Development of a Densification Equipment for Organic Biomass Solid Fuel Pellets

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Abstract — In South Western Nigeria, after the harvesting of maize cobs from the field, large amount of maize stock remains as agricultural residues and wastes. The maize stock constitutes a menace to the environment if not properly handled. In this study, densification equipment was designed, fabricated and tested using maize stock grind as raw material. The equipment consists of mixer/moisture conditioner and a pelleting machine. The power rating for the mixer/moisture conditioner is 0.069 kW with an input capacity of 81 kg/h while the power consumption of the pellet machine is 0.8 kW with throughout capacity of 40 kg/h. The result of the test showed that the highest product temperature, which gives an indication of the quality and durability of the pellets produced was 93°C at 0.8 mm hammer mill screen size, 10% moisture content and 150 rpm die speed, at this temperature the machine is operating at optimum efficiency of 74%. High product temperature is an important parameter during pelleting/briquetting operations because it gives the degree of compaction and binding of the pellets/briquettes. The densification equipment for organic biomass was developed using locally sourced materials as a means of converting agricultural wastes into pellets for domestic cooking and cottage industry uses.

Keywords — Biomass, Densification, Equipment, Maize stock, Moisture content and Pelleting machine

1. INTRODUCTION

Biomas is any type of organic material that is available on a renewable or reoccurring basis, and includes such things as agricultural crops and waste, wood and wood wastes, animal wastes, aquatic plants, and organic fractions of municipal and industrial waste (BIOCAP, 2004). Biomass energy (bioenergy) is the chemical energy stored in organic matter and derived from solar energy via photosynthesis (Hall and Rosill-Calle, 1999). According to Egger et al (2003), several factors make maize stock pellets an attractive option for power generation; it does not add carbon dioxide to the atmosphere, low sulphur content means biomass combustion is much less acidifying than with coal, the ashes from biomass are very low in heavy metals, it can be recycled and used in soap industries.

Nigeria is still largely an agrarian society. About 54% of the country’s total labour force of about 42.8 million (~19% of the entire population of about 120 million) is still engaged in agriculture ((Nigeria Bureau of Statistics, 2014). A wide variation in climate across the country, equatorial in the south, tropical in the centre, and arid in the north makes possible the cultivation of several agricultural and forestry products such as cocoa, peanuts, palm oil, corn, rice, sorghum, cowpea, millet, cassava (tapioca), yams, rubber, and timber; and the raising of livestock such as cattle, sheep, goats, and pigs. About 3% of the country’s total land area of approximately 910,768 sq. km is devoted to the cultivation of permanent crops while about 44% is devoted to permanent pasture (Nigeria Bureau of Statistics, 2014). Residues generated in the agricultural/forestry sectors of the Nigerian economy are many and varied. They include products such as bagasse, corncobs, cotton stalks, rice husks, groundnut (peanut) shells, wood bark, sawdust and other wood residues, shrubs, fish waste, food processing wastes, animal wastes, etc. Added to these are municipal and industrial waste products such as waste paper, and used motor oil (Olorunnisola, 1995).

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Although there are no reliable current data on the total quantities of these waste products generated in the country annually, a study by Fadare (2000), indicated that about 900 tonnes of food, animal and wood wastes is generated daily in the 42 organized open markets located in Ibadan, one of the three largest cities in the country. Mark (2008) also reported that about 227,500 tonnes of animal waste was being generated daily in the country. Much of these waste products are made up of food and other organic materials of high water content. They are either dumped in landfills or incinerated (often times in situ). The relatively large volume of biomass waste products being generated in the country, the great potential for these resources to contribute to the energy needs of the country cannot be over emphasized, more so given emerging and persistent problems associated with the supply of traditional domestic fuel products.

Densification of biomass is a form of promoted agglomeration wherein pressure (along with other process variables) is utilized to force the smaller particles together. It can increase the bulk density of biomass materials. Densification of biomass materials could reduce the costs of transporting, handling, and storage. In addition, because of uniform shape and size, densified products can be more easily handled using existing handling and storage equipment (Kaliyan et al, 2009).

