost estimation of the system is economical, and the fabrication is designed to be stainless steel 316 material, which has high corrosion and heat resistance. This design approach is environmentally friendly with little or no generation of pollutants to the soil and groundwater, unlike the burning of plastic which produces toxic substances such as dioxins.

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