Feasibility of Pelletization and torrefaction of agricultural and woody biomass

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ABSTRACT Torrefied biomass represents a high quality renewable energy commodity that can be used to substitute fossil fuels such as coal. Densification processes such as pelletisation is necessary to improve the tradability of “low-dense” torrefied biomass. The problem with torrefied biomass is difficulty of densifying the materials and production of durable and dense pellets. This research found that steam treatment of raw biomass produced durable pellets from difficult to-pelletize torrefied woody and agricultural biomass. Softwood chips (Pine and Douglas-fir) and agricultural biomass (switch grass, wheat straw and corn stover) were pelletised and torrefied. Moisture content of the feed and the residence time in the pellet press were key role factors affecting density and durability of pellets. No binder was needed when biomass was steam treated

Keywords: Biomass, steam treatment, torrefaction. Palletization, pellet density and durability

INTRODUCTION

Torrefaction is a thermal pretreatment process to upgrade the properties of lignocellulosic biomass to a high quality “energy and carbon carrier” which can be effectively used to substitute fossil fuels (Agar et all, 2012, Arias et all, 2008). The process is generally considered as a mild pyrolysis or carbonisation where the biomass is subjected to temperatures ranging from 200 to 300 °C in the absence of oxygen (Bridgeman et all, 2008). The high heating value of the currently marketed wood pellets is approximately 19 GJ per metric ton which is substantially lower that of coal (28–30 GJ per metric ton). This lower heat content limits the proportion of biomass that can be used in co-firing...
with coal (Gilbert et al, 2009). Torrefaction process increases the heat value of the biomass closer to that of coal by removing the volatile substances including water (Hilten et al, 2009a,b).

Shang et al. (Kokko et al, 2010. Kaliyan et al, 2012) have shown that torrefaction increased the higher heating value of Scots pine from 18.4 MJ/kg to 24.3 MJ/kg. In addition to be an effective substitute to coal, torrefied biomass can be processed to both gaseous/liquid fuels and a range of chemicals/ materials (Kumar et al, 2012. Mani et al, 2006). The syngas produced from the gasification of torrefied biomass was found to have a significantly higher heat value compared to the syngas generated from the raw biomass (Ohliger et al, 2013). In addition, torrefying biomass prior to pyrolysis improved the properties of biooil (Ohliger et al, 2012. Peng et al, 2012). Some other beneficial properties of torrefied biomass include their high hydrophobicity and enhanced grindability compared to untreated biomass (Pirraglia et al, 2013. Ren et al, 2013). Torrefaction has also been recognised as a robust strategy to overcome the heterogeneity among different types of cellulosic feedstocks thus producing a uniform-quality energy commodity with improved fuel/carbon values (Repellin et al, 2010).

Despite many advantages of torrefied pellets, there are several challenges that need to be addressed for the commercial use of torrefied material as a “tradable energy commodity”. Bulk density of the torrefied material is often poor; i.e., even lower than that of the raw biomass making the transport and storage of the material economically challenging (Sarvaramini et al, 2013. Shang et al, 2012a). In order to facilitate the effective use of torrefied biomass as a “globally traded bioenergy commodity”, the material will have to be densified. It should be noted that it was the recent developments in densification technologies such as pelletisation, that enabled the global transport of biomass as an energy commodity (Shang et al, 2012b). As a consequence, Canadian wood pellet industry has rapidly evolved as an inevitable part of the global bioeconomy with British Columbia being one of the leading exporters of wood pellets.

It is apparent that combining the torrefaction and densification processes to make “torrefied wood pellets” has a great potential to upgrade the properties of biomass to a transportable high value energy commodity with several end use applications (Sheikh et al, 2013). However, torrefied pellets should be produced with minimum energy consumption without compromising the energy and carbon values of torrefied materials while also ensuring that the resulting pellets are stable and durable under varying environmental conditions such as different temperatures and humidity.

There has been some previous work, which has looked into densifying the torrefied biomass. As a result, there are some pilot scale industrial units that produce torrefied wood pellets. Most of this units first torrefy biomass and subsequently densify them. However, the main challenge associated with this traditional approach is the difficulty in densifying biomass particles after they have been torrefied. It was found that torrefied biomass particles were not easy to bind as effectively as the untreated biomass particles (Shuttleworth et al, 2013) and the resulting pellets had poor storage and transport characteristics albeit a greater amount of energy required for pelletisation (Stelte et al, 2013. Stelte et al, 2011).

