FACTORS AFFECTING DENSIFICATION OF AGRICULTURAL RESIDUES – AN OVERVIEW

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ABSTRACT

Agricultural residues often discarded or burned as wastes, occur in large amounts and have the potential to be an important source of fuel for many people, especially those in rural areas. However, these residues in their natural form could not be effectively and efficiently utilized. Therefore, this study investigated those factors that may affect densification characteristics of agricultural residues.

Various factors and variables affecting densification of agricultural residues were identified. Prominent among these factors were particle size, moisture content, temperature of the biomass feedstock as well as the temperature of the die. Other factors were external additives, densification pressure and retention or hold time. Included in the cluster were composition of biomass, use of binder and the pre-heating of biomass feedstock.

The study concluded that all the factors and variables examined had to certain extent significant effects on the densification of agricultural residues and there exists optimum or threshold value for each feedstock to produce high briquette density and strength.

Keywords: Agricultural residues, biomass energy, densification characteristics, operating factors

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1.0 Introduction

Agricultural biomass residues have the potential for the sustainable production of bio-fuels and to offset greenhouse gas emissions (Campbell et al., 2002; Sokhansanj et al., 2006). These residues represent an abundant, inexpensive and readily available source of renewable lignocellulosic biomass (Liu et al., 2005).

There are many advantages to be derived from the use of agricultural residues for biomass energy generation. Notable among these advantages are low emissions of green-house and acid gases, which are friendly both to human and ecology. However, there are many challenges with the use of agricultural residues in their original form. Some of these drawbacks are the variable quality of the residue, the cost of collection, and problems in transportation and storage (Sokhansanj et al., 2006).

Due to its high moisture content, irregular shape and size, and low bulk density, biomass is very difficult to handle, transport, store, and utilize in its original form (Sokhansanj, et al., 2005). In order to reduce industries operational cost as well as to meet the requirement of raw material for bio-fuel production, biomass must be processed and handled in an efficient manner. New methodologies were developed to process the biomass making it suitable feedstock for bio-fuel production. Densification of biomass into durable compacts is one the effective solutions to these problems and it can reduce material waste as well as management of waste disposal.

According to Kaliyan and Morey (2008), densification can be defined as the process of compaction of residues into a product of higher density than the original raw materials. It is also known as briquetting (Wilaipon, 2007). Densification can increase the bulk density of biomass from an initial bulk density of 40-200 kg/m^3 to a final compact density of 600-1200 kg/m^3 (Adapa et al., 2007; Mani et al., 2003; McMullen et al., 2005; Obernberger and Thek, 2004). Biomass can be compressed and stabilized to 7–10 times densities of the standard bales by the application of pressures between 400–800 MPa during the densification process (Demirbas and Sahin, 1998).

2.0 Materials and Methods

The study was undertaken with detailed literature search. In-depth review of results of notable researchers (including the present author) on the subject matter were reviewed and conclusions drawn.

3.0 Factors Affecting Densification of Agricultural residues

In order to produce good quality briquettes, feed preparation is very important. Feed parameters play a practicable role in densification technology. For densification of biomass, it is important to know the feed parameters that influence the extrusion process. Some of these parameters are particle size and its distribution, moisture content and temperature among others (Grover and Mishra, 1996). Therefore, the broad objective of this paper was to highlight and discuss those factors that have effects on densification of agricultural residues. Some of these factors are discussed in subsequent sections.

3.1 Effects of Particle Size

Particle size and shape are of great importance for densification. It is generally agreed that biomass material of 6-8 mm size with 10-20% powdery component gives the best results (Kaliyan and Morey, 2009). Although, the screw extruder, which employs high pressure, is capable of briquetting material of oversized particles, the briquetting will not be smooth and clogging might take place at the entrance of the die resulting in jamming of the machine. The larger particles, which are not conveyed through the screw start accumulating at the entry point and the steam produced due to high temperature (due to rotation of screw, heat conducted from the die and also if the material is preheated) inside the barrel of the machine starts condensing on fresh cold feed resulting in the formation of lumps and leads to jamming (Gilbert et al., 2009). That is why the processing conditions should be changed to suit the requirements of each particular biomass. Therefore, it is desirable to crush larger particles to get a random distribution of particle size, so that an adequate amount of sufficiently small particles is present for embedding into the larger particles. The presence of different size particles improves the packing dynamics and also contributes to high static strength. Only fine and powdered particles of size less than 1 mm are not suitable for a screw extruder because they are less dense, more cohesive, non-free flowing entities (Mishra, 1996). Wilaipon (2007) noted that fine particles in general produce better densified products than their coarse counterparts. This was also confirmed by Oladeji (2011a).

