International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 07 July 2024, pp: 267-285 www.ijaem.net ISSN: 2395-5252

Design, Fabrication and Evaluation of an Improved Fixed-Bed Batch Reactor of a Pyrolysis Plant

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Date of Submission: 10-07-2024 Date of Acceptance: 20-07-2024

ABSTRACT
Pyrolysis is the thermo-decomposition of biomass in the absence of oxygen to produce biochar, pyro-oil, and bio-gas which are environmentally friendly products. The reactor is an enclosed chamber used for pyrolysis of biomass which includes palm kernel shell (PKS). A fixed-bed reactor is simple to operate with low operating cost. Features in reactors enhance functionality and reduce maintenance and production costs. Poor functional spring-type heating element breakdown during service due to small cross-sectional area. Bio-oil is contaminated with traces of biochar resulting in low quality. Passage of biochar through the flowline causes blockages of the flowline causing obstructions in the flow of the products. Poor maintenance strategy causes wear, rupture and damage to the product flowline made of copper material. A fixed-bed batch reactor with improved features was designed and fabricated. 3000W 10 mm diameter NICKEL-flex heating element was installed in place of 2000W 3 mm diameter spring-type. Two ASTM E 11 DIN ISO 3310-1 standard and nominal wire mesh were installed in the reactor. The reactor and the improved features were evaluated through the pyrolysis of 1, 2, and 3 kg batches of PKS at 200, 300, 400 and 500 °C. The NICKEL-flex was more efficient in heating PKS. The breakdown of the heating element was arrested during the process. The heating element had a longer life span. 28.5, 56.8, and 78.6 g masses of biochar were trapped at 400 °C during the pyrolysis of the three batches. Similarly, 31.4, 63.7, and 82.7 g masses of biochar were trapped at 500 °C. The product flowline was free of blockages as the product could flow seamlessly and the quality of the bio-oil was better. Maintenance costs were reduced. The functionality of the pyrolysis plant was enhanced.

KEYWORDS: Biomass, Fixed-bed reactor, Heating element, Improved features, Palm kernel shells, Pyrolysis, Standard wire mesh

I. INTRODUCTION

Pyrolysis is the process of applying heat to the feedstocks (biomass) in the absence of oxygen and the products are pyro-oil, char, and gas [1] [2] [3]. It is a form of treatment that chemically brakes organic materials through the application of heat in an oxygen free environment. Pyrolysis has been used for turning wood into charcoal since ancient times. It is an established and actively effective chemical technology that is utilized profoundly in the chemical industry [4]. One of the main products of the pyrolysis process is pyro oil which is useful as a fuel [5] [6]. Biomass means biological materials and is one of the most likely sources of energy, it is readily obtainable with; high carbon content, low ash content, low emission, low moisture content, and renewable [7]. Palm kernel fruit is a biomass that is rich in bio-oil (biofuels) which is an alternative fuel for running mechanical engines and ICE [8] [9]. Palm kernel is the eatable seed of the oil palm tree and the fruit is generally recognized for its helpfulness in making two kinds of oil; palm kernel oil from the kernels and palm oil from the fleshy portions of the fruit [10]. PKS are by-products from numerous palm oil mills, and industries around the world with challenges in management [10] [11 [12]. The world needs sustainable sources of energy that apply to manufacturing and automotive industries to stop overdependence on fossil fuels [13] [14].

Reactors are enclosed pressure vessels used for the pyrolysis of biomass. Reactors are designed and fabricated with the consideration of some factors such as the type of feedstocks, product yields, mass of feedstocks, method of heating, type of wastes, etc. The fixed-bed reactor is a convenient reactor for the pyrolysis process due to its simplicity of operation and low operating cost. The fixed-bed reactor consists of a few simple major components. The fixed-bed batch reactor could be oil-fired or gas-fired. It could also be fired by electricity to maintain a constant heating rate and prevention of environmental pollution. Electric heating elements are made in different shapes, designs, cross-sections, and ratings. The available shapes include tubular, universal plug-range, universal range surface, Crosley bake range, whirlpool range, range kleen, and range radiant surface amongst others. The shape and design are often determined by the shape of the housing or environment where it is being used.

The Pyrolysate (bio-oil) comprises pyroligneous acid and settled tar (biochar), constituting about 16.67% of the palm kernel shell [15].

Traces of the biochar as residual in the bio-oil causes contamination of the bio-oil and the quality of bio-oil is affected [15].

Particles of biochar are often trapped along the copper tube in which products pass through. The trapped biochar along the flowline causes blockages of the flowline [16]. The adopted maintenance operational strategy often resulted in wear and rupture of the flowline. The flowline lacks a trapping device for biochar. [16] reported that a heavy fraction of biochar frequently blocks the linking pipe (channels) and gathers inside the reservoir.

Heating elements with small diameters, as small as 5mm are poor in service due to long periods and the generated during operation. The power delivery corresponds to the thickness of the cross-section. This produces a limitation to supply high power when it is required. When it is used for an average period of 4 months results in breakages, corrosion, and malfunctioning due to operational conditions.

The challenges of the plant impacted negatively on product delivery, increased maintenance costs and caused plant malfunctioning, hence the need for improvement in the affected features for optimal product yield and function of the pyrolysis plant. The objectives of this paper are to design, fabricate, and evaluate an improved fixed-bed batch reactor to address the inherent challenges and function optimally with minimal maintenance cost.

II. LITERATURE REVIEW

Eastern Regional Research Center (ERRC) discovered both thermo-chemical and bio-chemical methods are used for feedstock conversion and pyrolysis technology is an future industry that will fuel tomorrow's development and protect the environment [16] [17].

Bio-fuels and bio-gas are emerging as present and key future alternatives to fossil fuels [18] [19].

There are three major types of pyrolysis process namely:

I. SLOW PYROLYSIS: Slow pyrolysis is the process of slowly heating the feedstock to the maximum temperature to produce the three products of pyrolysis [20] and applicable in agricultural wastes such as almond shells, corn leaves, corn straw, cotton stalks [21], fruit peels including jackfruit peels, lemon peels, and orange peels [22], pinewood and timothy grass [23], palm kernel shells [24].

II. FAST PYROLYSIS: Fast pyrolysis is the rapid heating of the feedstock for a short time to produce the three products of the pyrolysis process [25] and conversion of biomass to liquid fuels [26] [27] [28]. It is getting progressively significant in some affiliate countries of the International Energy Agency (IEA) [10].

