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Research article

Densification of biomass using a pilot scale flat ring roller pellet mill

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ABSTRACT

The production characteristics from a pilot scale flat ring die pellet mill were evaluated for four different biomass materials (miscanthus, corn stover, switchgrass, and wheat straw) to determine the effect of moisture preconditioning upon pelletization. The moisture content of the material entering the pellet mill was 10%, 15%, 20% and 25% for miscanthus, switchgrass, and wheat straw; while, only 15%, 20%, and 25% moisture content was evaluated for corn stover. For miscanthus, switchgrass, and wheat straw at the highest moisture content (25%), pellet formation was readily achieved with the percentage of pellets produced being 92%, 92%, and 96%, respectively. Corn stover preconditioned to a moisture content of 15% resulted in the highest rate of pellet formation, lowest specific energy requirement, and similar durability to other measured moisture contents. For the differing biomass materials, the specific energy requirements for the flat ring pellet mill was measured and varied between 101 to 324 kWh/Mg depending on the crop and moisture content. With energy consumption being one of the primary costs of pelletization, the on-farm/localized pelletization of biomass using a flat ring die pellet mill may be impaired by the high specific energy requirements of pelletization relative to other pellet mill designs.

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1. Introduction

The volumetric energy content of lignocellulosic material used for biofuels is lower than traditional fossil fuel sources [1], and this low energy density is largely a result of the low bulk densities of biomass materials. Therefore, the densification of biomass is essential to improving the transport, storage, and handling capabilities of this lignocellulosic material. Pelletization is one of the technologies that have been proposed to mechanically increase the bulk density of biomass. The advantages of pelletization go beyond increases in bulk density, as the handling and storage of pelleted biofuel can be performed similar to free-flowing granular products, such as corn, soybeans, and wheat [2]. Biomass pellets have multiple end use applications which range from smaller scale combustion for residential heating to a more industrial scale where pellets could be co-fired with coal at power plants [3]. Worldwide, the total production of pellets increased 10 fold from 2000 to 2010 with the US being one of the leaders in pellet production [4]. The increased demand of pelleted fuel sources in Europe and North America could allow for more non-woody biomass resources such as dedicated biomass crops or crop residues to be used for pelletization.

Pelletization has been performed using either a flat ring die or a ring roller die [5]. Advantages and disadvantages exist with each type of mill. Ring roller dies are commonly used at commercial facilities due to their high throughput and pelletization properties have been assessed at many different moisture contents [6]. However, the flat ring die manifests more robustness with input biomass material and generally requires lower capital investment due to their lower capacity relative to a ring roller die [7]. The potential to use flat ring dies has yet to be fully assessed for the biomass industry. Flat ring die studies have been performed for poplar, vine shoots, industrial cork residue, pine sawdust, grape pomace, and pyrenean oak [8–10] along with high moisture (28%–38%) corn stover [11] and pretreated corn stover [12]. Nonetheless, the influence of moisture content upon pelletization using a flat ring die has yet to be fully characterized for potential high tonnage biomass crop residues (corn stover and wheat straw) and dedicated biomass crops (miscanthus and switchgrass) [13].

One of the most important variables in pellet production is moisture content, as this property will ultimately determine the durability and density of pellets [6,14]. The objective of this study was to characterize the sensitivity of the flat ring die to changes in the initial preconditioned moisture content for miscanthus, corn stover, switchgrass, and wheat straw. The moisture content of the material entering the pellet mill was varied from 10 to 25% moisture content (wet basis) for all the biomass materials except for corn stover. Ten percent moisture was the general baseline preconditioned moisture content as this moisture has been used for the pelletization of poplar, grape pomace, and pyrenean oak pellets with flat ring die pellet mill [8,10]. Previous work by Tumuluru [11], showed corn stover pelletized at higher moisture contents; therefore the range of moisture contents investigated in this study went up to 25%. For the various preconditioned moisture contents, the potential of a flat ring die to produce pellets from biomass crops was evaluated by measuring the percentage of pellets produced, bulk density, durability, production rate, and specific energy consumption.

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2. Materials and methods

Alamo switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* × *giganteus*) used in this study were harvested at the University of Kentucky's North Farm, Lexington, KY. The sample material was harvested in late winter 2013 using a disc mower and baled into small square bales (36 × 46 × 120 cm). Wheat straw and corn stover were raked and baled at the University of Kentucky C. Oran Little Research Center in the summer and fall 2013, respectively. The bales were stored in a barn prior to transportation to campus. The biomass was ground using a No. 20 Hammer mill (C.S. Bell Co., Tiffin, OH) and was collected using a cyclone (Cincinnati Fan and Ventilation Inc., Mason, OH). Round hole screen sizes of 3 mm, 5 mm, and 10 mm were used with the hammer mill.

