Design and Construction of a Semi-batch Pyrolysis Reactor for the Production of Biofuel

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Abstract. Due to the fast depletion of crude oil wells, increase in greenhouse gas (GHG) emission, energy security challenges, etc. the world through its researchers is in search of sustainable energy sources. Renewable energy sources (RES) have been found to be among the best solutions to the world’s energy insecurity and other challenges, but due to Africa’s poor sustainable energy policies, the positive effect of renewable energy has not been felt in the continent though it has the necessary resources. Biofuel being one of the RES, during its production turns waste into wealth. Pyrolysis is an important method for the production of biofuel, but because of limitations facing the renewable energy technologies (RETs) in Africa (especially the sub-Saharan Africa), constructing a pyrolysis reactor that carries out this process is a challenge to many. A semi-batch reactor was designed (using SOLIDWORKS software) and constructed taking into consideration the process’ kinetics, temperature range (up to 1000 °C) and feedstock (quality and quantity). The system after being constructed was used to produce bio-oil from cashew nut shell, and polystyrene combined with cashew nut shell. They gave pyrolysis liquids of 61.3 % and 64.58 % respectively. This system was designed for laboratory usage; it can be used in homes if scaled to suit home usage.

Keywords: Energy policies, Renewable energy, Biofuel, Pyrolysis, Semi-batch reactor.

1. Introduction
The non-renewability of crude oil wells, climate change and global warming effects (through greenhouse gas emissions, caused by the consumption of fossil fuels [1]), etc. [2] have caused researchers to look for alternative energy sources which are renewable and friendly to the environment [3]. Furthermore, energy security concerns are emerging as more consumers request for more energy resources [1].

In 2015 the International Energy Agency (IEA) did a publishing which showed that, around 75% of the world’s energy is provided mainly by combustion of fossil fuels (gas, oil and coal), while the rest comes from renewable (about 8%) and nuclear energy [4]. Accessing energy for Africa as a continent remains a great challenge to development especially in sub-Saharan Africa, though the continent has more than enough resources required to meet its present and future demands [5]. Statistics show that about 600 million Africans or more, don’t have access to electricity, while above 700 million persons use traditional biomass for cooking [6]. Enhancing access to energy leads to a reduced amount of indoor pollution,
improves educational outcomes (by giving children in schools the opportunity to study with lightening conditions) improves health care facilities, and finally it reduces the rate of rural–urban migration [6]. The rate of growth of electricity in sub-Saharan Africa is very slow, this part of Africa has a 30.5% electrification rate due to poor implementation policies and reform issues [5], thereby raising doubts as to whether the region would be able to attain 100% access to electricity by 2030 as made mention by the United Nation’s Secretary General in 2012 through a program tagged “sustainable Energy for all” [7].

Energy policies in Africa are meant to be created, improved and implemented. Looking at the power generation sector, one of the best policies to mitigate GHG (greenhouse gas) emission is to modify existing oil and coal plants so they can run with natural gas and renewable energy sources [8]. Policies that promote efficiency and reliability, will reduce transmission and distribution losses, by so, will reduce the amount of emission. Added to infrastructural development [9], the growth of renewable energies and enhanced energy efficiency, are the two main elements of any systematic energy policy in Africa [8]. Also, when working on policies that promote use of modern renewable energy sources, agreements regarding the power purchase, access to the grid and markets for green electricity are meant to be considered [10].

In the world’s energy sector today, the problem of transition to technologies that are safe and environmentally friendly is of great concern. To this effect, different engineering solutions are being brought up (developed) to ensure the smooth transition of energy companies or facilities to renewable energy sources [11]. Biofuel and other renewable energy sources (solar power, hydropower and wind turbines) are expected to have increasing roles to play in the world’s sustainable energy management and climate change mitigation [12] now and in the years to come [13]. International Renewable Energy Agency (IRENA) estimates that by 2050 liquid biofuels may reach and even exceed the amount of fuel demanded from the transport sector of Ghana, Nigeria, South Africa, Mozambique and Uganda, provided structured policies are put in place [6].

Domestic, agricultural and plastic waste management is a big challenge to most countries in Africa, including Nigeria. It must be noted that, waste recycling is considered most times as a means of sustainable municipal waste management [14]. Agricultural and some domestic waste (Biomass) have been found to be good sources of renewable energy (biofuel) [15], while plastic waste which is fast increasing is also a source of biofuel [16]. [17] The world’s biofuel production within the last decades has had a fivefold increase, and researchers expected it to double by 2020. For Africa in particular, its interest in biofuel production started in the mid-2000s, triggered by policy priorities connected to energy security and economic growth. This growth of biofuel production in Africa is attached to many environmental and socio-economic impacts which may be positive or negative [18] depending on factors such as; the feedstock, use, trade, policies put in place during the production, environmental context of biofuel production, etc. Through careful planning and good implementation of sustainable energy policies, the negative impacts of biofuel production can be mitigated [19]. Biofuel’s place in Africa provides, displaces, diverts and degrades a huge number of provisioning, regulating and potentially cultural ecosystem services.

