PELLETISATION OF CEREAL STRAWS AS A SOURCE OF ENERGY AFTER SPECIFIC COMMINUTION PROCESSES.

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ABSTRACT: Utilization of the agricultural residues (straw) is often difficult due to their uneven and troublesome characteristics and also due to their low density (40 to 120 kg m⁻³) including baled density. This drawback can be overcome by means of densification, i.e. compaction of the residues into products of high density and regular shape. The higher bulk density and higher energy density results in lower transportation costs and higher energy efficiency. Pelletisation of cereal straws (Rye straw and Wheat straw) requires a product specific size reduction. The product specific size reduction was achieved with the help of two different comminution units (impact mill and twin-screw extruder). However, the moisture content is an important parameter in the pelletisation and also with respect to the energy characteristics. The pellets are prepared with increasing water contents and through which an optimisation of water content in the pelletisation process has been achieved. The results of the comminution unit’s impact mill and twin-screw extruder are discussed based on a detailed particle size characterisation (particle size and shape). Besides the high calorific value the main pellet quality parameters such as mechanical stability, abrasion resistance and further combustion technical characteristics have been investigated and verified with the existing norms (DIN 51731, Ö NORM M 7135 and DINplus).

The particle size characteristics indicate an ideal distribution of the particles for the combustion in boilers / furnaces. The durability and the mechanical stability of the pellets comminuted with the twin-screw extruder were comparatively better then the pellets prepared after comminuting with impact mill. Particle size characteristics, abrasion values and the strength characteristics showed a good co-relation. The pellets displayed optimal combustion characteristics. The present work also discusses the impact of additional components (binders, adhesives and additives), which assure the necessary binding and simultaneously increase the calorific value.

Keywords: agricultural residue straw, rye straw, wheat straw, straw pellets, solid biofuel

1 INTRODUCTION

Currently there is a tremendous interest in using biomass as an energy source through out the world. Biomass as an energy source would replace the fossil fuels and also reduce the green house gas emissions. Biomass is becoming an increasingly important energy source for the future. Biomass is an important fuel for heating and power generation because it is a readily available renewable energy source that reduces carbon dioxide emissions (Petrou & Pappis, 2009). Biomass is essentially composed of cellulose (40 – 45 %), hemicellulose (20 – 30 %), lignin (20 – 30 %) and extractives (2 – 5 %) (Sjostrom, 1993).

Biomass is very difficult to handle due to its irregular shape and size, high moisture content, and low bulk density. These problems can be overcome by densification of biomass into regular size and shape (briquettes and pellets). Biomass pellets are densified biomass particles formed into cylindrical pellets. Pelletisation is employed in many industries to form a more durable substance and to enhance the material characteristics such as (i) to facilitate storage, transport, and handling; (ii) to combine a number of substances (binders and additives); and (iii) to recycle / reclaim materials (Finney et al., 2009). The primary reason for pelletisation is to increase the bulk and energy densities of the material. Pellets of various agricultural residues can be used for energy production in a broad range from private house hold appliances to full scale power plants (Oberenberger & Thel, 2009).

The densification of biomass is generally carried out either with high pressure compaction or with the combination of medium pressure compaction and a heating device. The densified biomass conveys mechanical interlocking between the fibres under high pressure compaction (Grover & Mishra, 1996). During the high temperature compaction, the lignin softens and forms a fine layer on the solid particle (Gilbert et al., 2009). This layer of lignin helps in attracting the surrounding particles to bond with each other. There are several advantages of densified fuel pellets compared to direct incineration of raw materials. The higher bulk density and higher energy density results in lower transportation costs and higher energy efficiency (Holm et al., 2006). Moreover the reduced moisture content increases the long term storage capability (Kaliyan and Morey, 2009).

