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Research paper

Influence of moisture content and hammer mill screen size on the physical quality of barley, oat, canola and wheat straw briquettes

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ABSTRACT

In order to determine the briquetting characteristics of biomass in a commercial setting, a hydraulic briquetter was used to study the compaction behavior of biomass grinds from barley, oat, canola and wheat straw. The selected straw samples were ground with a hammer mill using screen sizes of 19.05, 25.40 and 31.75 mm and conditioned to three moisture content levels of 0.09, 0.12 and 0.15 (w.b.). The residence time was about 6–10 min before being extruded from the briquetter. The specific energy, throughput, as well as the density, and durability of manufactured briquettes were measured during or after briquetting. The applied compression pressure at different parameter combinations ranged from 7 to 14 MPa. Higher pressure resulted at higher biomass moisture content. Hammer mill grinding of biomass with a large screen size (31.75 mm) resulted in high energy consumption and low throughput during briquetting. The increase in moisture content decreased the total energy consumption and increased the throughput of the briquetter. Briquette densities were of consistently higher value when biomass samples were compressed at a lower moisture level. The moisture content and hammer mill screen size indirectly influenced the briquette densities by affecting the pressure and residence time in commercial briquette production. Briquettes were successfully formed without adding a binder.

1. Introduction

Biomass is an important renewable energy resource that could potentially replace traditional fossil energy. It can be directly combusted to produce heat or be transformed to electrical energy and other forms of energy [1]. But biomass materials have low bulk densities and have low volumetric heating values. Densification of biomass is an effective method to decrease the volume of loose biomass and the cost of storage, transport and utilization [2–4].

Lignocellulosic biomass such as agricultural and forest residues, e.g. crop straw and sawdust, respectively, have been reported to have been densified and used as fuel [3]. Compaction of sawdust and wheat straw was tested by pressure and temperature applications [5]. In the briquetting of olive cake, a byproduct in the extraction of olive oil, it was reported that moisture content and pressure had significant effects on briquette durability and stability [6]. Variables of densification (pressure, moisture, particle size, etc.) are very important in the forming process of materials as reported in previous research works. It is well known that the increase of compression pressure increases the briquette densities, but should be selected at an optimum value to produce high quality briquettes [7–9]. Several typical levels of pressure and moisture content were preset to compress the briquettes; for instance, good unit density and durability could be produced with low to medium moisture contents of 0.09–0.12 (wet basis (w.b.)) and high compression pressure of 12.5 MPa [10]. Low moisture corn stover (0.08–0.10 (w.b.)) resulted in denser, more stable and more durable briquettes than high moisture stover (0.15 (w.b.)) that had a lower density. This is because high moisture content results in the expansion of the briquette volume after extrusion due to moisture evaporation at high temperature [9,10]. Smaller particle sizes can produce higher density briquettes, but more energy is expended to grind the raw materials [11]. Tumuluru et al. [10] reported that large hammer mill screen sizes resulted in higher durability briquettes due to better interlocking of the variable sizes of particles.

In most of the previous studies, the plunger-die system was used to investigate the compaction characteristics of biomass on a

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laboratory scale [6,9,12–15]. In briquetting using the plunger-die system, the main goal is to understand the impact of pressure on the quality of briquettes and pressure was assumed as an independent variable, similar to other factors (temperature, moisture content and screen size). But in the commercial scale, especially using a hydraulic briquetting machine, the compression pressure can be adapted with process conditions. Thus, the pressure may be a dependent variable relative to other factors. In this study, we used a hydraulic briquetting equipment. The applied compression pressure varies with moisture content and screen size for grinding each type of straw.

The main objective of this research project was to investigate the effects of moisture content, in the range of 0.09–0.15 (w.b.), and hammer mill screen size used in grinding the straw, in the range of 19.05–31.75 mm, on the briquetting parameters of selected straw (barley, oat, canola and wheat) processed using a commercial-scale briquetter. The parameters of the commercial-scale briquetter that we monitored were applied pressure, energy consumption and throughput.

2. Materials and methods

2.1. Raw materials and preparation

Four types of raw materials (i.e., barley, oat, canola and wheat straw) were used for the experiments. Canola straw was acquired as small square bales (typically having dimensions of $0.45 \times 0.35 \times 1.00$ m) from RAW Ag-Ventures Ltd. (52.67° N, 107.79° W, Maymont, SK, Canada) during the summer of 2008. Wheat, oat and barley straw bales were acquired from the Central Butte area (50.83° N, 106.51° W) of Saskatchewan during the fall of 2013. The samples, except canola straw, were initially chopped to 44 mm using a chopper with no screen [16]. The canola straw was inflexible and difficult to feed into the chopper. It should be broken apart to short length by hand. Then the chopped straw samples were further ground using a hammer mill (Serial No. 6M13688, 230 Brookdale, St. Maywood, NJ) with screen sizes of 19.05, 25.40 and 31.75 mm [17].