III. FLASH PYROLYSIS: A flash pyrolysis method was established by Longanbach and Bauer to produce liquid fuels, chars, and gases from bituminous and sub-bituminous coal [29].

Typically, the concentration of sulphur and nitrogen of less than 1% correspondingly in the biomass signifies that the biomass is environmentally friendly [30]. Pyrolysis has been extensively investigated in current times due to its effective thermal conversion and green technology [31]. The compositions and yields of the finish products are extremely dependent on the operational parameters (temperature, mass of feedstocks, time) during the pyrolysis process [32]. Biochar is a product of pyrolysis and a soil enhancer, holding water and nutrients in the soil, energy sources, pollutant absorbents, and carbon sequestration [33] [34]. The pyrolysis process is determined by the moisture content of the feedstock, which must be around 10%. At higher moisture contents, more water is produced and at lower levels, there is a danger that the process only give out dust instead of oil [35].

Presently, there is an increasing research attention in the design and use of simpler systems for the collective production of bio-oil and char, both currently observed to be valuable products [36] [37]. However, the classification of reactors

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Volume 6, Issue 07 July 2024, pp: 267-285 www.ijaem.net ISSN: 2395-5252

can also be based on: (1) the final products targeted (oil, char, heat, electricity, gases), (2) the reactor's method of process (batch or continuous), (3) how it is heated (direct or indirect heating, auto-thermal, microwave), (4) the thermal source used (electric, gas heater, biomass combustion), (5) the method of loading the reactor (by hand, mechanical), (6) operating pressure for the unit (vacuum, atmospheric, pressurized), (7) the material used for the construction of the reactor (soil, brick, concrete, steel), (8) reactor compactness (stationary, mobile), (9) the reactor's location and (10) different types, shapes, and designs [8].

Generally, a reactor may either be a fixed bed or a fluidized bed. The feedstock is fixed at the reactor bed hence it is called a fixed-bed reactor. The losses in fixed bed pyrolysis are comparatively less than in fluidized bed pyrolysis. Moreover, fluidized bed pyrolysis is more complicated. The development of reactors from ancient times was born out of challenges encountered from time to time and the quest for higher product yields at minimal running costs. The development of reactors over the years has led to the fabrication of different types of reactors to process different types of biomass and wastes to achieve the desired product yields and efficiency [38].

The different types of reactors include (1) Continuous Stirred-Tank Reactor (CSTR), (2) Plug Flow Reactor (PRF) [39], (3) Continuous Oscillatory Baffled Reactor (COBR), (4) Semi-Batch Reactor (SBR), (5) Catalytic Reactor (CR), (6) Fixed-Bed Reactors (FBR) [40]. The fixed-bed reactor is capable of pyrolyzing biodegradable materials. Fixed-bed batch reactors have a modest design, are most cost-effective, have less product loss due to attrition and wear, and have efficient heat management which is very important in the reactor design [41] [42].

[43] uses catalytic pyrolysis to advance the quality of the bio-fuel product from lignocellulosic biomass. It is a hopeful approach for renewable biofuels and limited lignocellulosic biomass.

[44] reported that the use of a high-pressure fast pyrolysis process applies to biomass to scale up the product quality. However, the problems of pyrolysis on a practical scale appear to be associated with achieving high product quality and yield.

[45] reported an outline of microflow chemistry, electrification, their incorporation toward sustainable manufacturing, and their significant to biomass advancement. The flow chemistry at the microscale can empower non-stop sustainable manufacturing by initiating new working windows, accurate residence time control, improved mixing and transport, enhanced yield, productivity and essential safety. It is limited to the manufacturing of chemicals, microflow chemistry, and its electrification for sustainable chemical manufacturing.

[46] conducted a techno-economic analysis (TEA) and life cycle assessment (LCA) of a theoretical catalytic fast pyrolysis (CFP) facility that changes 240 metric tons/day of mixed plastic waste and predicted that the aromatic product stream can be cost-competitive with virgin BTX mixtures. The study refers to the significance of process parameters for improving the CFP of mixed waste plastics from economic and environmental viewpoints. TEA and LCA only were used as analytical tools.

[47] developed an integrated model proposal which validates that the synergistic incorporation of hydrothermal and hydrodeoxygenation promotion technologies can produce an optimum formation that optimizes fuel production, whilst forestalling the need for the procurement of hydrogen. The results of a techno-economic analysis (TEA) recommend that if the proposed integrated method is used, it is probable to produce biofuel (43% gasoline, and 57% diesel) at a very competitive minimum selling price. It is limited to Norwegian spruce.

[48] reviewed the progress and challenges of various types of reactors and potential feedstocks for pyrolysis were reviewed. Derived pyrolytic products in different phases have desirable properties. Catalytic pyrolysis and co-pyrolysis are methods with high product selectivity. It is a sustainable technology. The effects of methods of heating were not taken into consideration.

[49] reported that fast pyrolysis for liquids has been established in current decades as a fast and flexible technique. The adopted methods were pre-treatment and bio-oil advancement. The results are applicable as second-generation biofuels, as part of a biorefinery idea and upgrading to fuels and chemicals. The research did not consider the quality of the bio-oil.

[50] reported that methods in drug production and new advancement could advance the efficiencies, and performance for chemical applications. It incited the Enabling Technologies Consortium (ETC) in Washington, DC., to launch its novel chemistry reaction environment working group in 2020. The group birth Chemical Engineering Research and Design (CERD) which recognises novel reaction technologies as key to future reactor development and manufacturing. The

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scope of the research was limited to chemical reactors in the pharmaceutical industries.

[51] reported that fixed bed reactors are the modest type of reactor to design, and comprise of simple functional parts. However, there are repeatedly difficulties faced with the plastic feed such as high viscosities, low thermal conductivities and unequal shape when being loaded inside the reactor [51]. There are also difficulties faced with small catalyst surface areas inside the fixed-bed reactor [50]. Reactor challenges are major causes of malfunctioning and poor product yields which include the following:

i. the poorly durable and functional electric heater
ii. inefficient heat exchanger causes poor condensation of gases and product loss
iii. traces of biochar in the bio-oil cause contamination of the bio-oil
iv. Blockage and clogging of product flowline by the mixture of biochar and bio-oil
v. Destruction of product flowline during maintenance operation
vi. Wear of copper flowline during biochar removal

Plate 1 shows the traces of copper filling in biochar recovered from the copper flowline during maintenance operation.

