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Design and Fabrication of an Ablative Pyrolyzer for Production of Bio- lubricants and chemicals in Oil Well Drilling Application

Adegoke S.O.[1*], Adeleke A.A.[2], Ikubanni P.P.[2*], Falode A.O[1], Alawode A.J[1]., Agboola O.O., and Adediran A.A.

[1]Department of Petroleum Engineering, University of Ibadan, Ibadan, Oyo State.
[2]Department of Mechanical Engineering, Landmark University, Omu-Aran, Kwara State

Abstract

In this study, an ablative pyrolyser having 27.1 cm inner diameter, 41.2 cm outer diameter, the full chamber height of 74.7 cm and chamber volume of 40 litres was designed and fabricated. 150KW heater was wounded around the reactor chamber made of stainless steel to provide a higher temperature of up to 1400°C. The -40 to 105°C capacity heat resistance wires were used to conduct the heater into the electrical panel which has several components such as the contactor, temperature controller, thermocouple wire and so on to give a particular desired working temperature. This pyrolyser applies technology of thermal energy in the heated walls of the pyrolyser being transferred to the biomass by conduction in the absence of oxygen for onward disintegration into gas, bio-oil, and biochar. After fabrication, 12 kg each of *Tectona grandis* and *Rhopalosiphum maidis* was fed into the reactor and pyrolyzed at 500°C, the bio-oil product for both samples were mixed together and distilled at 120°C and the bio-oil distillate was characterized for density, kinematic viscosity, pH, acid value and free fatty acid content. The bio-oil distillate shows a density of 0.960 g/cc, pH of 7.2, kinematic viscosity of 84 cst and acid value of 42.20 compared to the bio oil crude which showed higher values. This pyrolyser has been found on average to melt 12 kg each of *Tectona grandis* and *Rhopalosiphum maidis* to 5353 and 3493 g crude bio-oil respectively for a period of at least 3 h. The mass of bio-char for *tectona grandis* and *Rhopalosiphum maidis* were 3325 and 2614 g respectively while the reactor requires 8 h to cool before discharging the bio-char from the reactor. This research work can provide a basic designing formula for effective and workable ablative pyrolyzer fabrication for Nigerian wastes having high energy content.

1. Introduction

Pyrolysis is the thermo-chemical decomposition of organic material at elevated temperatures in the absence of oxygen [1]. It involves the simultaneous change of chemical composition in the physical phase and is irreversible. Compared to other thermochemical conversion processes such as gasification, combustion, and liquefaction, pyrolysis is the most important. Pyrolysis was earlier known around 38,000 years ago to be useful for the production of charcoal as an unintentional residue from cooking fires for cave drawings by Cro-Magnon man [4]. It is only more recently that biomass and organic wastes have become a focus as feeds for pyrolysis and related thermal treatment processes for energy recovery and biodiesel production [20]. Biomass composes majorly of cellulose, hemicellulose, lignin, starch and protein and it has been adjudged to be carbon neutral which is renewable, storable, substitutive and abundant. Biomasses include agricultural crops, timber, marine plants, forestry and fisheries resources. Pulp sludge, black liquor, alcohol fermentation stillage, organic industrial wastes, municipal wastes such as kitchen garbage, sewage sludge and paper wastes are all considered to be biomass too. The use of biomass as a source of energy in many developing countries has risen to 40 - 50% which made it become the third-largest global source of energy [1]. The fabrication of the pyrolysis reactor and its further usage will help in the production of bio-fuel from biomass and therefore provide an alternative fuel that is biodegradable, non-toxic and environmentally safe fuel/oil compared to the unsafe conventional fuel from fossil origin [6]. This process is far better than incineration because it prevents soil and water pollution, it is not harmful and not toxic [8]. A pyrolyser can be used to control problems posed by plastic waste according to Dhruvkumar *et al.* [20], this was contained in the paper titled "design and analysis of waste plastic pyrolysis reactor". Pyrolysers can either use electricity as a heater or another source as a heater, Hossain *et al* [4] fabricated a fixed bed pyrolyser with cylindrical biomass as a source heater, it was found that bio-oil yielded was 51 wt% at 500°C. However, much work has to be done on the performance of a pyrolyser for high yield of quality bio-oil at a short time range.