The quality of biofuel pellets is evaluated based on the physical and chemical characteristics of the raw materials, which have been standardized in DIN 51 731, DINplus and ÖNORM M 7135. These standard values of the quality parameters are given in table I. The standards are specified especially for wood pellets. There are no specific standards for straw pellets. The physical characteristics include particle size distribution, bulk density and durability. The chemical characteristics include ash content, composition of chemical elements (C, H, N, S, Cl, K), the heavy metals concentrations (Cd, Pb, Zn, Cr, Cu, As, Hg, Sb, Ti), water content, lignin content etc. These properties also influence the suitability of the material as a fuel. Chemical properties mainly influence the burning and heating suitability and the heating value. Physical properties are of highest importance for the binding mechanisms which occur during the biomass densification (Hartmann, 2007).
Table 1: Standard quality values of the wood pellets as specified in DIN 51731, ÖNORM M 7135 and DINplus.

<table>
<thead>
<tr>
<th>Norms for Pellets</th>
<th>DIN 51731</th>
<th>ÖNORM M 7135</th>
<th>DINplus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>4 – 10 mm</td>
<td>4 – 10 mm</td>
<td>--</td>
</tr>
<tr>
<td>Length</td>
<td>≤ 50 mm</td>
<td>≤ 54 d</td>
<td>≤ 54 d</td>
</tr>
<tr>
<td>Abrasion</td>
<td>--</td>
<td>≤ 2.3 %</td>
<td>≤ 2.3 %</td>
</tr>
<tr>
<td>Heating value</td>
<td>17.5 – 19.5</td>
<td>&gt; 18</td>
<td>&gt; 18</td>
</tr>
<tr>
<td>Water content</td>
<td>≤ 12 %</td>
<td>≤ 10 %</td>
<td>≤ 10 %</td>
</tr>
<tr>
<td>Ash content</td>
<td>&lt; 1.5 %</td>
<td>&lt; 0.5 %</td>
<td>&lt; 0.5 %</td>
</tr>
<tr>
<td>Density</td>
<td>&gt; 540 kg/m³</td>
<td>&gt; 540 kg/m³</td>
<td>&gt; 540 kg/m³</td>
</tr>
<tr>
<td>Binders / Additives</td>
<td>Not</td>
<td>≤ 2 %</td>
<td>≤ 2 %</td>
</tr>
</tbody>
</table>

Agricultural residues require a product specific size reduction and liberation before pelleting. An investigation on Rye and Wheat straw as a raw material for pelleting has been carried out. Due to low bulk density of straw, straw has to be ground and compacted into dense and durable pellets in order to facilitate handling, storage and transportation (Adapa et al., 2007; Mani et al., 2003). In addition, because of uniform shape and size, densified products can be easily adopted in direct-combustion or co-firing with coal, gasification, pyrolysis, and in other biomass-based conversions (Kaliyan and Morey, 2006a).

The objective of this work is to produce 8 mm pellets which fulfil the quality standards as described in the norms. For producing 8 mm pellets, the straw should be ground to particles having a size less than 8 mm, such that the particles do not block the pellet mould (Obernberger & Thek, 2009). The size reduction of the Rye and Wheat straw was accomplished with the help of an impact mill / Hammer mill (HM) as well as a twin-screw extruder (EX). The aim of this work is to investigate 1) particle size distribution of the Rye and Wheat straws after different comminution processes, 2) optimisation of water content as a binding material in pellet production, 3) quality of pellets with the parameters abrasion and strength.

2 MATERIALS AND METHODS

The raw materials used in this study are straw of winter varieties of Rye straw (Secale cereale) and Wheat straw (Triticum vulgaris). The Rye and Wheat was grown in year 2005 and was harvested in the year 2006 in Goßmar, Brandenburg, Germany.

The impact mill / hammer mill (HM) employs a high speed rotating disc to which the hammer bars are fixed (figure 1a). The hammer bars are swung outwards by centrifugal force. The material is fed into the mill through a feeder. The material is downsized by being beaten by the hammer bars in order to reduce the particle size. The material was beaten until it was small enough to fall through the sieve having an aperture size of 6 mm. The Rye straw was comminuted in the industrial impact mill by the company Futtermittel und Dienstleistungs GmbH, Sonnewalde, Brandenburg.