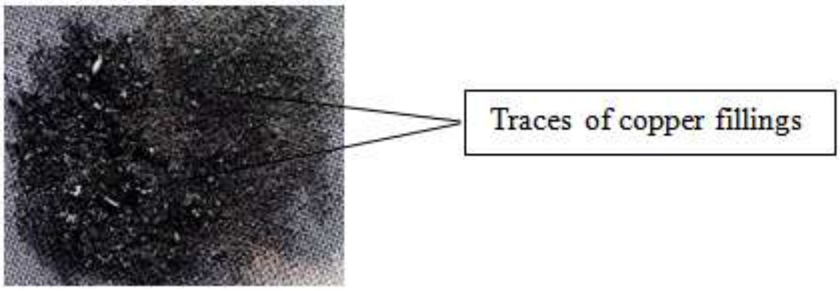

Plate 1: Traces of copper filling in biochar recovered from the copper flowline

The focus of this study is design, fabricate and evaluate of an improved fixed-bed reactor of a pyrolysis plant and overcome the challenges that were found the existing fixed-bed batch reactor.

III. METHODS

The components and parts were installed with adequate analysis to perform satisfactorily in the heating unit. The analysis of the components preceded the fabrication and installation of the parts. The heating unit consists of various components which include:

(a) furnace metallic case, fabricated from a 2 mm thick sheet metal supported by 25 mm x 25 mm 3 mm angular steel bar
(b) α-alumina (Al_2O_3) refractory clay for preventing heat loss
(c) reactor for the thermal decomposition of biomass at elevated temperature
(d) stainless steel wire mesh was installed in the reactor for trapping biochar and preventing biochar from blocking the product flowline
(e) electric heating element for the thermal decomposition of the biomass in the reactor
(f) automatic temperature control system for the heating element
(g) temperature indicators for indicating the heating and reactor temperatures

The furnace wall was fabricated with a 2 mm thick sheet. The furnace leg was fabricated using an angular steel bar specification of 25 x 25 x 3 mm. The furnace wall and legs were welded together by electric arc welding process. The refractory clay of adequate mineralogical, chemical, mechanical, and physical properties, provides the needed heat resistance for furnace lining and can withstand temperatures as high as 1800 ^oC depending on the value composition of the properties [52] [53]. The amount of α-alumina (Al_2O_3) in the clay is 23.3% which is satisfactory and adequate for lining purposes with no threat of any crack [54].

The refractory clay was prepared by using an ASTM E 11 normal opening of 500 µm and DIN ISO 3310-1 to achieve the desired texture. The chemical composition and the physio-mechanical properties of the clay deposit are given in Tables 1 and 2.

Table 1: Chemical composition analysis of refractory lining of Asero clay deposit

Chemical Composition	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
% Deposit	66.8	0.45	21.3	2.94	n.d	0.07	0.08	0.02	0.45	0.06	8.43

[54]

The physio-mechanical properties of the refractory lining clay are shown in Table 3.2.

Table 2: Experimental physio-mechanical properties of the clay deposit in Asero, Ogun state at 1600 ^{0}C

Properties							
Bulk Density (g/cm3)	% Dry Shrinkage	% Total Shrinkage	%Water Absorption	% Wallpage Length	Compressive (MPa)	Breaking Load (N)	Crack Formation
1.26	9.53	11.91	10.73	1.82	54.53	454.15	No Crack

[54]

The refractory lining was moulded in the furnace frame for proper positioning of the reactor. The heating element was connected to the control system using heat resistance 4 mm cable wire. Two thermocouple sensors were connected to the reactor to measure the heating and reactor temperatures. of the reactor. Figure 1 shows the exploded design drawing of the furnace steel frame and refractory lining.

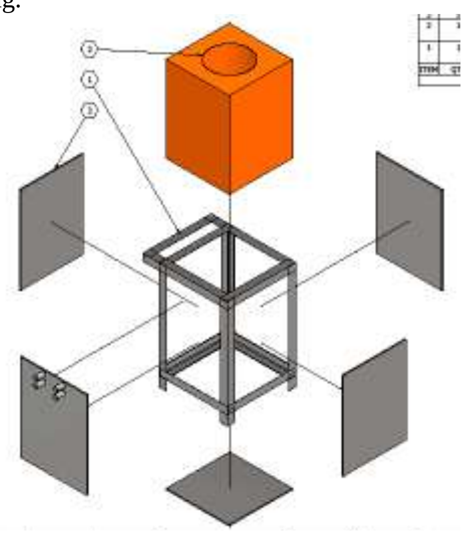

Figure 1: Design of the furnace steel frame and the refractory lining

The fixed-bed batch reactor was made from a conventional refrigerant cylinder. The volume of the reactor is 17.4 liters and it is designed to withstand a temperature of up to 1200 ^{o}C and a pressure of 3.5 MN/m^2 [55]. Cylindrical metal is a part of the reactor for positioning the standard wire mesh. The specifications of the cylindrical metal are a height of 112 mm, an internal diameter of 164 mm, and a thickness of 3 m. Two smaller flanges of 2 mm thickness each were welded inside the cylindrical metal shown in Figure 3. The distance between the two flanges is 65 mm. The two smaller flanges both have the same external diameter of 164 mm but different internal diameters of 154 mm and 148 mm. The two smaller flanges were used to hold the two stainless steel test sieves in position.

Figure 2 is the isometric drawing of the reactor with the stainless-steel wire mesh sieves in position. The conversion ratio X of biomass species in a reaction is equal to the number of moles of reacted biomass per mole to the number of moles of biomass fed into the reactor as given in Equation 1, 2 and 3:

$$X = \frac{moles\ of\ reacted\ biomass}{moles\ of\ biomass\ fed\ into\ reactor} \quad (1)$$

$$N_R = N_{AO} - N_A \quad (2)$$

$$X = \frac{N_R}{N_{AO}} \quad (3)$$

Where: X is the ratio of moles of biomass reacted to moles of biomass fed into the reactor

N_R is the moles of biomass reacted in the reactor

N_{AO} is the moles of biomass fed into the reactor

N_A is the moles of biomass left unreacted

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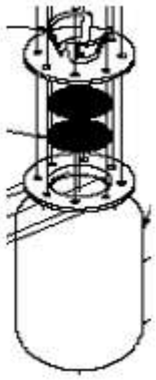

Figure 2: Isometric drawing of the reactor with stainless steel sieves

Two bigger flanges were fabricated to connect both the reactor and the cover. The flanges have a thickness of 4 mm each with internal and external diameters of 163 mm and 218 mm. Eight holes were drilled on each of the two flanges at equal distances. The dimension of the drilled holes is 8.5 mm. One of the flanges was welded to the reactor while the other was welded to the cover of the reactor. A metallic frustum was welded to the cover of the reactor to connect the reactor to the product flowline which passes through the heat exchanger. The two flanges used for closing the reactor are shown in Plate 2 (a to b).

