Journal of Natural Sciences Research www.iiste.org
ISSN 2224-3186 (Paper) ISSN 2225-0921 (Online)
Vol.5, No.10, 2015

Experimental Investigation of the Effect of Sample Shape on Biomass Pyrolysis Characteristics in a Fixed Bed Reactor

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Abstract
In this research work, the product yield distribution from four different sample shapes of a biomass feedstock (*Gmelina arborea*) was investigated. The biomass feedstock (*Gmelina arborea)* was procured from Pakiotan Sawmill in Ogbomoso, South-Western Nigeria. The biomass feedstock was machined into four different shapes (rectangular, cylindrical, disc and equant) of equal volume of 22.8 cm^3 on the wood Lathe machine at the Engineering Workshop of Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria. Experiments were carried out at four different temperatures (400, 500, 600 and 700 ^oC) at a residence time of fifteen minutes and at a constant vacuum pressure using a fixed-bed reactor. Results obtained showed that tar yield was 3.66% at 700 ^oC and 18.15% at 400 ^oC for cylindrical shape, and 7.5% at 700^oC and 25.04% at 400 ^oC for disc shape. From the experimental data, it was also observed that the cylindrical shape has the highest gas yield of 80.11% at a temperature of 700 ^oC while the disc shape has the lowest gas yield of 49.74% at 400 ^oC. Result also showed that, the rectangular shape has the highest char yield of 27.25% at 400 ^oC while the cylindrical shape gave the lowest char yield of 16.23% at 700 ^oC. This study established that, pyrolysis of the same feedstock with different sample shapes under the same pyrolysis conditions produced different product yield distribution. Also, sample configuration affects various intra-particle physical phenomena involved during pyrolysis.

Keywords: Biomass, Pyrolysis, Sample shapes, *Gmelina arborea*

1. Introduction

Sustainable heat and power generation from biomass are at the centre of scientific and industrial interest owing to the increasing awareness about the continuous diminution in the availability of fossil fuels and the higher sensibility toward environmental preservation from pollutants generated by conventional energy systems.

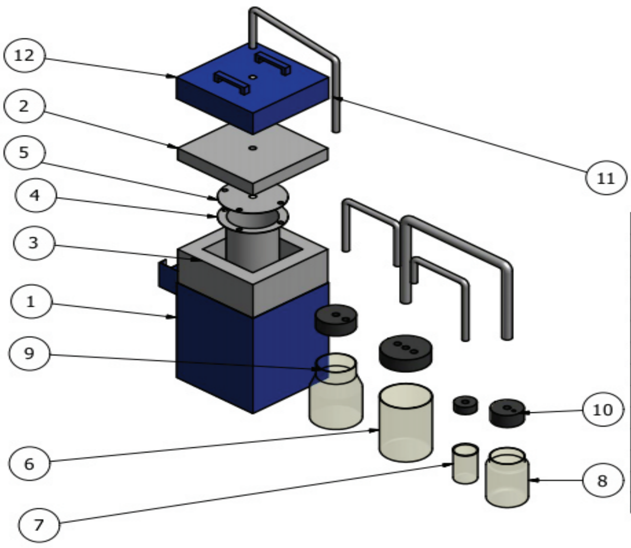
All biomass conversion technologies are constrained by a narrow tolerance range for the physical characteristics of the converted biomass, such as particle size, shape and moisture content. For example, a particle size larger than the accepted range will increase the amount of gas produced in the gasification process but, due to a slower gas diffusion speed, will decrease the quality of the gas produced, by reducing the amount of hydrogen and carbon monoxide present. A large particle size also gives rise to the intra-particle vapor-char interaction and increases the yield of undesirable, light bio-oil fractions. (Energy Independence and Security Act, 2007).

Biomass is a promising eco-friendly alternative source of renewable energy in the context of current energy scenarios. The current global energy supply is to a large extent based on fossil fuels (oil, natural gas, coal) whose reserves are finite. Being aware of the fact that energy consumption is sky-rocketing and that over dependence on fossils portends danger on the environment, energy analysts and stakeholders have realized the need to have all hands on deck in order to come up with long-term alternatives to fossils. Biomass energy is suitable for a number of applications, including home heating, heat for industrial processes and generation of electricity. Goyal *et al*. (2008) defined biomass as any living matter on earth. Biomass can be directly or indirectly produced by green plants converting sunlight into plant material through photosynthesis. The solar energy driving photosynthesis is stored in the chemical bonds of the structural components of biomass which is a natural process. During combustion, biomass releases this energy in the form of heat. For this reason, biomass species are considered as renewable sources of energy which do not add carbon dioxide to the environment in contrast to non-renewable fossil fuels. In addition, the unique feature of biomass is that it is the only renewable energy source which can be converted into convenient solid, liquid and gaseous fuels (Jahirul *et al*., 2012).