An alternative approach used in this work was to torrefy biomass after it has been densified. We have expected that this approach may be more promising compared to the traditional method of making torrefied pellets due to the easiness in integrating a torrefaction as a final step in the existing pellet plants. However, it is not investigated in detail whether woody and agricultural pellets can retain all of the desirable characteristics after they have been torrefied. Some of the preliminary work has shown that torrefaction can cause a decrease in the durability characteristics of the wood pellets such as compression strength (Kaliyan et al, 2010. Kokko et al, 2012). To overcome these weak quality of the produced torrefied pellets in this work, we have look for different methods (mechanical compression and steam explosion) to produce more dense and durable pellet from raw or pretreated materials prior to torrefaction.
We quantified almost all of the relevant parameters of raw, steam treated and torrefied pellets including density, durability, hydrophobicity, water absorption, fuel value and chemical as well as elemental composition. In addition to understanding the properties of torrefied pellets, it is important to understand the overall mass and energy balance of this proposed process. Some of the results have been included in this paper.

MATERIALS AND METHODS

**Raw material** Douglas fir and Mountain Pine wood chips with average size of 30 to 50 mm and shredded switchgrass, wheat straw, and corn stover with average length of 50-80 mm were used as raw material. Initial moisture content of wood chips were 40% (on a wet weight basis) and for agricultural samples were 15-20%. The woody samples were collected from Fibreco Company, North Vancouver from a large pile, stored outdoor. Immediately after collection, the samples were sealed in plastic bags and subsequently stored in the cold room (4°C). Switch grass harvested in Clinton Ontario on April 2012. The samples air dried. The sample compressed to rectangular bales and delivered to ConmetEnergy Ottawa and through them to Vancouver. Wheat straw and corn stover samples harvested in Ontario in summer 2012 and delivered to ConmetEnergy and through them in bales delivered to the University of British Columbia in October 2012. As received materials were first dried to reach 15% moisture content using the hot air convection oven (Cascade, TEK TFO-28). Raw material both the woody and the agricultural biomasses were ground using a lab mill (10HMBL, Glen mills). The grinding of material were required for pelletization process.

**Steam pretreatment** Steam pretreatment was conducted in a 2 L StakeTech III steam gun (Stake Technologies, Norvall, ON, Canada) in the Forest Products Biotechnology/Bioenergy Laboratory at the University of British Columbia. Briefly, batches of dry weight of 200 g of each corn stover, switchgrass, wheat straw, and wood chips (Douglas fir, pine) were steam treated in several temperature and pressure combinations. Steam explosion were repeated to collect 3 kg dry materials of each species to have enough material for palletization process. The steam explosion increased the moisture content to about 80% (wb). The liquid sampled was collected for composition and concentration analysis and the solid mass was dried for pelletization. The dry mass loss was calculated by subtraction dry mass yield from the untreated mass weight.

**Pelletization** Lab scale California Pellet Mill (CPM) was used for pelletizing both the steam exploded and the untreated materials (CL-397179, 230 V, 3 phase and 60 Hz). The pelletizer had 5 HP motor using 14 A with a rotational speed of 1750 rpm. The ampere indicator was used to monitor the instantaneous power consumption of the machine. Two sizes of dies thickness were tested, thin die (19 mm thickness) and thick die (31.5 mm).

Similar to the grinder, the pelletizing machine was connected to computer for recording the power consumption during the process. The flow rate of the material was controlled by adjusting the vibration of the feeding plate thus avoiding exceeding the maximum power consumption of the machine. The ground untreated material had conditioned in different moisture content varying from 12-18% prior to pelletization. The pellet density was measured by dividing its mass over the pellet volume. The volume was calculated by measuring pellet diameter and length using a digital caliper.

**Torrefaction** Torrefaction was carried out using the UBC-BTGA (University of British Columbia’s big thermo-gravimetric analyzer). The unit consisted of a Carbolite oven (650x480x 410 mm), which operated at temperatures ranging from room temperature to 600°C. A circulating blower inside the
chamber provided air circulation. A torrefaction chamber (385x385x330 mm stainless steel box) was installed inside the oven cavity. An oxygen-free environment for the inner chamber was provided by continuous flow of nitrogen. A tray (350 mm diameter) was suspended freely inside the inner chamber via a thin wire from a load cell located about 1 m from the top of the chamber. The tray could generally hold up to 200–1000 g of wood chips. There were two ports for gas input and output. An external heater initially heated up the nitrogen gas. The preheated gas entered chamber and flowed through a heat exchanger. The chamber was purged with preheated nitrogen gas. The gas carried the volatiles through externally heated tube, which was well insulated to prevent condensation and in-line deposition of the tar. The condensation unit was connected to the end of the tube which was cooled down using the cold water circulation outside the tube. We used 600 g of pellets to form a uniform layer on the tray. The height of the pellet in the tray was approximately 1.8 mm. The load cell converted the force to voltage and a data accusation card installed on the BTGA unit computer receives the data and mass loss was recorded instantaneously.