(a) Top flange for closing reactor

(b) Bottom flange for closing reactor

Plate 2: (a to b): The two bigger flanges used for closing the reactor

Two standard stainless-steel test sieve woven wire mesh were installed within the reactor. The distance between the two sieves is 65 mm. The specification of the sieve is ASTM E 11 DIN ISO 3310-1 with an opening of 2 mm and a wire mesh diameter of 500 µm.

Plate 3 shows the two smaller flanges used for positioning the stainless-steel test sieve in the reactor.

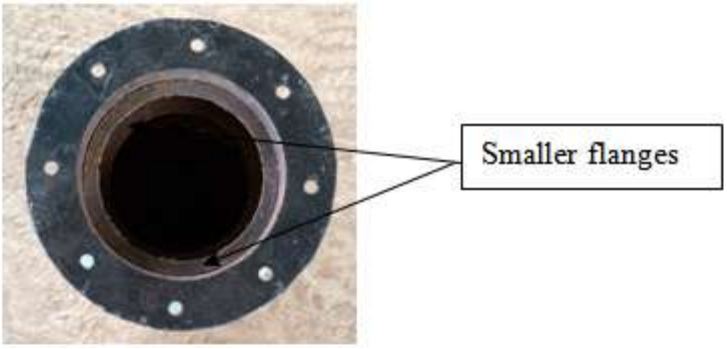

Plate 3: Two smaller flanges are used for positioning the stainless-steel test sieve in the reactor

An electric heating element of a high rate was installed in the furnace for heating the biomass in the reactor. The rating of the heating element is 3000W, 240 V, 12.5 A and 19.2 Ω. The length of the element is 10 m with a circular cross-sectional diameter of 10 mm. The heating element is made of NICKEL-flex material. It is flexible, foldable, and laminated to prevent electric shock. The heating element was coiled to the shape of the surface of the reactor and installed in the furnace to heat the reactor. The element was connected to the control system. A contactor is an electro-mechanical device that makes and breaks electric circuits automatically using a solenoid and other electrical components to control the power supply to the system to control the temperature of a reactor at the pre-determined value.

The control system consists of two temperature indicators, one contactor device, two thermocouple sensors, and an automatic switch. The electrical components were connected by 2.5 mm and 4 mm cable wires. The specifications of the temperature indicator are model number REX-C PID and, intelligent temperature controller. It can measure temperature range of 0 to 1300 ^{o}C. The accuracy of the temperature indicator is 1 ^{o}C. The two thermocouples were connected to the two temperature indicators. The sensor of the thermocouple was placed inside the reactor to measure the temperature of the feedstock which is the reactor temperature. The second sensor was placed on the external surface of the reactor to measure the heating temperature which is the temperature of the heating element. The temperatures were easily read through an LCD board on the temperature indicator. Plate 4 (a to d) is the components used in the control system of the heating unit.

(a) Electrical contactor

(b) Electrical switch

(c) Digital LCD Temperature indicator

(d) Thermocouple sensor

Plate 4 (a to d): The control system components and devices

The isometric view of the heating unit is shown in Figure 3. The exploded drawing of the heating unit is shown in Figure 4. The two improved features which are the two standard wire mesh sieves and the high-power heating element are shown in the exploded drawing in Figure 4.

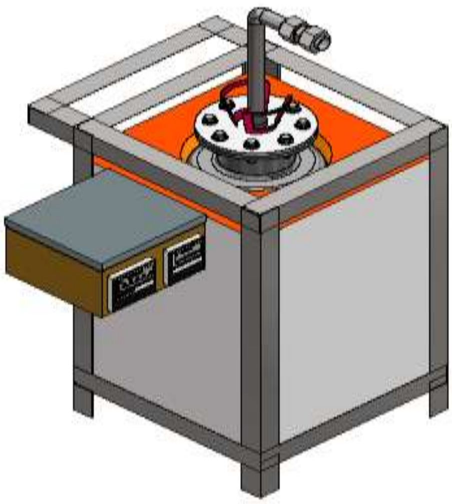

Figure 3: Isometric drawing of the heating unit

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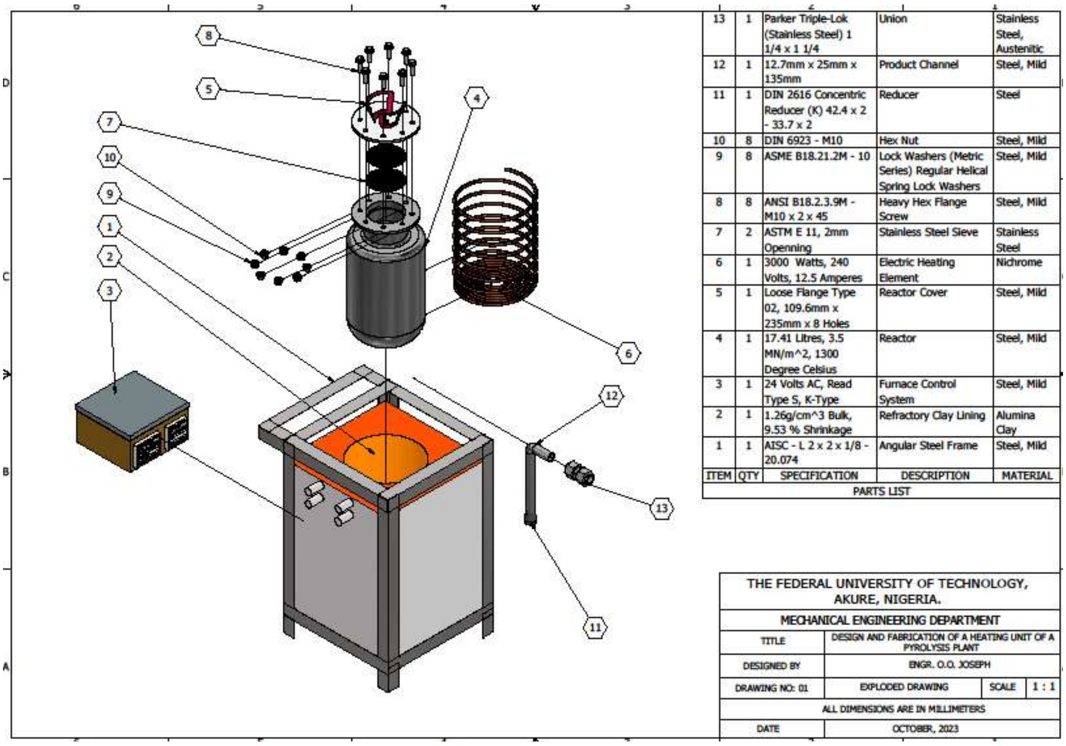