The twin screw extruder (EX) works with the principle of defibration (figure 1b). The straw is fed into the twin screw extruder, where it is taken by the rotating screws. The material is brought with the rotating screws through the barrel and compacted against a die. This helps with building up of a pressure gradient along the screws. The material gets ground in close contact between the barrel walls and the rotating screws which causes frictional effects and leads to shearing forces. A destruction of the material’s cells occurred through the processing of moisture enriched material at high temperatures (80 °C – 130 °C) under pressure. Through high mechanical energy and high shear forces, the materials physical size (particle size) and chemical properties were changed. Through the extrusion process the straw surface gets partially destroyed which has influences on the contained lignin content and on the wax surface. Both Rye and Wheat straw are processed in the industrial twin-screw extruder by the company Lehmann Maschinenbau GmbH, Pöhl, Saxony.

The determination of particle size distribution can be carried out using different techniques (sieving, image analysis and laser diffraction). For quality control not only the particle size is of importance, but also the particle shape is an important characteristic. With the help of image analysis, the complete dimensions of the single particles can be analyzed. Image analysis was carried out with the help of Fibreshape from Innovative Sintering Technologies using a flatbed film scanner at a resolution of 2400 dpi. These settings enable to detect the particles having a size equal to or higher than 10 µm. The particle size distribution was carried out with three representative samples for each variant, each sample on average was having a minimum of 16,000 particles in each variant. Within image analysis different size characteristics (e.g. particle length, particle width) for each particle are measured.

The moisture content was determined using ASAE Standard S358.2 (ASAE, 2006a), where oven drying of the samples was carried out at 103 °C for 24 h. In order to achieve the optimized pellets, the raw materials Rye straw and Wheat straw were prepared with increasing water contents starting from 16 volume %. This was carried out by first measuring the water content of the raw materials and the additional water was supplied in the mixing process. The water was supplied as a binding agent in the pelleting of the raw materials. The moisture level greater than 15 volume % was used based upon the literature review as this moisture level would produce high density and quality pellets from various straws (Kaliyan and Morey, 2006b; Mani et al., 2006a; Obernberger and Thek, 2004; Shaw and Tabil, 2007). The water content was varied in...
percentage to develop the optimal mixture conditions for pelletisation and through which achieve lower abrasion and higher strength. The water content of the straw measured was in between 6.5 and 8.7 volume % after the respective comminution processes. The additional water ranging from 7.3 to 9.5 volume % has been supplied in to the mixing apparatus for obtaining a total water content of 16 volume %, and respectively repeated the procedure for the remaining water contents investigated.

Pelletisation was carried out with the help of a compactor (Hosokowa Bepex, Type L200/50G+K). The working principle of the compactor is similar to that of a hollow roller press. The material is auger fed towards the working area of the roller moulds, where it is pressed and the materials passes through the mould openings (figure 2). Densification of the raw materials takes place in the moulds. The mould openings are 25 mm long and have a diameter of 8 mm. The temperature measured during the pelletisation process was in between 80 °C to 100 °C.

Figure 2: Hosokowa Bepex laboratory compactor (Type L200/50G+K) with the working principle.

The pellet size and the range of variation influence the selection of the conveying systems as well as the combustion behaviour of the pellets. Pellets should be homogeneous in size and shape, which is recommended by the small scale pellet furnace manufacturers. The development of automatic biomass heating systems is only possible when the pellets have uniform size and shape (Obernberger & Thek, 2002).

The Rye straw and Wheat straw pellets were stored for 14 days at a temperature of 20 °C such that the water content of the pellets is stabilised. Abrasion tests and strength tests were carried out after the stabilisation of the water content in the pellets.