Pyrolysis being a thermochemical process that occurs in an oxygen free environment [20], has been used for charcoal production for many years (thousands of years), while in bio-oil production where it is used to produce potential biodiesel (considered the most attractive type of biofuel [21], [22], its presence has been felt for about 30 years now [23]. With regards to temperature range, the process exists as slow, fast and flash pyrolysis. Pyrolysis is used to
convert waste products into biofuel, producing little or no waste after the process is carried out [24], thereby causing the method to get more attention nowadays compared to other thermo-chemical conversion processes [25]. Since the start of biodiesel production through the process of pyrolysis, semi-batch reactors have been widely made use of [26]. Though in recent times more effective and efficient reactors have been constructed to carry out this process [27], the semi-batch reactors are still considered because they are easier to design, cheaper to construct and maintain. To effectively convert biomass, accurate and efficient methods for determining the pyrolysis kinetic parameters are crucial [28]. Figure 1 below shows a summary of a pyrolysis process.

![Diagram of pyrolysis process]

**Figure 1:** Summary of a pyrolysis process

2. Methodology

The aim of this study, is to design and construct a portable, efficient and unique semi-batch reactor for biofuel production, as a means of enhancing renewable energy technologies in sub-Saharan Africa and Africa as a whole. To achieve this study, many elements were taken into consideration, starting from the kinetic study of the process, calculation of power consumption, reactor’s design and construction, then to application of the reactor.

2.1. Kinetic model

Before constructing a pyrolysis reactor, it is very important to understand the chemistry of the reactions that will be taking place in the reactor, that’s why we took some time to study the kinetics of the process involved. Our choice of reactor’s volume, shape, etc. are also influenced by the reaction’s kinetics. Many kinetic models have been developed to describe the process of pyrolysis, these models fall under finite and infinite rate kinetics. Infinite rate models suggest that the degradation occurs at a constant temperature while finite models take into consideration some form of reaction functions. The finite rate model describes pyrolysis as a three-way parallel process (production of gas, pyrolysis oil and char) [2] as shown in Figure 2.

![Diagram of kinetic model]

**Figure 2:** Representation of the kinetic model used in this design.
First order Arrhenius type reaction is assumed to be the form that better explains the model [2].

\[ \frac{da}{dt} = k(T)f(\alpha) \]  \hspace{1cm} (1)

where \( i = (\text{gas (g)}, \text{oil (o)}, \text{char (c)}) \), \( A \) = frequency factor, \( E \) = activation energy, \( R \) = gas constant, \( T \) = temperature (K), \( \alpha \) = dimensionless reaction extent (fuel conversion), and \( \rho'f \) = relative density of the virgin feedstock.

The lower the \( E \) value, the more reaction rate is proportional to \( A \), theoretically, this is considered the process’ maximum rate [28]. In predicting the activation energy (\( E \)), frequency factor (\( F \)) and information on the actual reaction models, the isoconversional kinetics is used.

Having put in place isoconversional kinetic triplets, that is \( E, A, f(\alpha) \), where \( \alpha = (0, \ldots, 1) \), conversion profiles can then be modeled based on Equation (1) [28]. We can summarize the isoconversional (Friedman method) equation as;

\[ \ln \left( \frac{da}{dt} \right)_{\alpha} = \ln[Af(\alpha)]_{\alpha} - \frac{E}{RT_{\alpha}}. \]  \hspace{1cm} (3)

Where \( i \) stands for the \( i^{th} \) heating rate, while \( T_{\alpha,i} \) corresponds to the constant \( (\alpha) \) of \( i^{th} \) heating rate. \( E\alpha, A\alpha \) stand for the activation energy (kJ/mol) and pre-exponential factor (1/min), for specific \( \alpha \), respectively [24]. Using the linear fit, equation (3) can be represented in an equation of a straight line, and a graph plotted with the aim of getting the unknown parameters.

\[ y = mx + c \]  \hspace{1cm} (4)

where, \( y = \ln \left( \frac{da}{dt} \right)_{\alpha} \), \( m = E\alpha \), \( x = -1/T \) and \( c = [Af(\alpha)]_{\alpha} \).