3.2 Effects of Moisture

The percentage of moisture in the feed biomass to extruder machine is a very critical factor. In general, it has been found that when the feed moisture content is 10-12%, the briquettes will have 8-10% moisture (Grover and Mishra, 1996). At this moisture content, the briquettes are strong and free of cracks and the briquetting process is smooth. However, when the moisture content is more than 15%, the briquettes are poor and weak and the briquetting operation is erratic (Kaliyan and Morey, 2009). Excess steam is produced at higher moisture content leading to the blockage of incoming feed from the hopper, and sometimes it shoots out the briquettes from the die. Therefore, it is necessary to maintain optimum moisture content.

Moisture present in the biomass facilitates starch gelatinization, protein denaturation, and fibre solubilisation processes during extrusion, pelleting, or briquetting. Steam-treated biomass is superior, as the additional heat modifies physiochemical properties (gelatinization of starch, denaturation of protein) to such an extent that binding between the particles is significantly enhanced, resulting in improved densification quality (Thomas et al. 1997). Mani et al. (2003) observed that moisture in the biomass during the densification process acts as a binder and increases the bonding via van der Waal's forces, thereby increasing the contact area of the particle. Tabil and Sokhansanj (1996), in their article on pelletisation of alfalfa grinds, found that larger die (of 7.8 mm) can handle conditioned grind moisture contents above 10%, but the durability after cooling of the pellets was low. They also found that the smaller die became plugged when the moisture content of the conditioned grinds exceeded 10%. Demirbas, et al (2004) found that increasing the moisture content from 7 to 15% of spruce wood sawdust significantly increased the strength of the pellets. In their article on densification of corn stover, Mani et al. (2006) found that low moisture (5–10%) resulted in denser, more stable, and more durable briquettes. Li and Liu (2000) researched the compaction of tree bark; sawmill waste, wood shavings, alfalfa hay, fresh alfalfa, and grass in a punch and die assembly and found that an optimum moisture content of approximately 8% was recommended to produce high-density briquettes. They also recommended that a moisture content of 5–12% is necessary to produce good quality (in terms of good density and long-term storage properties) logs from hardwood, softwood, and bark in the forms of sawdust, mulches, and chips. They also remarked that pellets or briquettes tend to become fragile in just a few days if the moisture content is less than 4% (w.b.) due to absorption of moisture from the environment. Moshenin and Zaske (1976), in their study on densification, report that materials having lower moisture content and fewer long fibres (more fines) gave more stable wafers due to limited expansion. Tabil and Sokhansanj (1996) observed that during compression, the protoplasm present in fresh alfalfa of about 19% moisture content acted as a binder, and pellets with highest durability were produced. Sokhansanj et al. (2005) identified that feed material that contains higher proportions of starch and protein will produce more durable and higher quality pellets than the materials with only cellulosic material. They also identified that the optimum moisture content for pelleting cellulosic materials is 8–12%, whereas that for starch and protein materials (mostly animal feeds) can reach up to 20% (w.b). Ollett et al. (1993), in their article on understanding the compaction behaviour of food powders, concluded that the effect of moisture on the compaction behaviour of the food powders was a complex phenomenon.

Many researchers have found that the optimum moisture content for densification of biomass is different for each individual feedstock and operating condition. It is important to establish the initial moisture content of the biomass feed so that the briquettes produced have moisture content greater than the equilibrium value, otherwise the briquettes may swell during storage and transportation and disintegrate, when exposed to humid atmospheric conditions (Grover and Mishra, 1996).

Ryu et al. (2008) studied the effects of moisture content on the pelletisation of spent mushroom compost using a simple compaction machine. They noted that too dry particles become hard, while losing the plasticity, which increases the friction between particles that partially consumes the compression energy applied. In the similar manner, they observed that, the pellets from wet particles also had much lower density. In their study, they concluded that, the ideal value of moisture content was about 10 % in the materials, for which the pellets has three times higher density compared to that materials with 2 % of moisture content. Another study by Uslu and Faaij (2008) also reported that, if the biomass is too wet, the pressure required for briquetting would increase dramatically. However, in contrast, Al-Widyan et al. (2002) reported that, the briquette density increases with increase in moisture content for olive cake. Therefore, it can be concluded that, optimum moisture content exists for each feedstock to produce high briquette density and strength.

3.3 Effects of Temperature of Biomass

By varying the temperature of biomass, the briquette density, briquette crushing strength and moisture stability can be varied (Joseph and Histop, 1999). In a screw extruder, the temperature does not remain constant in the axial direction of the press, but gradually increases. Internal and external friction cause local heating and the material develops self-bonding properties at elevated temperature. It can also be assumed that the moisture present in the material forms steam under high-pressure conditions, which then hydrolyses the hemicelluloses and lignin portions of biomass into lower molecular carbohydrates, lignin products, sugar polymers and other derivates.