Figure 4: Exploded drawing of the heating unit

Performance evaluation of the pyrolysis plant was done. The pyrolysis process of three batches of 1kg, 2kg, and 3 kg at the pyrolysis temperatures of 200 ^{o}C, 300 ^{o}C, 400 ^{o}C, and 500 ^{o}C was carried out. The masses of deposited biochar were obtained by determining the masses of empty stainless-steel test sieve and stainless-steel test sieve with the biochar. The mass of the biochar deposited was obtained using the simple difference method given by equation (4).

$$G = C + O \quad (4)$$

Where: G is the mass of the biochar

C is the addition of masses of biochar and stainless-steel wire mesh

O is the mass of the stainless-steel wire mesh

Figure 5 shows the standard stainless-steel wire mesh that is used for trapping the biochar.

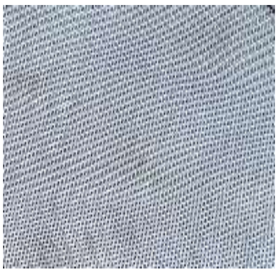

Figure 5: Stainless steel test wire mesh for trapping the biochar

The heating and reactor temperatures were recorded at 10-minute intervals.

Figure 6 shows the experimental test procedure used for the pyrolysis of the PKS to evaluate the performance of the standard test wire mesh sieves in the reactor and the high-power heating element in the furnace.

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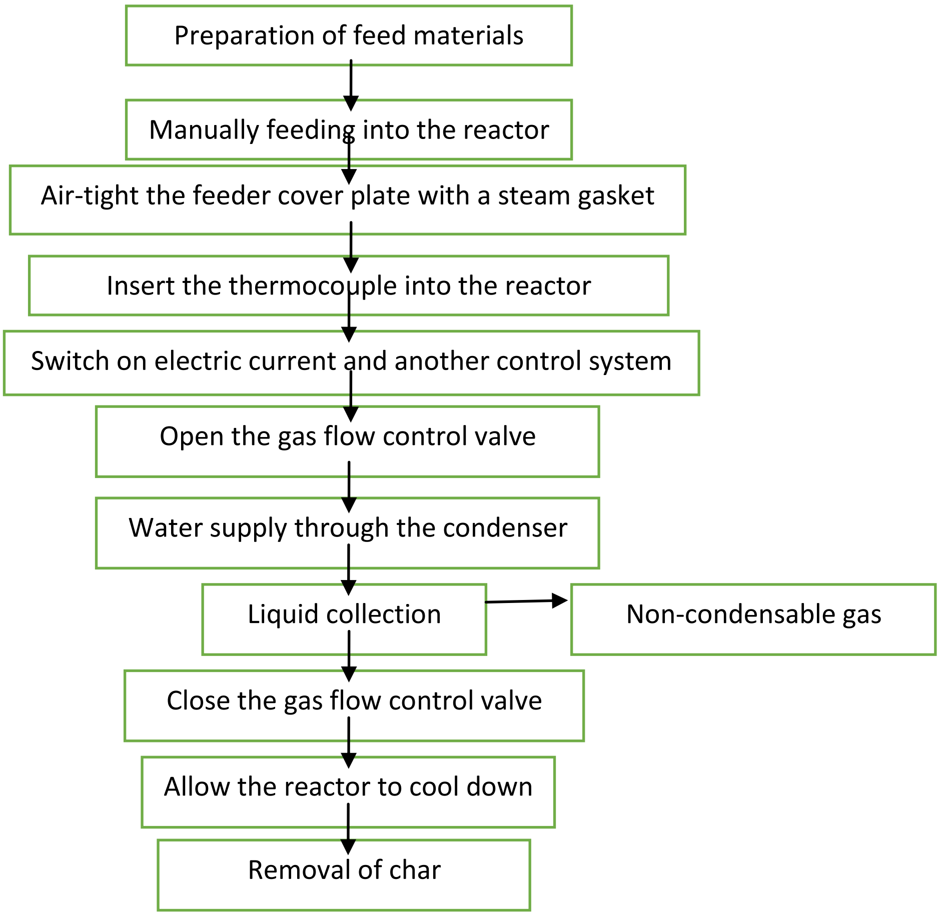

Figure 6: Operational procedure for the pyrolysis process of palm kernel shell

However, in this study, the evaluation of the improved features is limited to the pyrolysis of PKS biomass. Palm kernel shells are by-products of palm oil mills in many parts of the world.

IV. RESULTS

4.1 RESULTS OF EVALUATION OF THE STAINLESS-STEEL WIRE MESH SIEVE

Wetness of the stainless-steel sieve was observed at the pyrolysis of 1 kg, 2 kg, and 3 kg batches of PKS at 200 ^{o}C. Similarly, when 1 kg, 2 kg, and 3 kg batches were pyrolyzed at the temperature of 300 ^{o}C, the wetness of the sieve with bio-oil was equally noticed.

Plate 4.20 (a to f) is the wetness of the stainless steel with bio-oil during the pyrolysis of 1 kg, 2 kg, and 3 kg batches of palm kernel shells at the process temperatures of 200 ^{o}C and 300 ^{o}C.