### 2.2. Calculation of reactor’s power consumption

\[ \text{Resistance (R)} = \frac{V^2}{P} = \frac{\text{(Voltage)}^2}{\text{Power}} \]  \hspace{1cm} (5)

\[ \text{Resistance (R)} = \frac{\delta L}{A} = \frac{\text{Resistivity} \times \text{Length}}{\text{Cross-sectional area}} \]  \hspace{1cm} (6)

\[ 1 \) = (2) implies, \( \frac{V^2}{P} = \frac{\delta L}{A} \), that means, \( P = \frac{V^2 A}{\delta L} \) \hspace{1cm} (7)

\( \text{Voltage, V} = 240 \text{ volt} \)

\( A = \pi \frac{D^2}{4} \), \( D \) = diameter of the wire.

\( D = 1 \text{ mm} = 0.001 \text{ m} \)

\( \delta \) = Resistivity of the Nichrome 80 wire, \( \delta = 1.5 \times 10^{-6} \mu \text{m} \)

\( L \) = length of the wire, \( L = 12 \text{ m} \)

\( P = \frac{(240)^2 \pi \times (0.0005)^2}{1.5 \times 10^{-6} \times 12} = 0.04523893421169 =2513.27 \text{ W} \)

\( P \approx 2.5 \text{ KW} \), meaning the system is meant to consume approximately 2500 watts of energy.

### 2.3. Designing of pyrolysis reactor

#### 2.3.1. Design of the sample container

The stainless-steel sample container as shown in Figure 3 was designed to have an internal diameter of 6.0 cm, external height of 15.0 cm and a thickness of 0.2 cm. It had inlet and outlet channels for Nitrogen gas and pyrolysis products respectively. At the side of the sample container was a hole for the thermocouple (to monitor the temperature inside the container).
2.3.2. Design of the reactor’s body, heating and insulating chambers. The insulating chamber was designed to have a length of 20.3 cm, width 20.3 cm and a height of 34.0 cm. This chamber was located between the heating chamber and the reactor’s external body (having a height of 50.0 cm and diameter of 31.8 cm). Figure 4 shows the designed semi-batch reactor.

3. Results
After the design, follows the construction, then the production of biofuel using our constructed reactor. The construction and biofuel production processes are considered the results of this study, since they mark the end point of the study.

3.1. Construction of the semi-batch reactor. With the help of the design, the reactor was constructed. Using scrubbed stainless steel, the construction started from the sample container, heating and insulating chambers then to the external body of the reactor.
Nichrome 80, wire (it is an alloy of 80% nickel and 20% chromium, melting point of 1400 °C) coiled on the refractory material (made from kaolin) was used as the heating element, while glass fibre as the insulator. A k-type thermocouple acted as the temperature sensor, while a PID (proportional, integration and derivative) temperature controller was used to monitor and control the temperature of the reactor. The PID controller was relayed to the power supply with the help of a steady state relay (SSR). Figure 5 are images of the constructed reactor.

Figure 5: The constructed reactor while closed (with sample container) and opened (without sample container).

3.2. Biofuel production. The reactor was used to carry out a reaction for the production of bio-oil from Cashew nut shell, and polystyrene combined with cashew nut shell. The sample was loaded into the sample container, then Nitrogen gas left to flow through the reactor for about 2 min before powering ON the reactor. The gas flowed throughout the pyrolysis process, carrying the produced gas from the reactor to the condensing unit. The condensing unit was made of 4 Buchner flasks dipped into ice blocks. At this unit, the condensable gas was condensed into liquid (bio-liquid) while the non-condensable gas (bio-gas) was sent out. The bio-char was collected from the sample container as solid residue. The system gave a pyrolysis liquid of 61.3% for cashew nut shell and 64.58 % for polystyrene combined with cashew nut while varying the time, temperature and sample weight. The system was operated at a temperature range of 500 to 800 °C, heating rate of 100 °C/min. A detailed report on this process is yet to be published, that’s why we gave just a summary of the production process. Figure 6 shows a sketch of the complete pyrolysis process.
Figure 6: The complete pyrolysis system

4. Discussion
Haven implemented the design by constructing the reactor, and a successful pyrolysis process carried out, it is very important to know that the constructed reactor had some unique features compared to the others. The reactor could be operated at least 3 times a day with a cooling time of about 2 hours, this reactor had a weight less than 25 kg which made it portable, its power consumption was 2.5 kw (almost as that of an electric iron), last but not the least, the reactor could be dismantled at any time when necessary. While designing and constructing a pyrolysis reactor, there are many factors that are to be taken into consideration, starting from the feedstock, the temperature range, design, the metal to use during the construction etc. It becomes a challenge when one starts constructing without taking note of these factors.

5. Conclusion
The semi-batch pyrolysis reactor was easier to design, construct and maintained. The bio-liquid after being produced was sent for analysis, the results showed that further treatments were required on the liquid before making use of it as a fuel. Better policies are meant to be made that will enhance researches on renewable energy sources, since it is the gate way for sustainable energy management. Solutions on energy insecurity in Africa are not implemented by the African continent due to unstructured policies, little or no funding, and limited renewable energy technologies.

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