Biomass conversion technology is any technology or process that is used to convert a biomass resource into a more useful form of energy or a higher grade of fuel. Conversion of biomass to energy is undertaken using two main process technologies: thermo-chemical and biochemical/biological. Bio-chemical conversion involves the enzymatic transformation of biomass to sugars and fermentation to bioethanol (Damartis and Zabiniotou, 2011). In most cases, micro-organisms are used to perform the conversion process, which converts biomass to ethanol and methanol (Mustafi *et al.*, 2006). The two main processes used are: fermentation and anaerobic digestion. Thermo-chemical conversion involves the following processes: torrefaction, carbonization, combustion, and pyrolysis: Pyrolysis is a thermo-chemical decomposition of organic material at elevated temperatures in the absence of oxygen. Some researchers have studied the effect of thermo-physical properties on biomass pyrolysis characteristics (Di Blasi, 1997; Babu and Chaurasia, 2004; Okekunle, 2013). Other researchers also have worked on the effect of process parameters and particle size on pyrolysis (Luo *et al*., 2010; Demibas, 2004; Okekunle *et al*., 2011; Wang *et al*., 2008; Antal and Grønli, 2003; Jahirul *et al*., 2012,). Very few, however, have considered the effect of sample configuration (Babu and Chaurasia, 2004; Luo *et al*., 2010; Zanzi *et al.,* 1996) on product distribution during pyrolysis. Therefore, this work investigated the effect of sample shapes on pyrolysis characteristics in a fixed bed reactor.

2. Experimental set-up

The pyrolysis unit comprised a fixed-bed reactor, retort, pipes, product collectors and a carrier gas cylinder. The electrically powered fixed-bed reactor heats up the pre-loaded retort, hence the giving-off of the volatile stream. The product pipes channel the volatile stream into the product collectors which are immersed in an ice-bag (tar trap). Staged tar trapping was employed so as to collect tarry components which escaped the first tar trap in order to ensure efficient trapping of the tar. Figure 1 shows the exploded view of the pyrolysis set up used.



1	1	Metal casing
2	1	Furnace cover
3	1	Furnace
4	1	Crucible
5	1	Crucible cover
6	1	Flask 2
7	1	Overflow flask
8	1	Gas collection flask
9	1	Conical flask
10	4	Glass seal
11	4	Pipe and Hose
12	1	Casing cover
ITEM	QTY	PART NAME
PARTS LIST		

Figure 1: Exploded view of the pyrolysis unit

2.1 Experimental procedure

In the experiment, four temperature levels were considered (400, 500, 600, and 700 ^{o}C) at a residence time of fifteen minutes and vacuum pressure for rectangular, cylindrical, disc and equant shaped samples. The reactor was raised to a desired pyrolysis temperature and the retort, already loaded with the sample, was put afterwards in the reactor with its lid firmly secured in place by using the hold down bolts with the gasket in position. The product collectors were then weighed to ascertain their initial weights and afterwards immersed in ice-bags. The stop watch was set to a fifteen minutes countdown. At the lapse of the fifteen minutes residence time, the reactor was switched off and the retort was removed from the furnace chamber. The collected tar was measured on the weighing balance while retort was allowed to cool. The bolts holding the retort lid in position were then loosened and a tong was used to collect the char from the retort. The char was then weighed thereafter, and its value recorded. From the measured weight of tar and char, the weight of gas let off was obtained as well as the percentage weight of all products. The furnace was raised again to the desired temperature and the entire process was repeated for other runs and temperature levels for all the considered sample shapes.

2.2 Products analyses

The mechanism for collection of products was in such a way to assist separating the tar and gas in the volatile stream. The char remained in the retort while the fluids were expelled; the liquid (tar) was separated from the gas in the same collection mechanism based on the simple principle of condensation. The parameters for comparison include weight of char, tar and gas produced in each experiment. A Camry electronic kitchen scale of accuracy ±1g was employed in measuring the weight of the samples and the products. Product yields were expressed in percentage of the initial weight of the pyrolysed samples.