(a) Bio oil-stained sieve for 1 kg at 200 ^{o}C

(b) Bio oil-stained sieve for 1 kg at 300 ^{o}C

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(c) Bio oil-stained sieve for 2 kg at 200 °C (d) Bio oil-stained sieve for 2 kg at 300 °C


(e) Bio oil-stained sieve for 3 kg at 200 °C (f) Bio oil-stained sieve for 3 kg at 300 °C

Plate 4 (a to f): Results of bio oil-stained sieve during the pyrolysis of PKS

However, at the process temperature of 400 °C, 1 kg of PKS shell deposited 28.5 g of biochar on the stainless-steel sieve, 2 kg deposited 56.8 g and 3 kg deposited 78.6 g. Similarly, pyrolysis of 1 kg of PKS gave a deposited 31.4 g, 2 kg of PKS deposited 62.7 g and 3 kg of PKS deposited 82.7 g, all at the process of 500 °C. Table 3 shows the masses of biochar trapped by the stainless-steel sieve and the corresponding process temperatures.

Table 3: Masses of trapped biochar and process temperatures

Temp. (	Mass of biochar from 1 kg batch (g)	Mass of biochar from 2 kg batch (g)	Mass of biochar from 3 kg batch (g)
200	0	0	0
300	0	0	0
400	28.5	56.8	78.6
500	31.4	63.7	82.7

In Figure 7, during the pyrolysis of 1 kg batch of PKS no biochar was trapped at the temperatures of 200 and 300 °C. 48% was trapped at 400 °C and 52% at 500 °C. The mass of biochar increased with an increase in the process temperature.

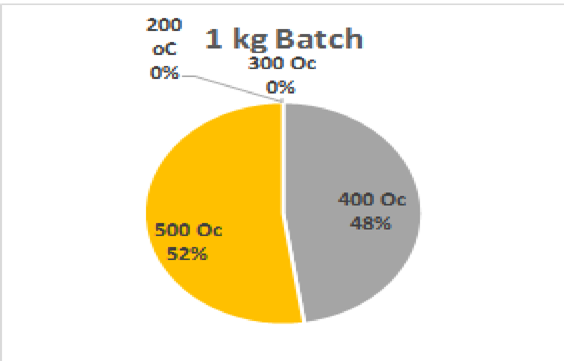

Figure 7: Masses of trapped biochar and the process temperatures by %

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In Figure 8 during the pyrolysis of 2 kg batch of PKS no biochar was trapped at the temperatures of 200 and 300 ^{o}C. 47% was trapped at 400 ^{o}C and 53% at 500 ^{o}C. The mass of biochar increased with an increase in the process temperature.

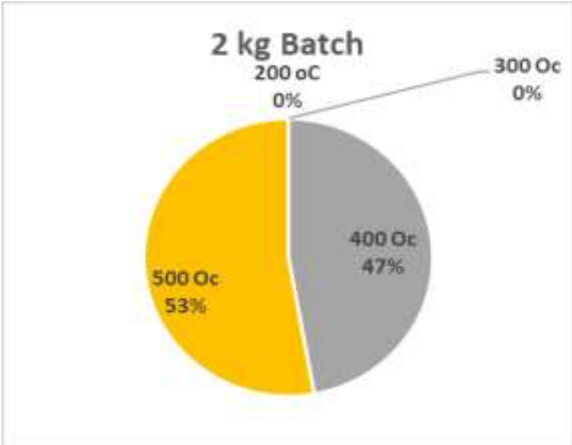


Figure 8: Masses of trapped biochar and the process temperatures by %

In Figure 9 during the pyrolysis of 3 kg batch of PKS no biochar was trapped at the temperatures of 200 and 300 ^{o}C. 49% was trapped at 400 ^{o}C and 51% at 500 ^{o}C. The mass of biochar increased with an increase in the process temperature.

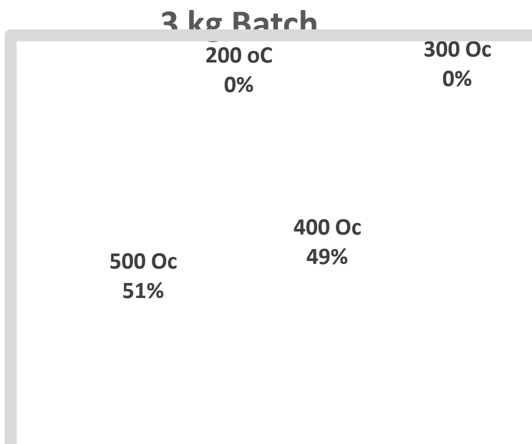
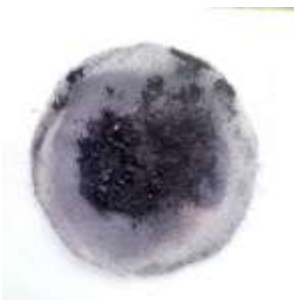


Figure 9: Masses of trapped biochar and the process temperatures by %

Plate 4.21 (a to f) presents the results of the trapped biochar by the stainless-steel sieve at the exit point of the reactor.



(a) Trapped biochar from 1 kg at 400 ^{o}C **(b) Trapped biochar from 1 kg at 500 ^{o}C**

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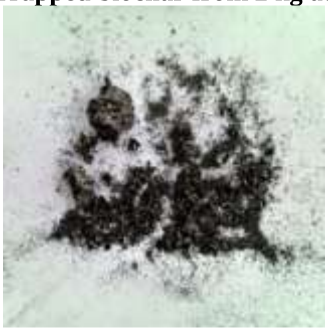
(c) Trapped biochar from 2 kg at 400 ^{o}C **(b) Trapped biochar from 2 kg at 500 ^{o}C**




(a) Trapped biochar from 3 kg at 400 ^{o}C **(b) Trapped biochar from 3 kg at 500 ^{o}C**

Plate 5 (a to f): Results of trapped biochar by sieve during the pyrolysis of PKS

4.2 RESULT OF PERFORMANCE EVALUATION OF THE ELECTRIC HEATING ELEMENT

The thickness of the diameter of the heating element was increased from 3 mm to 10 mm. The thickness of the heating element was increased by 233%.

The temperature rise was slower in the 3 mm diameter element than the 10 mm diameter element. The 3 mm diameter element was more fragile than the 10 mm diameter element.

The heating element of the fabricated reactor was made of NICKEL-flex (2.4068) material.

The 3 mm diameter heating element is spiral in nature and rated 2000 W while the 10 mm diameter is solid and rated 3000 W. Plate 6 shows the heating element of the 3 mm diameter element before use.

Plate 6: Heating element of the reviewed reactor for pyrolysis process before use

Consequently, the 3 mm heating element rusted during the pyrolysis process and broke into pieces after the pyrolysis process. Plate 7 is the broken 3 mm spiral heating element.