Solid fuel made from agricultural waste and sawdust is a desirable fuel because it does not add carbon dioxide to the atmosphere and it produces hot long lasting and smokeless fire. Solid fuel is produced when agricultural residue and sawdust are mixed with binder and it is pelleted into uniform chunks. Solid fuel pelleting has the potential to meet the energy demands of rural and urban sector thereby making a significant contribution to the economic advancement of developing countries. Solid fuel pellets have advantages over fuel wood in terms of greater heat intensity, cleanliness convenience in use and relatively smaller space for storage (Yaman et al, 2000; Olorunnisola, 2004). Hence, efficient and good quality pellet product could be produced by developing...
indigenous densification equipment. The design, fabrication and preliminary testing of locally developed densification equipment for biomass maize stock is therefore imperative.

2. MATERIALS AND METHODS

2.1 Machine Description

The densification equipment comprises of pelleting machine and mixer/moisture conditioner. The biomass pellet machine is made up of three component units namely, the feeding unit, the pelleting unit and power transmission unit. The feeding unit comprises of a hopper which transfers grind biomass materials to be pelleted to the pelleting unit. The pelleting unit is made up of serrated rollers, a die and an inverted hopper. The serrated rollers forced the biomass grind into the cylindrical roller for pelleting. The die is the unit where pelleting takes place.

The pelleting chamber houses the pelleting die, the inverted hopper, the rotating shaft and a discharge duct. The power transmission unit comprises of V-grooved pulley, belt and speed reduction gear of ratio 1:20 (a bought out component). A single phase electric motor with power rating of 1.5 kW (2HP), provides power necessary for the pelleting machine.

The mixer/moisture conditioner comprises the feeding unit, the mixing unit and the power transmission unit. The feeding unit of the mixer/moisture conditioner is a hopper which facilitates easy movement of grind biomass and other additives into the mixing unit of the machine. The mixing unit of the machine comprises of barrel and mixing auger. The power transmission unit consists of V-grooved pulley, belt and an electric motor. The pulley is made of mild cast steel. A single phase electric motor of power rating of 1.0 kW (1.5 hp) provides necessary power for the mixer/moisture conditioner machine. The densification equipment is as shown in Fig. 1.

![Diagram of densification equipment](image)

**Fig.1:** The densification equipment

2.2 Design Analysis

The design analysis was carried out as follows:

- **Determination of the theoretical volumetric capacity of pelletizer:** The theoretical volumetric capacity was calculated using the equation by Srivastava et al., (1996)

  \[ Q_t = \pi N(d^2) l_d \]  

- **Specific weight of biomass materials = 0.297x10^3 kg/m^2** (Mohsenin, 1978)

  Where: \( Q_t \) = Theoretical volumetric capacity (m^3/l), \( d \) = Die diameter, \( l_d \) = Thickness of the die

  \( K = \) Numbers of holes on the die, \( N = \) die speed (rw/s),

  Mass flow rate = specific mass X Volumetric capacity

- **Determination of Power requirement of pelletizer:** The power requirement for the pelletizer was calculated using the equation by PSG TECH, (1982)

  \[ P = M_t \times h \times \rho \times W_o \]  

  Where; \( M_t \) = mass flow rate, (ton/h), \( H = \) Height of the die (m), \( \rho = \) Efficiency of gear reducer (1.2), \( W_o = \) Material factor (4 for powder)

- **Determination of Shaft Diameter:** The horizontal shaft driving the die plate was designed using the ASME code equation

  \[ d^2 = \frac{16}{\pi} s_2 \times \left( \frac{m_k c_i}{c_d} \right)^2 + \left( \frac{m_k p_d}{c_d} \right)^2 \]  

  \( \text{Where; } K_b = \text{combine shock and fatigue to bending} = 2.0, \ K_t = \text{combines shock and fatigue to torsional} = 1.5, \ M_t = \text{maximum torsional moment} \ Nm, \ M_b = \text{maximum bending moment} \ Nm, S_s = \text{Allowable shear stress for shaft without keyway} \ N/m^2, d = \text{shaft diameter}. \)

- **Determination of the Capacity of the Conveyor:** The design of the screw anger for the mixer was carried out according to the procedure outlined by PSG TECH, (1982). Capacity of the conveyor is calculated as

  \[ Q = \frac{15nD\sin\beta}{\pi\rho} \]  