The abrasion of pellets is one of the most important parameters in the pellet production. Abrasion is an essential criterion to be considered by the end user as lower abrasion value produces less particulate emissions, has lower transportation losses and prevents bridging (clusters of irregular size and shape) of particles during storage (Obernberger & Thek, 2002). A high amount of fines in the pellets can cause failures in the feeding system. Abrasion has been measured using a rotating quadratic crate (Pföst pellet tester) as described in the ASABE standard S269.4 (figure 3). The quadratic crate (LxBxD: 30x30x12 mm³) rotates at a speed of 50 rotations/min for ten minutes. The sample was then sieved with a sieve having an aperture of 6.3 mm (0.8 * pellet diameter) as suggested by Thomas and Van der Poel, (1996). The difference in the weights of the pellets before and after the abrasion test gives the abrasion value.

Figure 3: Quadratic Abrasion testing device (ASABE standard S269.4).

The strength indicates the quality of pellets. The quality of pellets is noticeable by an exceptionally smooth pellet surface without any fissures. Moreover stronger pellets develop less particulate matter during handling. The strength tests (diametrical pressure test, point pressure test and three-point bending test) are carried out with the help of a ZWICK-ROELL (type: ZMART.PRO) material testing (tensile and compressive strengths) machine. These pressure tests were selected as such pressures occur during handling, transportation and storage of the pellets.

3 RESULTS AND DISCUSSIONS

The water content of the Rye and Wheat straw were in between 6.5 and 8.7 volume %. The pellets were prepared with increasing water contents starting from 16 volume %. The water content of the straw pellets measured after stabilisation for 14 days at 20 °C was in between 8.3 and 10 volume %. The 10 % water content improves the durability of the pellets (Kaliyan and Morey, 2009; Nielsen et al., 2010). The obtained water content is below the value mentioned under the standards for wood pellets. The water content has an influence on the net calorific value, combustion efficiency and the temperature of combustion (Obernberger & Thek, 2002; Nussbaumer & Kalschmitt, 2001). The higher water content reduces the durability and energy efficiency. The optimum water content for pellets should be less than 10 volume % as specified in DIN 51 731, DINplus, ÖNORM M 7135. Kaliyan and Morey, (2006a); Obernberger and Thek, (2004); Shaw and Tabil, (2007) state that the 10 % moisture content of pellets would result in longer storage, high combustion efficiencies and through which high energy efficiency.

The important fuel property which changes with the pelletisation is the bulk density of the raw materials (Ryu et al., 2006; Gilbert et al., 2009). The straws generally have very low bulk density values usually ranging in between 40 and 120 kg m⁻³ including baled density (Kaliyan and Morey, 2009). The measured bulk density of the Rye straw pellets on average was 560 kg m⁻³. The increase in bulk density significantly reduces the costs for storage, transportation, handling, feeding of the biomass and also increases the energy density.

The particle size and shape distribution analyzed after the comminution process are depicted in figure 4. The distribution curves start from 10 µm as the resolution of the scanner was set to 2400 dpi. The particles are classified into different particle size classes which are
long particles (length: 800 µm and above, width: 80 µm and above), short particles (length: 200 – 800 µm, width: 25 – 80 µm), slime stuff (length: upto 200 µm, width: upto 1 µm) and flour (length: 20 - 200 µm, width: 1 – 30 µm). Long particles and short particles are fibrous materials, whereas the slime stuff and flour stuff are fines (Pruden, 2005). Similar particle size distribution was observed with impact mill and also with twin-screw extruder for the Rye and Wheat straws. The fines (slime stuff & flour stuff) make up to 40 % of the total particles in the length distribution and 20 % in the width distribution.

Particle size distribution also affects the combustion process. Small particles and fines have higher burning rates and ignition front speeds (Ryu et al., 2006). Larger particles are thermally thick having slow devolatilization rate and more distributed heat transfer to the nearby particles. Ryu et al., (2006) states that with the increase in particle sizes (from 5 mm to 35 mm) there is a decrease in burning rate and also a decrease in heat influx from larger particles to the smaller particles and fines. The results show that 60 % to 80 % of the particles can be classified into smaller particles and fines, indicating that the burning rate and the heat influx would be optimal in the combustion process. 20 % to 40 % of the particles are classified as fibrous particles, which intertwine with each other during pelleting and act as an additional binding feature (Gilbert et al., 2009).