So, much reliance on imported product reduces our dependency and doesn't translate to economic growth for us but rather destroys us and lead to unemployment for teeming growth youth, thus the need to fabricate a pyrolyser here with various materials such as stainless steel, mild steel, and so on that are sourced locally. Biomass with high energy content can be fed into this pyrolyser and translated to energy use; this will create employment and increase in Gross domestic product for our dear country. An ablative pyrolyser uses thermal energy to decompose the biomass in contact with the heated wall into bio-oil, biochar and gas. This design is simple, workable and easy to use, even in the field unlike many other reactors that have been produced in the past.

2 Materials and Methods

2.1 Design of vessel geometry

A pyrolysis reactor is adjudged as the heart of the pyrolysis process which is the reason why it was kept cylindrically vertical with a small opening to reduce air-influx into the chamber. The ablative reactor was designed to produce temperature up to 1400°C, the heat supplied from the heated wall causes the biomass inside the heating chamber to heat up by conduction process without air. The biomass consequently turns to vapour and rises through the vapour line into the condenser for condensation (bio-oil production). Fig 1a shows the heating principle of an ablative pyrolyser. The innermost part of the chamber was made of stainless steel (EN 1.4401) [7], this is because, stainless steel does not readily corrode or stain with water as ordinary steel does [6,8]. Five pieces of 3 KW heater (model: EPK 4590E25) were wounded round the stainless steel parts from the top to bottom as shown in Fig 1b and mild steel of 0.3 cm thickness was used to cover those parts covered by the heater. A small allowance up to 9 cm thickness was applied to fix a lagging material usually found in deep freezers called Cellulose. Cellulose contains next to no oxygen within it, it is the most fire-resistant forms of insulation. This helps to minimize the amount of damage that a fire can cause [7]. The primary manufacturing process of cutting using lathe machine and welding using a welding machine, electrode, and grinding machine for smooth finishing was adopted for the fabrication of this reactor as shown in Fig 1c. The pyrolysis reactor fabrication specification is shown in Table 1 and Fig 2 gives the engineering drawing of the pyrolyser.

Fig 1: (a). Schematic of heat transfer method in ablative pyrolyser (b). Heater wounded round the stainless steel (c). Full assembly system of the pyrolysis reactor

2.1.1 Analysis of the exact heater wattage selected. The heater wattage was calculated using Equation (1):

$$\mathrm{KW} = \frac{W_T \times C_P \times \Delta T}{3412 \times Time} \quad (1)$$

Where KW is kilowatt, W_T is the weight of the satinless steel, C_P is the specific heat capacity, ΔT is the change in Temperature and Time is the hours to reach the set temperature. 3412 is the compression factor [7].

$$W_T = \text{Density} \times \text{Volume} = 8.0\text{kg/dm}^3 \times 40\text{litres} = \frac{8.0 \times 2 \times .205 lbs \times 40 litres}{litres} = 705.6\ lbs$$

$$C_P = 500 J/KgK = \frac{500 \times 0.000948\ BTU}{2.205 lbs \times K} = \frac{0.215 BTU}{lbsK}$$

$\Delta T = 600 - 25 = 575°C = 848.15$ K, Time = 0.25 h

$$KW \square \frac{705.6lbs \times 0.215\ BTU/lbsK \times 848.15K}{3412 \times 0.25h} = 128647.392/_{853} = 150.8\ KW$$

2.1.2 Analysis of reactor mild steel thickness

Inner design pressure (P)= $8\ bar = 8 \times 103425 = 827400\ N/m^2$, Inner radius (r)= $13.55\ cm$, Allowable Stress (S)= $70\ MPa$ @ 300°C, Weld joint efficiency (E) = $70\%\ for\ butt\ joint$

Therefore, thickness of reactor mild steel (t) $= \frac{P \times r}{(S \times E) - 0.6 \times P} = \frac{827400 \times 0.1355}{(70 \times 10^6 \times 0.7) - (0.6 \times 827400)} = \frac{112112.7}{48503560} = 2.3\ mm.$

However, 3 mm has been used for the mild steel thickness for safety purpose.