  \( \text{Where; } Q = \text{Capacity of conveyor tonne/h}, \ D = \text{Screw diameter}, \ S = \text{Screw pitch}, n = \text{speed of screw shaft}, \ \rho = \text{Bulk density of biomass material}, 150kg/m^3, C = \text{Factor for inclination to horizontal}, 1.0 \)

- **Determination of Power to Drive the Screw:** Power require to drive the screw,

  \[ N = \frac{QL}{367} \left[ W_o \pm \sin\beta \right] \left( \frac{l}{a} \right)^{\frac{1}{2}} \]  

  \( \text{Where; } L = \text{Length of screw}, W_o = \text{Material factor}, 4.0, \ \beta = \text{Angle of inclination of screw shaft to horizontal}, 0.03 \)

2.3 Testing and Machine Evaluation.

Maize stock residues were harvested from the teaching/research farm of Rufus Giwa Polytechnic, Owo. The maize stock residues was milled and characterized into 0.8, 2.5 and 3.5 mm particle sizes i.e. fine particle sizes, medium size particles and coarse particle sizes ASABE,(2006) The maize stock grind was fed into the mixer/moisture conditioner and 5% binder (cassava starch) was added in accordance with the method by Tabil et al., (1997). The moisture of the grind was conditioned to the required moisture content using equation 6 as suggested by Tabil and Sokhansanj, (1996).

\[ M_w = \frac{M_i(M_{wf} - M_{wi})}{1 - M_{wf}} \]  

Where: \( M_{wi} = \text{Mass of water added to biomass grind}, \ M_i = \text{Initial mass of biomass grind}, \)
During the evaluation process, the method suggested by Tumuru et al (2010) was used. Parameters such as moisture content of the biomass material, die speed and hammer mill screen size were varied. Die speeds of 150, 250 and 350 rpm, hammer mill screen sizes of 0.8, 2.5 and 3.5 mm and moisture contents of 8%, 10%, 12%, 14% and 16% were used. Three replicates of moisture analysis were performed for each sample. Moisture meter (digital meter HTCC LSKC-608) was used for instantaneous moisture content measurement of the maize stock grind. According to Tumulu et al (2010), the quality attributes of pellets like durability and bulk density are significantly influenced by barrel temperature of the machine. The temperature measurement for the biomass pellets produced was taken by the use of infrared thermometer (HDE infrared thermometer, ST380A). The temperature of each batch of pellets produced was recorded immediately the pellets came out of the delivery chute of the pellet machine. The procedure was replicated three times.

Machine efficiency was evaluated using the relationship given by Ojomo, (2008).

\[ T = \frac{Q \times K}{W_a} \]  (7)

Where: \( Q \) = Feed rate (kg/h), \( K \) = 0.83 co-efficient of friction between die orifice and the biomass materials (Mohsenin, 1976). \( W_a \) = the quantity of actual pellets obtained at the machine outlet.

Machine efficiency \( \eta_{ME} \) was estimated using the relationship;

\[ \eta_{ME} = \frac{W_a}{T_i} \times 100 \]  (8)

3. RESULTS AND DISCUSSION

The effect of moisture content, hammer mill screen sizes and machine die speeds on product temperature of pellets produced are shown in Figures 1, 2 and 3. The product temperature gives an indication of the quality and durability of the pellets produced.

At constant die speed of 150 rpm and increased screen sizes of 0.8, 2.5 and 3.5 mm, there was considerable increase in product temperatures. The increments in the product temperatures were appreciable between 12 to 45 minutes of pelleting beyond which there was no appreciable increment in the product temperatures. For 2.5 mm particle size, there was appreciable increment in the product temperature of the pellets produced; the product with 10% moisture content has 70°C temperature. Also particle sizes of 3.5 mm pellets product temperature increases with increase in the duration of pelleting time. It was observed that 0.8 mm particle size with 10% moisture content has the highest product temperature of 91°C followed with particle size 2.5 mm and 3.5 mm at 80°C and 78°C respectively (Fig 2).