3. Product yields from the four different sample shapes

The product yield distribution resulting from the pyrolysis of four different shapes are presented in Table 1 to 4. From the tables, it can be seen that the disc shape produced the highest tar yield at 400, 500 and 600 ^{o}C (25.04%, 25.13% and 12.52%, respectively) while at 700 ^{o}C, equant shape gave the highest tar yield (8.61%). Results also showed that the rectangular shape gave the highest char yield at 400 and 500 ^{o}C (27.25% and 26.43%) while at 600 and 700 ^{o}C, the disc shape gave the highest char yield (24.96% at both temperatures). At all the four pyrolysis temperatures considered (400, 500, 600 and 700 ^{o}C), the cylindrical shape gave the highest gas yield (63.70%, 63.57%, 75.25% and 80.11%). In all, increase in temperature caused increase in gas yield, and decrease in tar and char yields for all the shapes considered.

Table 1: Product yield at 400 ^{o}C

Sample shapes	Tar yield (%)	Char yield (%)	Gas yield (%)
Rectangular	18.16	27.25	54.59
Cylindrical	18.15	18.15	63.70
Disc	25.04	25.22	49.74
Equant	21.10	25.12	53.78

Table 2: Product yield at 500 ^{o}C

Sample shapes	Tar yield (%)	Char yield (%)	Gas yield (%)
Rectangular	18.41	26.43	55.16
Cylindrical	18.28	18.15	63.57
Disc	25.13	24.96	49.91
Equant	20.89	25.34	53.77

Table 3: Product yield at 600 ^{o}C

Sample shapes	Tar yield (%)	Char yield (%)	Gas yield (%)
Rectangular	9.11	18.15	72.74
Cylindrical	7.24	17.51	75.25
Disc	12.52	24.96	62.52
Equant	10.02	20.04	69.94

Table 4: Product yield at 700 °C

Sample shapes	Tar yield (%)	Char yield (%)	Gas yield (%)
Rectangular	7.25	18.22	74.53
Cylindrical	3.66	16.23	80.11
Disc	7.50	24.96	67.54
Equant	8.61	19.76	71.63

3.1 Char yield

The response of char yield of various shapes at different temperatures is shown in Figure 2. As shown in the figure, of all the sample pyrolysed, rectangular shape gave the highest char yield (27.25%) at 400 °C while the cylindrical gave the lowest (16.23%) at 700 °C. Antal and Grønli (2003) suggested that higher temperature leads to a lower char yield in all pyrolysis reactions because the controlling variable of pyrolysis reaction kinetics is temperature. They argued that the effect can be thought of as forcing more volatile materials out of the char at higher temperatures thereby reducing char yield but increasing the production of carbon in the char. Therefore, chars produced at higher temperatures have higher carbon contents, both total and fixed-carbon. Regression equations for char yields from all the shapes considered were generated and are presented in section 3.4.

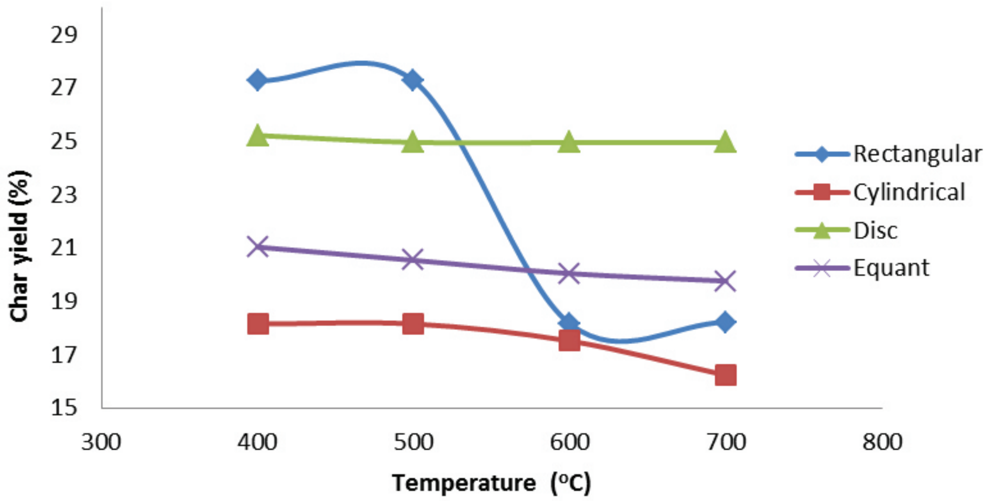


Figure 2: Char yield from different sample shapes at different temperatures

3.2 Tar yield

Figure 3 shows the tar yield obtained from the pyrolysis of the four different sample shapes of Gmelina (*Gmelina arborea*). The tar yield range between 3.66% and 25.13%. As shown in the figure, disc shape has the highest tar yield of 25.04% while the cylindrical shape has the lowest tar yield of 18.15% at 400 °C. At 500 °C, the disc shape has the highest tar yield of 25.13% while the cylindrical has the lowest tar yield of 18.28%. It was observed that for all sample shapes, tar yield decreased with increase in temperature except for disc shaped sample. This is because as temperature increased, secondary reactions causing vapour decomposition became more dominant and the condensed liquid yields are reduced. Regression equations for tar yields from all the shapes considered were generated and are presented in section 3.4.