**Analysis** Moisture content of the pellets was measured gravimetrically using the convection drying oven method according to the ASABE standards. The durability was measured using the tumbler testing unit according to American Society of Agricultural Engineers Standard S269.4. The unit consisted of a rectangular stainless steel container with inner dimension of 300 mm and height of 125 mm. The rotation speed was adjusted to 50 rpm and the rotation time was 10 min. Exactly 500 g of sample was used for the test. The tumbled sample was sieved using round screen holes of 3.15 mm. The percent of original pellets that remained unbroken provided the percent durability. The higher heating value (HHV) of solid samples was determined in an oxygen bomb calorimeter (Model 6600, Moline, IL) fitted with continuous temperature recording. A small mass 0.6–1.2 g of densified sample was placed in the instrument chamber. The measurements were repeated three times on three different pellets. The bulk density of pellets was measured by filling a 2.2 liter cylindrical container (h/d=1) and measuring the pellets weight. By having the volume and the weight the density was calculated. For single pellet density the length and the diameter of pellets measured using digital caliper and the volume of the pellets calculated. Weight of pellet measured using balance with 10 mg sensitivity. Having mass and volume, the single pellet density was calculated.

**RESULT AND DISCUSSION**

**Untreated pellet** Table 1 lists the measured properties of agricultural pellets made using thin die (19 mm thickness) and thick die (31.5 mm). Pellets made using thin die were very brittle pellets. Increasing temperature and moisture content did not help to improve the produced pellets quality. The agricultural biomass needed conditioning with higher moisture content for pelletization compared to the woody biomass. Increasing material residence time in die required even higher moisture content. For this reason as Table 1 shows that when agricultural materials were conditioned to a higher moisture content (from 14% to 17%) the durability and density of pellets increased. Increasing residence time in the pelletizing die results to more dense pellets. Agricultural pellets had a lower bulk density than woody pellets.

**Steam exploded pellet** Table 2 and 3 list the measured properties of the steam exploded woody and agricultural biomasses. Table 2 compares properties of the woody (Douglas fir) and the agricultural (switch grass) biomasses in different states (untreated, steam exploded, and torrefied). The Pellets made from steam exploded materials were very dense and durable. The density of the Douglas fir single pellet were increased from 1.17g/cm$^3$ to 1.30 g/cm$^3$ in effect of the steam explosion treatment. Also durability of the pellets was increased from 98% for the untreated to 99.7% for the steam exploded Douglas fir pellets. Bulk density of the pellets were increased following increase of the single pellets. Also the heat value of the pellets were increased during the process of steam explosion. Same property improvement was happen for the agricultural biomass
(switch grass). Table 2 list the properties of the switch grass pellets before and after steam explosion. Same as the woody pellets the single pellet density, durability, and heat value of the switch grass pellets were increased in effect of the steam explosion pretreatment. Table 3 list the measured properties of the steam exploded pellets in different conditions. The corn stover was steam exploded in several different temperature (150°, 170°, 190°, 210° C). All pellets made from the corn stover sample had improved properties. The single pellet density increased from 1.15 g/cm³ for the untreated pellet to 1.30 g/cm³ for the steam exploded pellets in all the treatment conditions. Also durability of the steam exploded corn stover pellets were increased to 99.7-100.0%. Base on the test results steam explosion of agricultural biomass in 150°C was satisfactory to produce dense and durable pellets.

Steam explosion increase the contact surface area. Increasing the contacting surface area and decreasing the materials contact distance increase the chance of physical interlocking and chemical bonding in between the particles. The accumulation of lignin on the surface of the steam exploded material increase by steam treatment. This is also additional parameter for improving the density and durability of the produced pellets (Kumar et al. 2012). Sugar released during the steaming process works as binder and it also increase the pellet durability.

Scanning electron microscopy images, figures (4) and (5) show close look on the particles and fiber arrangement on external surface (figure5) and inside (figure 4) of the produced steam exploded pellet. Comparing to the raw pellet internal picture (Figure 2) the steam treated particle shape a uniform and compact structure (Figure 4). Figures (1), and (3) show the external surface of the raw and steam exploded pellets. In these pictures the effect of steam explosion on increasing the flexibility of material is clear. The steam exploded fibers are oriented in directions to stay close to each other, and have shaped much smooth surface in compare to the rigid raw biomass. These quality improvement are satisfactory if both woody and agricultural biomass are planned to be used as feedstock for bio refinery and ethanol production. When the point of densification is the production of mass and energy dense biomass for combustion its quality need to improve in aspects of hydrophobicity, grind ability and heat value. This can happen through the torrefaction process.