The addition of heat also relaxes the inherent fibres in biomass and apparently softens its structure, thereby reducing their resistance to briquetting which in turn results in decreased specific power consumption and a corresponding increase in production rate and reduction in wear of the contact parts (Grover and Mishra, 1996). However, the temperature should not be increased beyond the decomposition temperature of biomass, which is around 300^0C.

3.4 Effects of Temperature of the Die

The distinctive feature of a screw type briquetting machine is that heat is applied to the die 'bush' section of the cylinder. This brings about two important operational advantages (Joseph and Histop, 1999). The machine can be operated with less power and the life of the die is prolonged. It has been shown that by heating the material for a determined temperature interval, a more stable product with a lower recovery of original dimensions could be obtained than was possible with unheated materials **(**El-Saeidy, 2004**)**. It has been also concluded that bio-residue having relatively high moisture content could be stably compacted at an elevated temperature, whereas this was not possible at ambient conditions. The temperature of the die should be kept at about 280-290^0C. If the die temperature is more than the required one, the friction between the raw material and the die wall decreases such that compaction occurs at lower pressure, which results in poor densification and inferior strength. Conversely, low temperature will result in higher pressure and power consumption and lower production rate (Grover and Mishra, 1996).

3.5 Effects of External Additives

The briquetting process does not add to the calorific value of the base biomass. In order to upgrade the specific heating value and combustibility of the briquette, certain additives like charcoal and coal in very fine form can be added. About 10-20% char fines can be employed in briquetting without impairing their quality (Tabil, 1997). Furthermore, only screw pressed briquettes can be carbonized. When carbonized with additives in the briquette to make dense char coal, the yield is remarkably increased. However, depending upon the quality of charcoal and coal powder, various formulations can be evolved for optional results. In piston press technology, the effect of particle size and moisture content is similar to that of the screw press (Kaliyan and Morey, 2009). But in this case, preheating of raw material is not employed and the die is not heated. In fact the die needs cooling for smooth briquetting

3.6 Densification Pressure

Pressure plays an important role in the quality of pellets made from agricultural biomass. Yaman et al. (2000) recommended that briquetting pressure should be selected at an optimum value that influences the mechanical strength by increasing plastic deformation. However, above an optimum briquetting pressure, fractures may occur in the briquette due to a sudden dilation. For a given die size and storage condition, there is a maximum die pressure beyond which no significant gain in cohesion (bonding) of the briquette can be achieved (Ndiema et al. 2002). Demirbas et al. (1998), in their article on compaction of biomass waste materials like waste paper, observed that increasing the pressure from 300 to 800 MPa, with about 7% moisture (w.b.), increases the density sharply from 0.182 to 0.325 g/Ml, and then the densities slightly rise to 0.405 g/mL

Oladeji (2013) noted that, the axial expansion of briquettes decreased as the compaction pressure increased. The implication of this is that, the higher the compaction pressure, the more stable and better the quality of the briquettes produced. Mani, et al. (2004) conducted experiment on compaction of corn stover, where they concluded that, the density of briquettes produced from corn stover significantly increased as pressure was increased. Several other researchers who agreed with this affirmation are Al-Widyan et al. (2002); El-Saeidy (2004) and Wilaipon (2008) among others.

3.7 Retention or Hold Time and Relaxation Time

The quality of the briquettes is significantly influenced by the retention or hold times of the materials in the die (Tabil and Sokhansanj 1996). Al-Widyan et al. (2002) found that retention times between 5 and 20 seconds did not have a significant effect on olive cake briquette durability and stability. Li and Liu (2000) found that the hold time for oak sawdust had more effect at lower pressures than at higher pressures. At the highest pressure (138 MPa), the effect of hold time became negligible. They also observed that the holding time had little effect on the expansion rate, and that holding time had more effect at lower pressure than at high pressure. It appeared that hold times greater than 40 seconds had a negligible effect on density. A 10-second hold time could result in a 5% increase in log density whereas at holding times longer than 20 seconds, the effect diminished significantly. In general, relaxation time has a great affect on the density of the materials.

3.8 Biomass Composition

Feedstock composition is one of the major variables that contribute significantly to the quality of the densified materials. Plant biomass has both low molecular weight and macromolecular compositions. Low-molecular-weight substances include organic matter and inorganic matter, while macromolecular substances include cellulose, hemi-cellulose, and lignin (Mohan et al. 2006). As the densification of the biomass is coupled with process variables like temperature, pressure, die geometry, and mechanisms of densification, changes in these variables will bring about significant changes in the chemical compositions of the biomass by the mechanisms known as interaction reactions.