(a) Rusted and broken heating element (b) Rusted and broken heating element

Plate 7 (a to b): Broken heating element after usage

Plate 8 is the 10 mm diameter NICKEL-flex heating element.

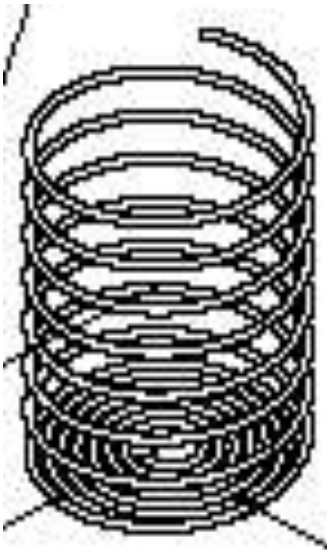


Plate 8: Heating element of the fabricated reactor used for pyrolysis of the PKS

Pyrolysis of PKS showed that the product yields were enhanced when the 10 mm NICKEL-flex heater was used. When a 3 mm diameter heater was used, 1 kg of PKS yielded 0.41 kg/h, 2 kg yielded 0.53kg/h and 3 kg yielded 0.75 kg/h of bio-oil. However, when a 10 mm diameter heating element was used, 1 kg of PKS yielded 0.49 kg/h, 2kg yielded 0.64 kg/h and 3 kg yielded 1.02 kg//h of bio-oil. The NICKEL-flex heater enhanced the product yields by 27% concerning time. Table 4 shows the product yields obtained from the heater of 3 mm diameter and the 10 mm diameter heater. The product yield in the heater of 10 mm was greater than the product yield in the 3 mm.

Table 4: Product yields obtained from heaters of 3 mm and 10 mm diameters

S/N	Diameter of heater (mm)	Product Yields			Total Yield
		1 kg Batch	2 kg Batch	3 kg Batch	
1	3	0.41	0.53	0.75	1.69
2	10	0.49	0.64	1.02	2.15

In Figure 10 the product yield from a 10 mm diameter heater is greater than the product yield obtained from 3 mm per time.

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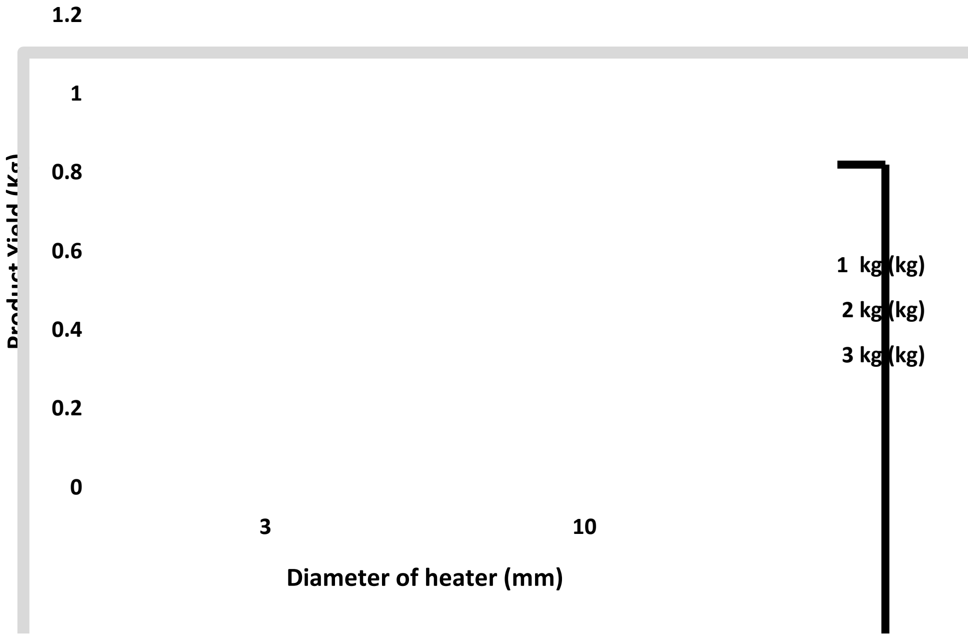

Figure 10: Relationship between the product yields and the diameter of the heater

In Table 5, the heating rates of the 3 mm diameter heating element decrease with the increase in process temperature. The heating rate is 8.26 ^{o}C/min at 200 ^{o}C and 1.55 ^{o}C/min at a temperature of 500 ^{o}C during the pyrolysis of 1 kg batch. The heating rate is 5.98 ^{o}C/min at 200 ^{o}C and 2.91 ^{o}C/min at 500 ^{o}C for 2 kg batch and 5.62 ^{o}C/min at 200 ^{o}C and 1.55 ^{o}C/min at 500 ^{o}C for 3 kg batch.

Table 5: Heating rate obtained in the 3 mm diameter heating element

Temp (^{o}C)	1 kg (^{o}C/min)	2 kg (^{o}C/min)	3 kg (^{o}C/min)
200	8.26	5.98	5.62
300	6.95	4.98	4.75
400	3.95	3.74	2.85
500	2.00	2.01	1.55

Figure 9 shows that the heating rate of the biomass decreases with an increase in the process temperature of the pyrolysis from 200 to 500 ^{o}C.

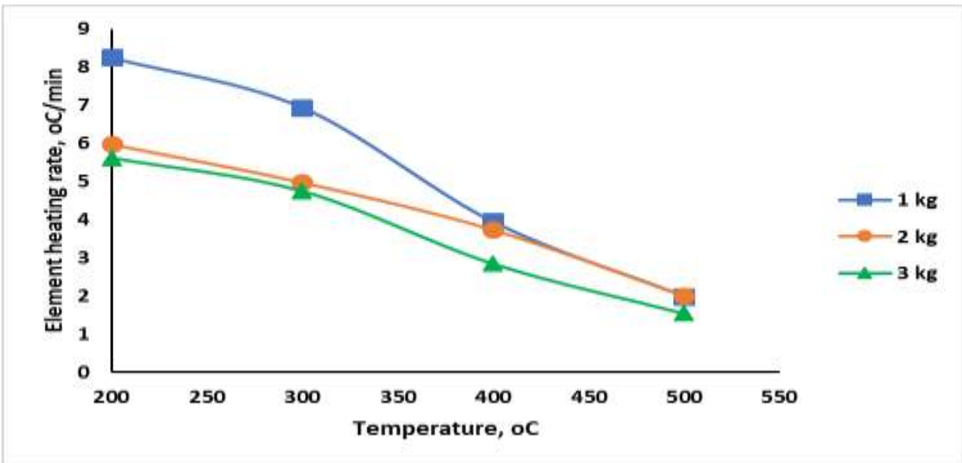

Figure 9: Relationship between the heating rate of the biomass and process temperature