Table 1: Specifications of the pyrolysis reactor

specifications	value
Outer Diameter	41.2 cm
Inner diameter	27.1 cm
Height of reactor	74.7 cm
Upper opening diameter	14.2 cm
Bio char discharge pipe	10 cm
Height from the vapour line to the ground	98.4 cm
Size of bolts	0.5 cm
Total length of the vapour line	97.8 cm
Length of the pyrolyser stand	45.2 cm
Volume of the reactor chamber	40 litres

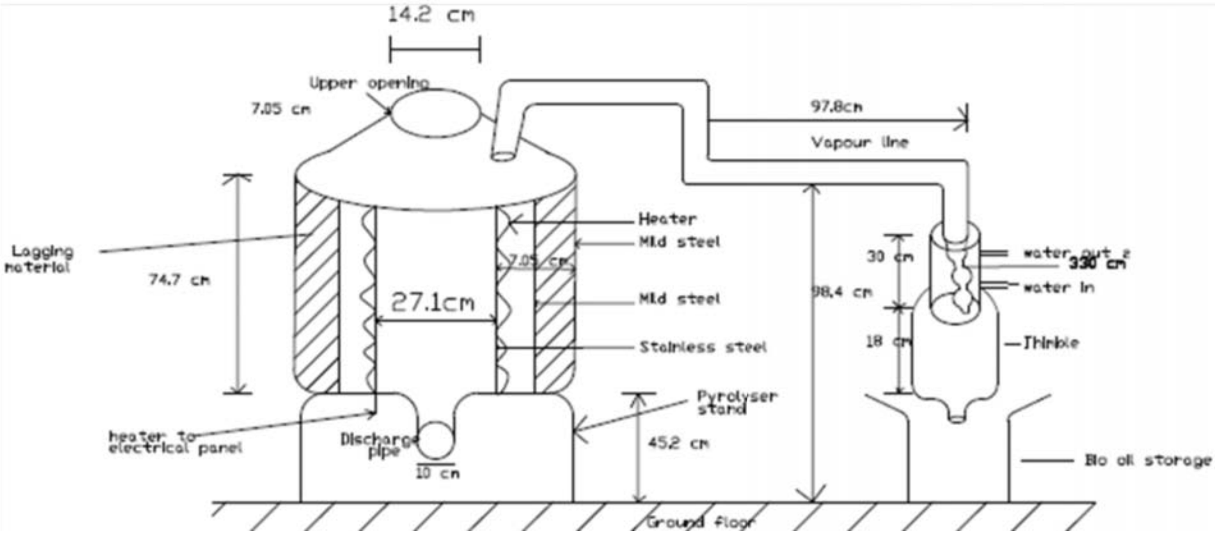

Fig 2: The Pyrolser showing the dimensions using AutoCAD.

2.1.3 Design of Electrical Panel

The electrical panel (25.2 × 16.5 × 30.2 cm) was welded to the side of the pyrolysis reactor. Inside this panel was the digital temperature controller (Model: C100FK06-M-AN)/ Serial no: 121125) which has capacity up to 1300°C. It helps to maintain a desired temperature coming from the heater with the help of 125 A contactor which helps in switching on/off the power circuit. A heat resistance cable having a capacity of -40 to 105°C coming from the heater wounded round the stainless steel is connected to the contactor. A K2m thermocouple attached to the temperature controller helps to detect the working temperature in the pyrolyser chamber. An IEC 947-S-1, UIMP 16 kv latch switch and APT AD6-22D/S indicator are also seen in the electrical panel.

2.2 Method

2.2.1 Sample collection

The saw dust of *Tectona grandis* (TG) sample (12kg) *and 12 kg of Rhopalosiphum maidis* (RM) were collected at a saw mill and market in Ibadan, Oyo state. Table 2 gives the physical properties of the two samples.

Table 2: Physical properties of the two samples [9-10].

category	biomass	Moisture content (wt. %)	Organic content (wt. %)	Ash (wt. %)	High heating value (MJ/dry-kg)
waste	*TG*	15-60	99.0	1.0	20.5
Derivative	*RM*	5-15	80.8	19.2	15.2

2.1.4 *Sample preparation*

The two samples are pulverized using a knife milling machine and dried for two weeks (5 h/day) under a 35 °C atmospheric condition. This was done to reduce the moisture contents.