Thomas et al. (1998), in their article on the pelleting of animal feeds, identify starch, protein, sugar and non-starch polysaccharides (NSP), fat, fibre, inorganic matter, and water as some of the important ingredients that influence pellet quality. Shankar and Bandyopadhyay (2004 and 2005) and Shankar et al. (2008) found that the protein and fat in the feed material significantly affect the quality of the extruded feed and also impact flow behaviour.

3.9 Use of Binders

The importance of binder in briquetting of agro-residues cannot be overemphasized. This is because, without proper agglomeration, the briquettes may eventually disintegrate. Kaliyan and Morey (2009) in their investigations into some factors affecting quality of densified biomass products mentioned binder as one of the major determinants as far as the quality of briquettes produced from agro-residues is concerned. Furthermore, Oladeji (2011b) noted that employment of binder is necessary especially during briquetting under low-pressure technique.

Binders can improve the binding characteristic of the biomass and produce more durable product (Tabil, 1997). Binders also help reduce wear in production equipment and increase abrasion-resistance of the fuel. In pellet production, binders are usually allowed, but must be specified on the final product. The addition of some binders can result in an increase in the sulphur content of densified biomass. Briquettes with binder are usually carried out with low pressure. Many materials are briquetted with binders (Tabil, 1997). For example, rice could be briquetted with a binder consisting of starch, cow dung and molasses. Corncob briquettes could be produced with cassava starch as a binder, while sawdust could be briquetted using starch or pine exudates. There are situation where two or more binders could be used like a mixture of starch and cow dung (Pathak and Singh, 2000).

The study by Dobie (1975) showed that grass hay could not be formed into good quality cubes without the application of a good bonding agent. Cubes produced from blue panic grass, Timothy grass, range hay, Pangola grass, and Congo grass without a binder had durability of 15-44%. By adding 5.0 – 10% (by weight) of a liquid binder (containing ammonium lignin sulfonate, wood sugars, 2.4% nitrogen in the form of ammonia, and 50% water), durability of cubes increased to 93 – 97%. Addition of about 5% (by weight) of the same liquid binder to bagasse pitch increased the durability of the cubes from 88.8 to 99.3%.

Singh and Singh (1998) reported that adding 10 – 25% (by weight) of molasses or sodium silicate, or a mixture of 50% sodium silicate with rice straw produced briquettes with 40 – 80% durability at a particle size of 0.15mm and a forming pressure of 29.4MPa. The higher the amount of binders added, the higher the briquette durability. Binding of molasses might occur due to solid bridges created by re-crystallization of sugars or glass transition after cooling/drying of pellets (Thomas, et al., 1998 or 1997).

3.10 Preheating of Biomass

Appreciable number of researchers studied the effects of feed pre-heating on briquetting of different biomass. Preheating the biomass before densification is widely used as it results in a higher quality product. Most commercial pellet or briquette producers use preheating to form more stable and dense pellets or briquettes (Bhattacharya et al. 1989; Bhattacharya 1993). Aqa and Bhattacharya (1992) indicate that preheating biomass could significantly increase the throughput of the pelletizing machine and reduce the energy requirement per kilogram of the biomass pellets formed. Some of the studies have revealed that the addition of heat, benefits by relaxing the inherent fibres in biomass and apparent softening its structure, resulting in the release of some bonding or gluing agents (Joseph and Histop, 1999).

It has also been reported that pre-heating the raw material reduces the power required for the briquetting, allows higher quality briquettes for given energy input, lowers wear on the dies or a combination of these. Joseph and Histop (1999) reported the results of briquetting of pre-heated papyrus by the Intermediate Technology Development Group (ITDG), papyrus briquettes were produced at pressures between 25-30 N/m^2 with pre-heat, compared to a pressure of approximately 180 N/m^2 without pre-heat. The authors concluded that, existing briquetting plants modified for pre-heat should operate at lower pressures, wear rates and power requirements.

Conclusion

From the synopsis, the following conclusions were drawn:

(i) Many researchers have found that the optimum moisture content for densification of biomass is different for each individual feedstock and operating condition. Therefore, it can be concluded that, optimum moisture content exists for each feedstock to produce high briquette density and strength.

(ii) In general, relaxation time has a great affect on the density of the materials.

(iii) The density of briquettes produced significantly increases as pressure increases.

(iv) The addition of heat is useful by relaxing the inherent fibres in biomass and apparent softening its structure, resulting in the release of some bonding or gluing agents.

(v) Pre-heating the raw material reduces the power required for the briquetting, allows higher quality briquettes for given energy input, lowers wear on the dies or a combination of these.

(vi) The quality of the briquettes is significantly influenced by the retention or hold times of the materials in the die.

(vii) Feedstock composition contributes significantly to the quality of the densified materials. This is because, the protein and fat in the feed material significantly affect the quality of the extruded feed and also impact flow behaviour.

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