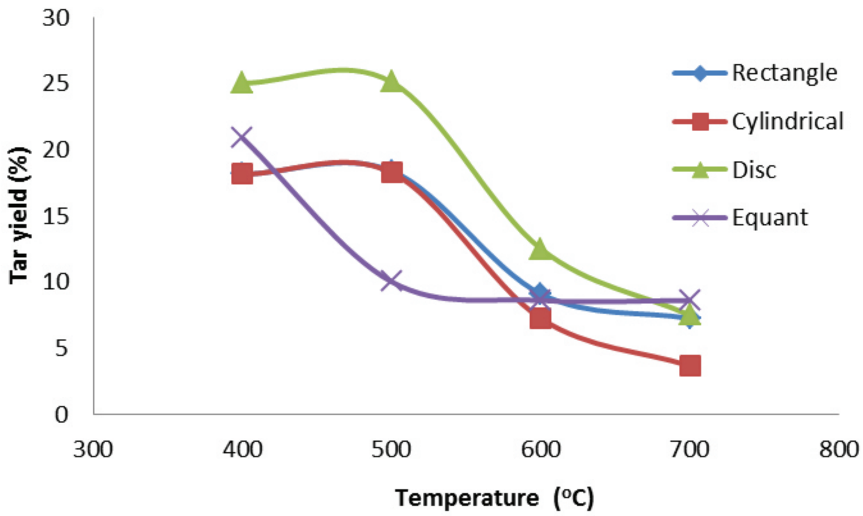


Figure 3: Tar yield from different sample shapes at different temperatures

3.3 Gas yield

Figure 4 shows the gas yields obtained from the pyrolysis of four different sample shapes of Gmelina (*Gmelina arborea*). As shown in the figure, of the four sample shapes pyrolysed, the cylindrical shape has the highest gas yield of 80.11% at a temperature of 700 ^{o}C while the disc sample shape has the lowest gas yield of 49.74% at 400 ^{o}C. The results are in congruence with the findings of Puntun *et al*. (1999). They attributed the increasing yields of gaseous products with increasing temperature during conversion of biomass to volatile materials at high temperatures. It should be expected that at very high pyrolysis temperature, liquid production will decrease while gas production will increase. The effects of temperature on the yield and composition of the product of pyrolysis have been extensively studied by many researchers (Putun *et al*. 1999; Antal and Grønli, 2003; Demirbas, 2004). They all agreed that increase in pyrolysis temperature increases the yield of gaseous products and decreases residual char production. This could be explained by the rapid devolatilization of cellulosic and hemicellulosic materials at a very high temperature according to Puntun *et al*. (1999). Therefore, higher temperatures favour tar decomposition and the thermal cracking of tar to increase the production of syngas, resulting in decreased oil and char yields (Kantarelis and Zabaniotou, 2009). Regression equations for char yields from all the shapes considered were generated and are presented in section 3.4.