2.1.5 *Bio-oil extraction*

The lower part is firmly closed and the sample fed into the reactor chamber. 6 bolts were employed to close the upper lid effectively while nitrogen serve as the carrier gas for inert environment and the temperature was set to 550°C, the latch switch indicator shows an orange color once the reactor is on. It takes about 15 mins for the desired temperature to be reached. A condenser was attached at the end of the vapour line with chilled water flowing in and out of the outer section of inner tube .The first vapor is discovered through the condenser opening when the temperature reached about 400°C (10 mins after). A round bottom flask is set at the bottom of the condenser to collect the bio-oil for characterization. The bio char in the chamber was discharge through the discharged pipe after 8 h and weighed.

2.1.6 *Bio-oil yield*

A weighing balance (Model no: PB3002-S/Serial no: 1119401867) was used to measure the weight (in grams) of the total bio-oil and the bio-char yielded.

2.1.7 *Phase separation*

A 500 ml round bottom flask was half-filled with bio-oil and a condenser thimble was placed on top of the flask to distillate storage. A condenser with chilled water flowing in and out was placed on top of the thimble being suspended by a Soxhlet chamber to prevent the vapor from escaping before condensation. The whole distillation set up was placed on an 1800 W Lab-line Multi-unit extraction heater (Serial no 5000/5002; Model no: 0677). ASTM D86 standard test method was adopted at 120°C [11].

2.1.8 *Physio-chemical properties of the oil*

A calibrated 51.1 ml pycnometer was used to determine the density of the bio-oils based on ASTM D4052 standard method [11]. A Viscosimeter (200Kmax USA C12) was used to calculate the viscosity of the sample bio-oil using ASTM D 446 standard according to Khan *et al* (2016) recommendation [12]. A pH meter (pH98108) probe was dipped into the test liquid and the value displayed on the meter is recorded as pH.

2.1.9 *Acid value determination.*

Free fatty acid and acid value were obtained based on the recommendation of Abdullah *et al* [13]. TG/RM oil (bio-oil) of 5g was weighed into 250 ml conical flask and 50 ml neutral alcohol (isopropyl alcohol) was added along with a drop or two of 0.5 ml of alcoholic phenolphthalein as the indicator. The content was swirled and placed on a hotplate. The mixture was then titrated warm with 0.02N KOH to persistent pink color which persisted for 15 seconds. The titration was done in duplicate following Equation 2

$$\text{Acid value} = \frac{\text{ml of alkali} \times \text{N}56.1}{\text{weight of the sample (g)}} \tag{2}$$

3 Results and discussion

3.1 *Colour, bio-oil and bio-char yield*

Fig 3 represents the bio-oil crude, bio-oil distillates and bio-char yield for RM and TG. Both bio-oil crudes show a dark brown color while the distillates show light brownish color as shown in Fig 3b. This could be that the heavier component responsible for the dark color such as micro carbons and chemical compositions has been distilled off and only the lighter ends are collected in the condenser thimble [1]. However, more purification techniques such as esterification can be done to reduce the density and viscosity further [14]. This distillate oil yield can be used as synthetic base fluid for the formulation of drilling mud for drilling industry sequel to the toxicity and non-biodegradability encountered in the conventional base fluid [15]. The colour of the biochar is black as shown in Figure 3c, this is as result of high carbon content in lignin responsible for bio char production [1]. The mass of bio-char for TG and RM were 3325 and 2614 g, respectively and the oil yield for TG and RM were 5353 and 3493 g respectively as shown in Fig 3d. Biochar production is a function of lignin composition of the biomass and thus a possible reason for lower yield in RM because its lignin content is lower than TG [1]. Also, the result displayed in Fig 3d shows that the highest yield was from TG because it contains high content of cellulose which is a major determinant of the bio-oil yield compared to RM with low cellulosic composition [1,16]. The general low yields from both samples showing 44.6 and 29.1% for TG and RM respectively were as a result of the rate of heating, the temperature applied and the biomass composition as far as this study is concerned. More yield would be collected if temperature is increased and at low residence time [17]. The results recorded in this section is in consonant with the studies of Jahirul *et al* on biofuels production through biomass pyrolysis [1] and Lettieri *et al* [16] on recycling and recovery routes of plastic solid waste (PSW).

Fig 3: (a) bio-oil crude. (b) bio-oil distillates. (c) bio-char yield. (d) % yield of bio-oil and bio char.