**Torrefaction** The produced raw and steam exploded pellets are torrefied in the temperature range of 250-320°C. The steam explosion helps to increase the density and durability of the produced pellets. But it is not too much effective on increasing heat value of the treated material. The test result shows that 8-15% of the materials dry mass loss via steam explosion process. This mass loss percentage is related to the severity of the treatment. For the set of experiments on corn stover sample we proceed treatment for duration of 5 minutes. Temperature set on 150, 170, 190, and 210°C. Table (3) shows the produced pellet quality and effect of treatment temperature on property of materials. By increasing the temperature the mass loss increase. The mass loss for treatment temperature variation in the range of 150-210°C include almost same ratio of carbon and endothermic reactants. As a result the heat value of the steam exploded materials do not change considerably. It looks the mass loss of the biomass via steam explosion does not affect the carbon to the oxygen ratio seriously.

Table (2) shows that the torrefaction of steam treated materials as like as raw material helps to overcome to the low heat value property. The torrefied pellets become fully hydrophobic. The torrefied pellets stay stable and durable after immersing in water for 24 hour. Even the water color did not change (Figure 8). The problem with the steam exploded pellets and the pellets produced from torrefied materials with aid of binder is that when the material stored outdoor or sink in water they release some chemical that dissolve in water and change its color. Torrefaction of raw and steam exploded pellets result in very stable pellets without releasing chemicals and contaminants when they expose to water or rain.
Figures (6,7) show close look on rough (inside) and smooth surface (outsid) of the torrefied steam exploded pellet. Figure 6 shows that the layer structure of the pellet disappeared and it looks the pellet has mostly crystalline structure. This is same for raw and steam exploded torrefied pellet.

The heat value of the woody and agricultural biomass increase through torrefaction process. The raw material even directly pelletized or go through steam explosion and then get torrefied show almost same mass loss in whole process of thermal treatment. The Figure 1 and Table(2) show the mass loss and heat value change of both woody and agricultural biomass via torrefaction process. Direct torrefaction of raw pellet and torrefaction of steam treated pellet result in pellets with almost same high heat value, hydrophobisity, and grindability, the process of steam explosion improve durability and density of the pellets.

**DISCUSSION**

The compression of raw material under increased moisture content and temperature resulted to better pellets in term of density and durability. But the pellets (both woody and agricultural) when immersed in water or expose to a humid atmosphere disintegrated to its particles. The reason for disintegration of raw pellets was that the particles swelled when they expose to water. When we processed the material through thermal treatment (wet and/or dry) the cell wall and fiber structure of the raw material get modified and as a result the volume of material did not expand in contact with water. The treated materials get wet as it has porous structure and water penetrate in to the body of material but as the cell wall structure of the materials get destroyed through thermal treatment the reverse osmose phenomena cannot cause the swelling of materials and as a result pellets dose not disintegrate. In case of the steam explosion process as the test result show it not only cause the cell wall structure deformation causing loss of water holding and swelling properties, but also the materials get more flexible and loss its rigidity in compare to untreated material. This added property to the raw material via steam explosion help the particles to get much closer to each other and interlock to each other in better condition.

The agricultural biomass densification through pelletization is an effective process on reduction of material volume per unite mass. The problem with agricultural biomasses is that they have low bulk density and to reach to the density of regular pellets we need to reduce the mass unit volume 5- 6 times from its ordinary bulk density. Compare to woody biomass the agricultural biomass need to have longer residence time in the palletization die to shape more dense and durable pellets. The quality of produced pellets using dies with two different thickness shows that as the thickness of die increase the density and durability of the agricultural pellets increase as well. The conditioned material face with much friction force using thicker die. But the problem with using thicker die is that as material reside in die for longer time, they lose their moister and the material get much dry and warmer. As a result water content is not sufficient to work as binder and heat transferring agent. To overcome this problem the materials need to be conditioned at a higher moisture content or need to be added steam during pelletization process. The Steam explosion treatment improve durability and density of the pellets. Via process of the steam explosion, pelletization, and torrefaction produced pellets will have high heat value, density and durability with improved grindability and hydrophobicity.
REFERENCES