Figure 4: Particle size distribution (length & width) of Rye and Wheat straw after two different milling processes. The black dashed bars represent the borders of different particles classes based on length and width.

The usage of straw in different forms is dependent on its characteristics. The Carbon (C), Hydrogen (H) and Nitrogen (N) values (table II) in the Rye and Wheat straws comply with the natural ranges of the raw materials (Obernberger & Thek, 2002). The optimal value of N should be less than 0.3 % (DIN 51 731). The values of N in the Rye straw analysed were above 0.3 %. This indicates that the use of straw would result in increased NOx emissions (Schaffenberger & Stastny, 2008). C, H and Oxygen (O) are the main components of the biomass fuels; C and H are oxidized during combustion by exothermic reactions and therefore influence the calorific value of the fuel. The organic O provides a part of the O for the combustion process. Additional O must be supplied by air injection in the furnace (Obernberger & Thek, 2009).

As per the standard DIN 51 731, the values of the Chlorine (Cl) and Sulphur (S) should be less than 0.03 % and 0.08 % respectively. The values of Cl and S obtained in Rye straw were above the values specified in the standard. The concentrations of Cl and S should be limited as they have negative influences on the combustion processes.

Table II: Chemical properties of Rye and Wheat straw (Hartmann, 2007).

<table>
<thead>
<tr>
<th>Raw material</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rye straw</td>
<td>46.6</td>
<td>6.0</td>
<td>42.1</td>
<td>0.55</td>
<td>0.085</td>
<td>0.19</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>45.6</td>
<td>5.8</td>
<td>42.4</td>
<td>0.48</td>
<td>0.082</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The amount of S in the Rye and Wheat straw is very close to the standards mentioned. High amount of S can cause problems regarding emissions (SOx). There is no high risk of SOx emissions as the obtained S values in straw are almost equal to the values mentioned in standards. The Cl content in the straw is very high in comparison to the values mentioned in standards, which would cause problems in depositions and corrosion of the furnace (Schaffenberger & Stastny, 2008). The heating value of the Rye and Wheat straw can be calculated based on the chemical composition of the raw materials using equation (1) (Kalschmitt et al., 2009). The water free (wf) heating value of 17.4 MJ kg⁻¹ and 17.2 MJ kg⁻¹ has been calculated for the Rye and Wheat straws respectively.

\[ H_{\text{u(wf)}} = 34.8^\circ C + 93.9^\circ H + 10.5^\circ S + 6.3^\circ N - 10.8^\circ O \ (1) \]

Another characterization of straw is the definition of the lignocellulosic composition. Lignin plays an important physiological role in plants as it works as a natural adhesive between fibres. In biomass pellets, lignin acts as a natural binding agent (Oliveira et al., 2009; Gilbert et al., 2009). Lignin is one of the important parameters to be considered in pelleting. The lignin polymer gives firmness to the pellets, through which the durability characteristics of the pellets can be improved (Obernberger and Thek, 2009). Chen et al. (2007) stated that agricultural straws contain 10-27 % of lignin. White (1987) gives an equation with which the amount of lignin content in biomass can be calculated once the higher heating value of biomass is known (equation 2). With the
help of equation 2 and equation 1, the lignin content of Rye and Wheat straw was calculated. The lignin content in the Rye and Wheat straws obtained was 26.7 % and 27 % of the dry matter.

\[
he = 7,500 + 39.0 \times X_l
\]  

(2)