3.2 *Physio-chemical properties of bio-yield*

Table 3 gives the various physicochemical properties of the bio-oil samples. The density of RM *crude* was 1.02 g/cc compared to TG crude which was 1.20 g/cc. RM density is greater than water but lower to that of TG. This suggests that RM contains *a* lighter component compared to TG. The viscosity of RM was lower to TG with 180 and 222.5 cst respectively. Usually, higher viscosity generally means higher density and it is a known fact that the density and viscosity of oil from biomass origin are high but can be reduced by purification through esterification or catalytic hydro-processing [18]. The density and viscosity of the bio-oil distillate were 0.960 g/cc and 84 cst respectively. These are lower compared to bio-oil crude values [1]. The reason for this is that the distillate contains lighter ends compared to the bio-oil crude and this can be a good product for lubrication and base fluid to formulate drilling mud [15]. The pH of RM and TG were 4.56 and 5.09 respectively. They were seen to be acidic compared to bio-distillate which was 7.2. The pH indicates the level of acid and the corrosiveness of the oil and in this study, RM tends to be more corrosive/acidic compared to others. Jahirul *et al.* [1] suggests that the level of acidity in both bio-oil crude may be traceable to the amount of hemicellulose present in each of them. This is because the degradation of hemicellulose in wood contributes to the presence of carboxylic, acetic and volatile acids in bio-oil [19]. Also, the acid value shown in Table 3 buttresses the pH value as observed for both bio-oil crudes. The acidic values were high, however, the bio-oil distillate was observed to be the least. The acid value of RM and TG was 733.33 and 66.67 respectively while that of bio-oil distillate was 42.20. Bio-oil contains carboxylic acid, fatty acid and a mixture of other compounds and this suggests the high acid value in the bio-oil [19] On a general note, the results show that bio-oil distillate is lower in density, viscosity, acid value and pH because of lighter end composition in the bio-oil and this are in consonant with existing literatures [1,19]. The bio distillates are useful as bio-lubricant and base oil for drilling mud formulation. However, further purification can be done to reduce it acidity, viscosity and density like catalytic hydro processing or esterification [15,19] .

Table 3: Bio-oil physio-chemical properties

biomass oil	Density (g/cc)	pH	Acid Value	%FFA	Kinematic Viscosity (cSt)@25℃
Bio-oil D	0.960	7.2	42.20	21.10	84

RM	1.02	4.56	73.33	36.67	180
TG	1.20	5.09	66.67	33.33	222.5

4 Conclusion

A locally fabricated pyrolyser having 27.1 cm inner diameter, 41.2 cm outer diameter, the full chamber height of 74.7 cm and chamber volume of 40 liters was used in this study to produce bio oil, bio char. The bio oil were taken to the laboratory and distilled at 120°C and discovered to show a better compositional characteristic which can be used either as chemicals or synthetic base fluid for the drilling industry in place of the conventional hazardous base fluid and chemicals used in the petroleum industry, however, further work can still done which is not covered in the study. Lathe machine was employed to cut while grinding machine was used for smooth finishing of various materials like stainless steel and mild steel that were welded together to produce this type of pyrolyser. 150 KW heaters were wounded round the pyrolyser chamber to give us a higher temperature up to 1400°C. A mild steel of 3mm thickness was used to cover the outer part of the reactor for safety purpose. A very cold condenser is also required to ensure maximum condensation to bio oil of the vapour coming out from the reactor chamber. All this makes the pyrolyser simple and very easy to operate. This pyrolyser showed that the pyrolysis of 12 kg each of TG and RM at 500°C yielded up to 44.6 and 29.1% of bio oil respectively. The pyrolyser disintegrates the biomass between 3-5 h after which the vapour line cools down. The bio char can be discharged after 8 h from the shutting down hour. The bio-oil distillate got at 120°C shows a very good result useful in drilling industries both as lubricants and base fluid. Also, other type of wastes can also be pyrolyzed using this pyrolyser. However, there is a need to optimize the pyrolysis process to know at what temperature can produce the maximum amount of biofuel. Incorporation of drier and grinder is also very essential for smooth assembly system. The parameter such as pyrolysis temperature for maximum bio-oil yield can be investigated in further work

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