Table 1: Raw pellet quality test result. The effect of die thickness on durability of pellet for agricultural material have been tested.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Die thickness (in)</th>
<th>Biomass Moisture content %</th>
<th>Pellet Moisture Content %</th>
<th>HHV (MJ/kg) Dry mass</th>
<th>Durability %</th>
<th>Single pellet density (g/cm³)</th>
<th>Pellet Bulk Density* (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglass fir</td>
<td>0.75</td>
<td>14</td>
<td>7.1</td>
<td>19.2</td>
<td>98.1</td>
<td>1.17</td>
<td>660</td>
</tr>
<tr>
<td>Mountain pine</td>
<td>0.75</td>
<td>14</td>
<td>6.8</td>
<td>18.95</td>
<td>98.0</td>
<td>1.15</td>
<td>670</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>0.75</td>
<td>14</td>
<td>9.2</td>
<td>18.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>1.25</td>
<td>17</td>
<td>7.5</td>
<td>18.7</td>
<td>98.0</td>
<td>1.19</td>
<td>630</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>0.75</td>
<td>14</td>
<td>10.0</td>
<td>18.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>1.25</td>
<td>17</td>
<td>8.9</td>
<td>18.2</td>
<td>99.0</td>
<td>1.22</td>
<td>650</td>
</tr>
<tr>
<td>Corn Stover</td>
<td>1.25</td>
<td>17</td>
<td>8.35</td>
<td>17.9</td>
<td>99.5</td>
<td>1.15</td>
<td>650</td>
</tr>
</tbody>
</table>

*The woody biomass produced longer pellet than agricultural material using the same die set up

Table 2: Woody (Douglas fir) and agricultural (switch grass) pellet properties (raw, steam treated, pelletized and torrefied)

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>HHV MJ/Kg</th>
<th>Density (g/cm³)</th>
<th>Durability Tumbler %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torrefied steam treated DF* pellet (280°C, 15 min)</td>
<td>22.8</td>
<td>1.23</td>
<td>99.2</td>
</tr>
<tr>
<td>Torrefied DF* pellet (280°C, 15 min)</td>
<td>23.2</td>
<td>1.14</td>
<td>98.4</td>
</tr>
<tr>
<td>Steam treated DF* pellet (210°C, 5min)</td>
<td>20.3</td>
<td>1.29</td>
<td>99.7</td>
</tr>
<tr>
<td>DF* raw pellet</td>
<td>18.8</td>
<td>1.17</td>
<td>98.1</td>
</tr>
<tr>
<td>Torrefied steam treated switch grass pellet (260°C, 15 min)</td>
<td>21.3</td>
<td>1.2</td>
<td>99.0</td>
</tr>
<tr>
<td>Torrefied switch grass pellet (260°C, 15 min)</td>
<td>21.8</td>
<td>1.05</td>
<td>98.2</td>
</tr>
<tr>
<td>Steam treated switch grass pellet (210°C, 5min)</td>
<td>19</td>
<td>1.3</td>
<td>99.3</td>
</tr>
<tr>
<td>Switch grass raw pellet</td>
<td>17.3</td>
<td>1.15</td>
<td>97.8</td>
</tr>
</tbody>
</table>
Table 3: The quality of pellets produced from steam exploded corn stover in different temperature. Treatment duration 5 minutes

<table>
<thead>
<tr>
<th>Sample</th>
<th>Steam treatment temperature (°C)</th>
<th>Pelletization ratio (%)</th>
<th>Pellet Moisture content (%)</th>
<th>Single pellet density (g/cm³)</th>
<th>Pellet bulk density* (kg/m³)</th>
<th>Durability %</th>
<th>HHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Stover</td>
<td>150</td>
<td>85</td>
<td>7.5</td>
<td>1.28</td>
<td>680</td>
<td>99.7</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>92</td>
<td>6.8</td>
<td>1.30</td>
<td>675</td>
<td>99.9</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>94</td>
<td>7.0</td>
<td>1.30</td>
<td>690</td>
<td>100.0</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>88</td>
<td>6.2</td>
<td>1.29</td>
<td>695</td>
<td>99.8</td>
<td>18.2</td>
</tr>
</tbody>
</table>

1: mass loss of switch grass pellet (raw, and steam exploded) via torrefaction process
Figure 5: SEM image of steam treated Douglas fir pellet’s outside surface

Figure 6: SEM image of torrefied steam treated Douglas fir pellet’s inside surface after cutting pellet to half vertically

Figure 7: SEM image of torrefied steam treated Douglas fir pellet’s outside surface

Figure 8: Torrefied pellets (which species) were immersed in water for 24 hours. There was not any sign of disintegration and chemical dissolve in water.