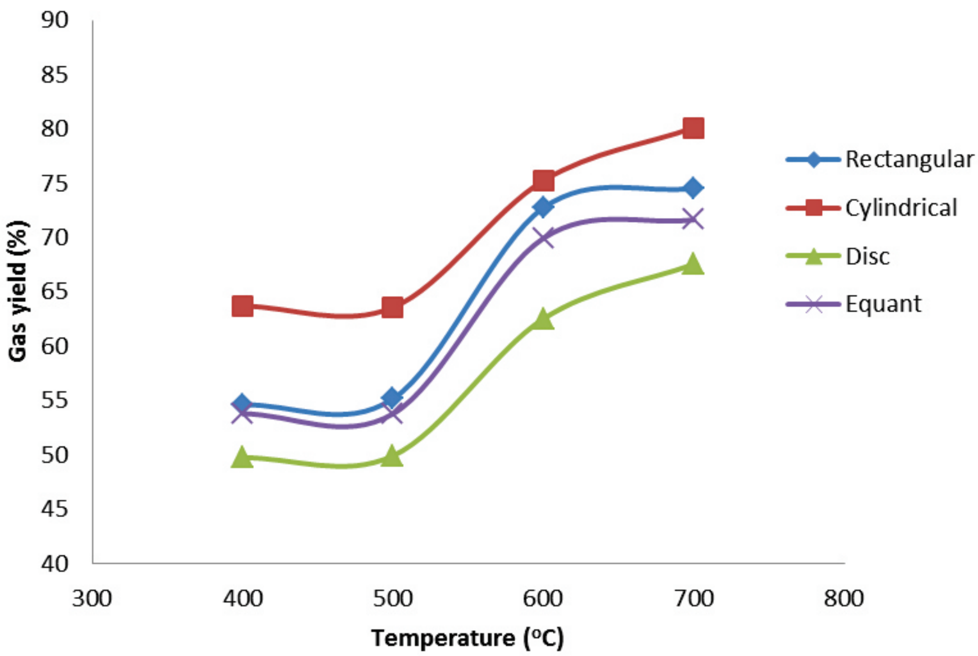


Figure 4: Gas yield from different sample shapes at different temperatures

3.4 Regression equations for product yields

The regression models between the reactor temperatures and product yields, and the respective square value of the coefficient of correlation (R^2) for all shapes of Gmelina (*Gmelina arborea*) wood samples are given below:

Char:

Cylindrical shape: $Y_{Cc} = -3E - 05T^2 + 0.0289T + 11.738$ $R^2 = 1$ (1)

Rectangular shape: $Y_{Cr} = 2E - 06T^2 - 0.038T + 43.121$ $R^2 = 0.7972$ (2)

Disc shape: $Y_{Cd} = 7E - 06T^2 - 0.0081 + 27.377$ $R^2 = 0.9333$ (3)

Equant shape: $Y_{Ce} = 5E - 06T^2 + 0.0101T + 24.245$ $R^2 = 0.9976$ (4)

Tar:

Cylindrical shape: $Y_{Tc} = -9E - 05T^2 + 0.0478T + 14.849$ $R^2 = 0.8979$ (5)

Rectangular shape: $Y_{Tr} = -5E - 05T^2 + 0.0162T + 20.991$ $R^2 = 0.8609$ (6)

Disc shape: $Y_{Td} = -0.0001T^2 + 0.0754T + 16.358$ $R^2 = 0.9143$ (7)

Equant shape: $Y_{Te} = -9E - 05T^2 + 0.0478T + 14.849$ $R^2 = 0.9694$ (8)

Gas:

Cylindrical shape: $Y_{Gc} = 0.0001T^2 - 0.0767T + 73.412$ $R^2 = 0.9173$ (9)

Rectangular shape: $Y_{Gr} = 3E - 05T^2 + 0.0439T + 30.51$ $R^2 = 0.8482$ (10)

Disc shape: $Y_{Gd} = 0.0001T^2 - 0.0673T + 56.265$ $R^2 = 0.9179$ (11)

Equant shape: $Y_{Ge} = 4E - 05T^2 + 0.0231T + 36.21$ $R^2 = 0.8387$ (12)

Where Y is the product yield and T is the corresponding reactor temperature. The subscripts C,T and G refer to char, gas and tar respectively while c, r, d and e refer to cydrical, rectangular, disc and equant shapes respectively.The models presented above are instrumental to predicting the response of the considered sample shapes of Gmelina (*Gmelina arborea*) pyrolyzed in a fixed bed reactor between 400 °C – 700 °C. The values of the correlation coefficients obtained indicate a high degree of agreement between the regression equations and experimental data.

4. Conclusions

Effect of sample shape on pyrolysis product distribution of Gmelina (*Gmelina arborea*) in a it was observed that the cylindrical shape has the highest gas yield of 80.12% at a temperature of 700 ^{o}C while the disc shape has the lowest gas yield of 49.74% at 400 ^{o}C. At 500 ^{o}C, disc shape produced the highest tar yield of 25.13% while the cylindrical shape has the lowest tar yield of 3.66% at 700 ^{o}C. Of the sample shapes pyrolysed, the rectangular shape produced the highest quantity of char of 27.25% at 400 ^{o}C while the cylindrical shape produced the lowest quantity of char of 16.23% at 700 ^{o}C. It is therefore concluded that, for high char yield, the rectangular shape may be considered for pyrolysis at a temperature not higher than 500 ^{o}C while for high tar yield, the disc shape may be considered between 400 ^{o}C and 500 ^{o}C and for high gas yield, the cylindrical shape is recommended at a temperature above 650 ^{o}C.

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