International Journal of Advances in Engineering and Management (IJAEM)
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In Table 6, the heating rates of the 10 mm diameter heating element decrease with the increase in process temperature. The heating rate is 9.92 ^{o}C/min at 200 ^{o}C and 2.93 ^{o}C/min at a temperature of 500 ^{o}C during the pyrolysis of 1 kg batch. The heating rate is 7.27 ^{o}C/min at 200 ^{o}C and 2.49 ^{o}C/min at 500 ^{o}C for 2 kg batch and 6.17 ^{o}C/min at 200 ^{o}C and 2.08 ^{o}C/min at 500 ^{o}C for the 3 kg batch.

Table 6: The heating rate obtained in the 10 mm diameter heating element

Temp (^{o}C)	1 kg (^{o}C/min)	2 kg (^{o}C/min)	3 kg (^{o}C/min)
200	9.92	7.27	6.17
300	7.81	5.72	5.38
400	4.15	4.01	3.45
500	2.93	2.49	2.08

Figure 10 shows that the heating rate of the biomass decreases with an increase in the process temperature of the pyrolysis from 200 to 500 ^{o}C.

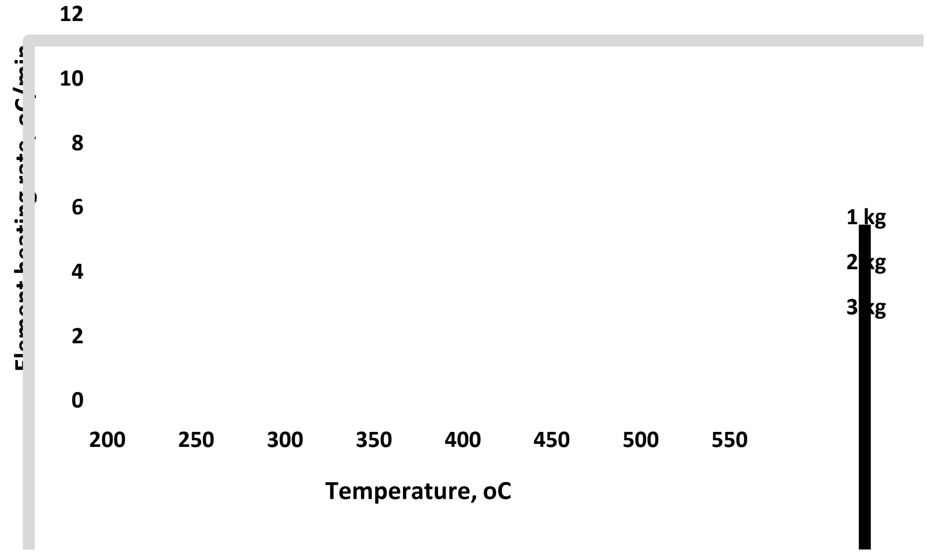

Figure 10: Relationship between the heating rate of the biomass and process temperature

V. DISCUSSIONS

The wetness of the sieve with bio-oil at temperatures of 200 ^{o}C and 300 ^{o}C was due to the low temperature of pyrolysis [55] [56]. At low temperatures often between 200 and 300 ^{o}C correction process takes place while the pyrolysis process takes at temperatures above 400 ^{o}C [57]. The mass of biochar trapped by the sieve increases from 28.5 g at 400 ^{o}C at 1 kg of PKS to 78.6 g. at 5000 ^{o}C in 3 kg of PKS. This is due to an increase in the temperature of pyrolysis and the mass of the feedstock and the secondary cracking of the PKS. At temperatures between 400 ^{o}C and 500 ^{o}C pyrolysis process occurred which produced pyrolysis products. Consequently, when the sieve stopped the biochar within the reactor, the product flowline was free from biochar blockage. Hence, the bio-oil could flow seamlessly for smooth product delivery. Loss of bio-oil due to convention and radiation was prevented. An effective maintenance strategy is the key to the optimal performance of equipment and machinery without compromising standards in maintenance operations [58].

The closeness of the heating element to the external surface of the reactor produced an efficient heating of the biomass. It also prevented heat loss by radiation. The NICKEL-flex heating element could be folded into the desired shape due to its flexibility and formability nature. A 50% increase in the power output of the heating element produced an increase in the thermal effect on the biomass. The breaking of the 3 mm diameter heating element was due to the fragility and effect of exposure to heat for a long period. The NICKEL-flex element possessed a longer lifespan than the spring-type element due to the increase in its diameter which made it more rigid.

The increase in the product yields with the 10 mm diameter NICKEL-flex element over the 3 mm spring-type element was due to the increase in the electrical power from 2000 W to 3000 W. The Increase in the electrical power produced a greater thermal efficiency on the biomass per time. The heating rate at the preliminary stage of the pyrolysis process is high but reduced as the temperature progresses due to the disappearance of the feedstock in the reactor as a result of thermal cracking and the formation of biochar which has a lower heat capacity than the feedstock [32] [59]. The heating rates of a 10 mm diameter heating element are greater than the heating rate of a 3 mm diameter heating element due to the difference in the power which is 50%. Heating rate and process parameters positively influence the product yields of the pyrolysis process [60]. Improved features have the possibility of enhancing the efficiency and functionality of machinery and industrial processes for optimal product yield.

VI. CONCLUSION AND FUTURE WORK

A stainless-steel test wire mesh sieve trapped the biochar within the reactor and prevented the blocking and clogging of the flowline. Progressively, the mass of biochar trapped by stainless steel wire mesh sieves increased as the mass of the PKS batch increased. The improved features kept the copper tube free of any obstruction for smooth product delivery. The electric heater made of NICKEL-flex (2.4068) material, rated 3000W and 10 mm diameter performed satisfactorily and better than the 3 mm diameter spring-type heating element. The improved features proffered solutions to the challenges and problems encountered in the reviewed reactors. The study will apply to biorefineries and biotechnology industries for better maintenance strategy and promotion of green technology for energy sustainability. It is recommended that other biomass should be utilized for the performance evaluation for future work.

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