where \(he\) = higher heating value and \(X_l\) = lignin content

Obernberger and Thek, (2009) state that the lignin polymer softens at a temperature of 190 °C. The softening temperature of lignin reduces with increasing water content in the biomass. The water content of Rye and Wheat straw measured was in between 6.5 and 8.7 volume %. With 10 volume % water content, the softening temperature of lignin reduces to 130 °C. The pellets were prepared with water as a binding material starting with 16 volume % water content, indicating the lignin softening temperature to be in between 80 °C and 90 °C (Uslu & Faaij, 2008; Gilbert et al., 2009). The temperature of the rotating moulds of the compactor measured was in between 85 °C and 100 °C, indicating that the lignin was softened and helped in the firmness of the pellets. Gilbert et al., (2009) observed that the firmness and bulk density of the pellets increased with increasing temperatures from 60 °C to 100 °C and a decrease in firmness and bulk density with further increase in temperatures from 100 °C to 130 °C. The moisture in the pellets evaporates completely when the pellets were prepared above 100 °C and affects the quality of the pellets. The complete evaporation results in harder and brittle pellets, which easily deform and have low strength. Special care was taken so that the temperature of the rotating moulds does not reach a value higher then 100 °C, with which it can be assured that the pellets were prepared under the optimum conditions.

The pellets were prepared with increasing water contents starting from 16 %. The pellets were then tested for abrasion and the optimal water content was determined with respect to the minimum abrasion values achieved. The minimum abrasion values of Rye and Wheat straw pellets were obtained at 17 volume % and 18 volume % water content in the mixture (figure 5). The pellets before and after the abrasion tests have been displayed in figure 6.

Obernberger & Thek (2002) state that there is a direct correlation between the abrasion and the particle size distribution. The particle size distribution after different milling processes show that there are 40 % fines present. The abrasion values achieved with impact milled material (4.7 % and 3.7 %) and with twin-screw extrusion material (2.6 % and 3.0 %) from Rye and Wheat straws correlate directly to the amount of fines in the raw material after comminution processes.

The standards ÖNORM M 7135 and DINplus state that the abrasion value of the pellets should not be greater than 2.3 %. The abrasion values of the Rye and Wheat straw obtained are greater than the specified abrasion values. The high amount of fines could be the reason for obtaining such high abrasion values. Higher percentage of fines can cause failures in the furnace feeding systems and also causes higher particulate emissions during combustion. Other parameters such as use of binding agents, additives etc also have an influence on the abrasion characteristics.

Figure 5: Abrasion of the Rye straw and Wheat straw pellets prepared with increasing water contents after grounding liberation of the fibres with Hammer mill and Twin-screw extruder.

Figure 6: Straw pellets prepared (left) with Hosokowa Bepex, Type L200/50G+K. The pellets after (right) the abrasion test.

For the evaluation of strength, the maximum pressure force which a pellet can withstand was analysed. Pellets need to withstand different pressure forces as they are confronted with such pressures during handling, storage and transportation. The results show that maximum pressure which a pellet can withstand was obtained with 17 volume % and 18 volume % water content for Rye and Wheat straw pellets (figure 7). These strength results also correlate with the abrasion values obtained.

Figure 7: The strength of the pellets as measured using three different strength testing methods with 17 volume % water for Rye and 18 volume % for Wheat straw respectively (point pressure, three point pressure and diametrical pressure).
4 CONCLUSIONS

There are some problems in using straw for heating and energy generation (dust, huge amount of ash, high emissions, etc.). The straw incineration results in high NOx and SOx emissions and also causes depositions and corrosion of the furnace due to high presence of Cl. Special furnaces with filters have to be used especially when straw has to be incinerated. The combustion of straw is profitable in full scale power plants. Regarding when straw has to be incinerated. The combustion of straw is CO₂-neutral, but the calorific value and the bulk density of straw is very low compared to that of woody biomass. Thus the high CO₂ emissions from the transport of straw should also be considered. The Rye and Wheat straws can be used in the form of pellets, which have high density (540 kg m⁻³) and a heating value of 17.2 MJ kg⁻¹ and 17.4 MJ kg⁻¹.

The moisture content of the pellets after stabilization was below 10 volume % indicating a longer durability of the pellets. Particle size characteristics showed a good correlation to the abrasion values and favourable combustion characteristics. The minimum abrasion values were obtained with 17 volume % water content for Rye straw and at 18 volume % water content for Wheat straw. The pressure tests also showed a good correlation with the abrasion values i.e. the pellets showed higher pressure resistance with lower abrasion values.

5 REFERENCES


6 ACKNOWLEDGEMENTS

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