At constant die speed of 200 rpm and varying particle sizes and moisture contents, the results obtained are shown in Fig. 3. For 0.8 mm particle sizes, there was an increase in duration of pelleting time that resulted in increase in product temperature of pellets produced. At 2.5 mm particle sizes, the observed temperature was slightly higher for 10% moisture content compared to that of 12% moisture content and 8% moisture content as the duration of pelleting tend towards 60 minutes. The highest product temperature of 98°C was attained when the machine was operating at 200rpm die speed, 2.5mm particle sizes and 10% moisture content. Same trend was observed at 3.5 mm particle size, the product temperature for 10% was highest at towards the end of 40 minutes pelleting time and product at 8% moisture content recorded the least product temperature. The product temperature for all the moisture contents increases with increase in pelleting time throughout the pelleting duration which is similar to the observations of Hill and Pulkinen (1988).
For 3.5 mm particle size, it was observed that the product temperatures were very low when compared to the others and this implies that as the particle size of the pellet increases, there is tendency for lower product temperature. The lowest temperature of 55°C was recorded when the machine was operated at die speed 250 rpm, 3.5 mm particle size and moisture content of 8%.

The obtained results showed that product temperature of the pellets produced increases with increase in the duration of pelleting time. This could have been due to frictional heat generated in the machine as a result of longer period of operation which assists the binding of biomass particle in the presence of moisture. Hill and Pulkinen, (1988) found out that high temperature of die increases pellet durability, during the pelleting of alfalfa. Mani et al., (2003) and Sokhansanj et al., (2005) observed a similar effect in terms of temperature, where higher temperature resulted in reduced resistance of the material against applied load and resulted in better quality of pellets. It was also observed that the product temperature increases with increase in moisture content of the biomass material. This confirmed the work of Kaliyan and Morey, (2007).

![Fig. 4: Effect of Particle Sizes, Moisture Content and Pelletting Time at Constant Die Speed of 250 rpm on the Product Temperature](image1)

The power rating for the mixer/moisture conditioner is 0.069 kW with an input capacity of 81 kg/h while the power consumption of the pellet machine is 0.8 kW with throughout capacity of 40 kg/h. The highest product temperature, which gives an indication of the quality and durability of the pellets produced was 930°C at 0.8 mm hammer mill screen size (product size), 10% moisture content and 150 rpm die speed. At this temperature the machine is operating at optimum efficiency of 74%. It provides a test rig which will be useful in further research and training in biomass solid fuel production.

Figure 5 shows the effect of particle sizes, die speed and moisture content on the machine efficiency. At 0.8 mm hammer mill screen size, the machine efficiency for the various die speed increases as moisture content of the materials increased from 8 to 10%. This could be attributed to the fact that machine speeds 150 and 200 rpm allow the particle sizes to stay a bit longer in the die (high retention time) and this leads to further binding of the particles together. This observation was also reported by Morad et al. (2007). The efficiency decreased with increased moisture content from 10 to 12%. It was also observed that increase in die speed from 150 to 200 rpm led to an increase in pelleting efficiency except when the machine was operated with 3.5 mm hammer mill screen size, the efficiency decreased to 46%. The highest machine efficiency of 74% was attained when the machine was operated at particle size 2.5 mm, die speed of 200 rpm and material moisture content of 10%. This was closely followed by 64% efficiency at the same particle size of 2.5 mm, die speed of 250 rpm at 10% moisture content.

![Fig. 5: Effect of Particle Sizes, Die Speed and Moisture Content on Machine Efficiency](image2)

4. CONCLUSION

Densification equipment for organic biomass has been developed using locally sourced materials as a means of converting agricultural waste (maize stock) into pellets for domestic cooking. The equipment was evaluated for performance in terms of product temperature and machine efficiency.

The obtained results showed that product temperature of the pellets produced increases with increase in the duration of pelleting time. This could have been due to frictional heat generated in the machine as a result of longer period of operation which assists the binding of biomass particle in the presence of moisture. Hill and Pulkinen, (1988) found out that high temperature of die increases pellet durability, during the pelleting of alfalfa. Mani et al., (2003) and Sokhansanj et al., (2005) observed a similar effect in terms of temperature, where higher temperature resulted in reduced resistance of the material against applied load and resulted in better quality of pellets. It was also observed that the product temperature increases with increase in moisture content of the biomass material. This confirmed the work of Kaliyan and Morey, (2007).

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![Image 3](image3)

![Image 4](image4)
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