2.1. Sample conditioning

After grinding, samples were preconditioned in batches with 9 kg (20 lb) being rewetted within plastic storage containers. The moisture content of the ground material was approximately 8% after storage. Material was rewetted and mixed to 10%, 15%, 20%, and 25% moisture contents (wet basis) using a sprayer. Furthermore, challenges with plugging of the die limited the maximum moisture content used to 25%. The moisture contents were randomly tested throughout the conditioning process and analyzed using an Ohaus moisture analyzer (Ohaus Corporation, Parsippany, NJ) with a 1 g sample dried at 130 °C. The moisture measurements with the Ohaus were equivalent to that of the convection air oven standard [15] with an $r^2 > 0.9$. Thus, the Ohaus was used since the determination of moisture content was conducted in minutes as opposed to days. The conditioned material was sealed inside the container and allowed to sit overnight. The material moisture content was retested the following morning and pelletized if the average was within 0.5% of the target value.

2.2. Pellet mill

Material was fed into the pellet mill using a belt conveyor system with a paddle at the end to allow for uniform feeding. Pelletization was performed using a Model PM605 (Buskirk Engineering, Ossian, IN) pellet mill flat ring die with a 3.7 kW (5 hp) grease-packed gear motor that possessed the capacity to pelletize up to 90 kg/h (200 lb/h) according to manufacturer's specifications. The dimensions of the die used were 15.2 cm (6 in.) in diameter and a 3.8 cm (1.5 in.) thick machined die plate with approximately two hundred sixteen 6 mm diameter holes drilled in the die. Typical pellets formed were approximately 6 mm in diameter and 18 mm in length. Prior to conducting each test, the die was preheated to 90 °C as this temperature is generally considered the minimum threshold for pelletization [3]. Preheating of the die to 90 °C was conducted using dried distillers grain and was subsequently flushed with the lignocelluosic material that would follow. The die did not possess any form of heater, only the friction from the pellet formation controlled the die temperature. The die temperature was measured using a Fluke Hydra Series datalogger (Fluke Corporation, Everett, WA) with three type T thermocouples connected to the outer edge of the die as shown in Fig. 1. The temperature was monitored during the test to ensure steady state operation, and the feed rate varied to maintain the temperature. At the completion of each test, the ending temperature was recorded.

2.3. Power consumption

The pellet mill operated on a 230 V three phase electrical system. Current within each line was measured with an AcuAMP current transducer (AutomationDirect, Cumming, GA, part number ACT050-10-S) which possessed a 1% accuracy. The voltage ouput from the current transducers was calibrated using an Extech Power Analyzer 380803 (Nashua, NH) with various devices providing the amperage source for calibration points. The current transducers were placed on the output side of the variable frequency drive (VFD) (Lenze Americas Corporation, Uxbridge, MA, USA) that drove the pellet mill. Current was logged using a Measurement Computing USB 1408FS analog to digital board (Norton, MA), and a program was written using Visual Studio (Microsoft, Redmond, WA) to log the data onto a tablet. The software clock was used to achieve a sampling rate of 10 Hz. The voltage was measured on the output side of the VFD using a Fluke multimeter. The total power was calculated in terms of RMS magnitude for a balanced wye load as shown in Eq. (1) [16].

Fig. 1. Pilot scale flat ring roller pellet mill with shielding removed showing rollers and location of thermocouples on die (circled).

$$P_T\ (\mathrm{kW}) = \frac{\sqrt{3} \times V_L \times I_L \times \mathrm{Pf}}{1000} \tag{1}$$

Where P_T was total power (kW); V_L was the line voltage (V); I_L was the line current (A); and Pf was the power factor (dimensionless). The power factor for the inductive cyclo drive motor was not directly measured. However, the motor specification stated a power factor of 0.817 under full load [17]. Power factor has been shown to change with load [18,19], but for cyclo drives, the power factor can remain constant over a range of speeds [20]. For the pellet mill used, all tests were performed at a constant speed of 1730 rpm for the cyclo drive motor. Furthermore, the feed rate of material into the pellet mill was manually controlled to keep the pellet mill's current draw to 10 A or greater, which would allow for the load amperage to remain above 75% of full load (motor name plate specification for full load amperage was 13.1 A). When operating at 75% of full-load and greater, the power factor remains relatively constant [19,21,22]. Thus, a constant power factor of 0.817 was assumed.

To determine the specific energy consumption per unit mass of pellets produced, the mass flow rate of the pellets was quantified by measuring pellet production during a 120 s time span with the pellet mill operating at steady state conditions. This was combined with the average total power consumption measured, P_Tavg, to determine the specific energy consumption (SEC) from Eq. (2).

$$SEC = \frac{P_T avg * \dfrac{120\,\mathrm{sec}}{3600\,\mathrm{sec}/h}}{M_P * \dfrac{1\ \mathrm{Mg}}{1000\ \mathrm{kg}}} \tag{2}$$

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