The bulk density of ground straw was determined using a standard 0.5 L cylindrical container. The sample was slowly poured into the container and excess sample at the top was leveled off using a round metal bar. The particle densities of the ground straw samples were determined using a gas multi-pycnometer (Quanta Chrome, Boynton Beach, FL) [2,12]. The measurements of bulk density and particle density for each sample were repeated five times. To determine the geometric length of ground straw, samples of about 150 g were sieved for 2 min using the screen shaker with sieve sizes 26.9, 18.0, 8.98, 5.61 and 1.65 mm. The geometric mean length of each straw sample was calculated using ASABE standard S424.1 [18]. Table 1 shows the physical characteristics of straw samples.

The moisture contents of the straw samples were measured using ASABE standard S358.2 [19]. The initial approximate moisture contents of ground barley, oat, canola and wheat straw were about 0.0482, 0.0578, 0.0698 and 0.0507 (w.b.), respectively. Each of the ground straw was conditioned to a moisture content of 0.09, 0.12 and 0.15 (w.b.), by spraying calculated amount of water, respectively inside a large and thick bag; after that, the moisture-adjusted samples were stored in a cool room at 4 °C for 72 h.

2.2. Biomass briquetter

The briquetter (Model BP-100, Biomass Briquette Systems, LLC, Chico, CA) was used in the briquetting experiments (Fig. 1). Fig. 2 shows the structural schematic of BP-100 briquetter. The straw grinds were fed into the square charging inlet by the rotation of blades and was pushed into the sleeve by the feeding hydraulic cylinder. The straw grinds were then compressed by the compressing hydraulic cylinder, where there was a pressing head inside the sleeve. Finally, biomass briquettes were extruded from the sleeve. The diameter of the sleeve was 50 mm and its length was about 500 mm. The compacted material was pushed ahead along the sleeve and it resided about 6–10 min before being extruded.

The charging inlet can be adjusted to control the volume of feed material. The bigger the charging inlet is, the more the material could be fed in. In this study, the inlet was set at the maximum position to make long briquettes for there was enough material. The applied compression pressure varies with the change of process parameters such as moisture content, screen size and the feed volume of material. The biomass briquetter (Model BP-100) is capable of maximum hydraulic pressure of 16 MPa. So, it was set at this value so that the materials could acquire enough compression energy for shaping. The surface temperature of the single briquetting outlet was about 50 ± 5 °C measured by a handheld infrared thermometer (TN408LC ThermaTwin, Radiant Innovation Inc. HsinChu, Taiwan); this resulted from compression and frictional heating.

A power analyzer (ELITE*pro* XC, DENT Instruments, Inc., Bend, OR) was mounted to the control panel of the briquetter, which calculated the power from voltage connections and current transformers on each phase of the three-phase power. A Honeywell pressure sensor (MLH 03KPSL01B, 0–20.7 MPa pressure range, Honeywell International Inc. Golden Valley, MN) was mounted at the hydraulic pipeline of cylinder (compression). The ELITE*pro* XC also has some spare input channels where the Honeywell pressure sensor was connected to measure the applied pressure during the compression and extrusion processes. Then, a computer with ELOG 14 software (DENT Instruments, Inc., Bend, OR) was connected to the ELITE*pro* XC to record pressure, time and energy consumption data at intervals of 1 s.

2.3. Experimental plan

In order to determine the effects of process variables (moisture content, hammer mill screen size and pressure) on the physical properties of briquettes for selected biomass materials (barley, oat, canola and wheat straw), experiments were designed at three levels of moisture content (0.09, 0.12 and 0.15, w.b.), and three levels of hammer mill screen sizes (19.05, 25.40 and 31.75 mm). Moisture content and screen size were the main factors that influenced briquetting, because maximum feeding volume was almost the same. The applied pressure that was affected by moisture content and screen size was measured using the pressure transducer. The physical properties of briquettes were specifically investigated in the study, including density-1 (D-1, density immediately after compaction), density-2 (D-2, density after two weeks of storage), specific energy consumption, throughput and durability rating. The dimensions of each briquette sample were about 50 mm diameter and 10–30 mm thickness.

The mass of straw grinds used for each kind of briquette sample was at least 4 kg in order to obtain steady-state operation and reliable experimental data. Ten briquette samples were selected to measure the quality parameters for every experimental combination of two independent variables (moisture content and screen size) at three levels. The residence time was about 6–10 min before being extruded from the briquetter.

2.4. Applied pressure and specific energy consumption

In this study, the briquetting equipment used was a piston press