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Data-based equation to predict power and energy input for grinding wheat straw, corn stover, switchgrass, miscanthus, and canola straw

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ABSTRACT

This study investigated size reduction of five herbaceous species: wheat straw, corn stover, switchgrass, miscanthus, and canola straw. The biomass samples were air-dried to moisture content of 10%. The instantaneous power input to grind the material was recorded. Grinding wheat straw, corn stover, and canola straw using a 3.2 mm screen inside the hammer mill consumed 32 to 35 kWh/t whereas grinding switchgrass and miscanthus on the same screen used 22 kWh/t of energy. All five biomass samples required almost the same amount of energy input (13 to 20 kWh/t) when a 6.4 mm screen was installed in the hammer mill. Some species like corn stover produced strings of fiber causing blockage of the inlet to the grinder. A linear relation was developed between geometric mean diameter (d_{gw}) of the ground particles and the screen size (*SS*). The screen size inside the hammer mill was used as the representative size of the particles. The Rittinger equation was fitted to the size data to estimate the equation constant k_R from energy input vs. screen size. The k_R value ranged from 96 to 267 J mm/g depending on the species.

1. Introduction

Herbaceous biomass from crop residues and purpose grown crops are targeted as potential feedstock for biofuels and bioproducts [1–3]. Examples of herbaceous crops include switchgrass, miscanthus, willows, and hybrid poplar. Extensive reports on production [1,4], post-harvest handling [5–8], characteristics and composition [9–11], and harvesting and preprocessing [12–15] are available. Structurally, a herbaceous biomass may be composed of one or a mix of plant parts, such as seeds, cones, stems, leaves, and bark. Compositional and physical properties of these morphologically differing fractions vary widely [16].

Biomass as it is available in the field cannot be used in biofuels and bioproducts manufacturing industries. Size reduction is an essential operation for preparation of biomass for harvest and post harvest handling. Size reduction increases the bulk density of biomass to facilitate its transport and storage. The increased particle surface area increases the rate of chemical processes. To demonstrate the effectiveness of size reduction in increasing the bulk density of biomass, Cundiff and Grisso [1] manually cut whole switchgrass plants into 50 mm diameter bundles. The bundles were then cut at 25 mm intervals. The bulk density of chopped switchgrass was 275 kg/m^3 at 25% moisture content (*wb*), comparable to 270 kg/m^3 for whole tree wood chips at 45% moisture content (*wb*). Lam et al. [10] also showed that the loose density of switchgrass stems increased from 49 to 266 kg/m^3 when the pieces of switchgrass were cut from 51.8 mm to 8.0 mm in length.

Equations developed to predict energy and power input to grind cellulosic biomass are empirical [12,13,17,18]. The equations are specific to a particular type of biomass and type of grinder. The three grinding equations of Kick, Rittinger, and Bond originated from one theory, which is discussed extensively in literature [19–23]. Bond relates energy input to a single size of particle. Rittinger assumed that the energy of size reduction is proportional to the surface area of the cut. Kick assumed that the energy is proportional to the volume of the particles [24,25].

Each of the three equations has one specific constant whose value must be estimated from experimental size reduction data. Our previous study [26] showed that Rittinger's equation had the best fit to the data of grinding Douglas-fir and willow wood chips. This observation was confirmed in grinding wood chips of various softwoods and hardwoods using a hammer mill and knife mill [27–29].

The Rittinger equation is written as follows,

$$E = k_R\left(\frac{1}{L_P} - \frac{1}{L_F}\right) \tag{1}$$

where E is the specific energy (J/g) input to the grinder; k_R *is* the slope of the Rittinger equation (Rittinger constant) (J mm/g); L_P is the product mean size (mm); L_F is the feed mean size (mm). In many situations

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the feed particle size is not well defined [29]. Eq. 2 is a form of Rittinger equation in terms of product particle size, L_P, assuming a specific constant, C_R, for the product of $k_R(1/L_F)$,

$$E = k_R\left(\frac{1}{L_P}\right) + C_R \tag{2}$$

The herbaceous biomass available in field is > 10 cm (100 mm) long ($L_F = 100$ mm). The term $1/L_F$ in Eq. (1) or C_R in Eq. (2) may be ignored when the feed particle size (L_F) is large,

$$E = k_R'\left(\frac{1}{L_P}\right) \tag{3}$$

$k_R{}'$ has the same dimension as k_R, but its value would be different as the fitted line to the data must go through the origin. Eqs. (2) and (3) were fitted to the experimental data obtained from grinding the biomass in this study. Different screen sizes were used for grinding. The objective of this research was to determine the applicability of Rittinger's equation to samples of biomass (wheat straw, corn stover, switchgrass, miscanthus, and canola straw) size reduction and to recommend a practical equation for predicting the grinding energy based on a representative size of ground particles.

2. Material and method

2.1. Material

The bags of shredded wheat straw, switchgrass, miscanthus, and corn stover were received from Ottawa on September 26, 2012. The biomass were from a recent harvest in Ontario. A bag of shredded canola straw was received from Alberta on October 8, 2012. Upon arrival at the lab in Vancouver, the samples were weighed and the moisture content was measured using halogen lamp moisture analyzer, Model MF-50 (A&D Company Ltd.,Tokyo, Japan). Grinding tests were conducted during the month of October 2012. An entire sample bag was spread on a tarp on the floor inside the lab. The spread material was divided into two parts by creating a line in the middle of the spread. One half was collected and bagged. The other portion was mixed manually. The sampling procedure was repeated until a desired amount of representative sample remained on the tarp for the size reduction test. The representative sample was weighed on an electronic scale.

2.2. Equipment

A chipper/shredder (Model 80, Bear Cat Chipper/Shredder, Crary Industries, Inc., West Fargo, ND) was used for precutting, when feeding biomass to the hammer mill was impossible due to long entangled stems. Size reduction was performed using a hammer mill (Model 10HMBL, GlenMills Inc., Clifton, NJ). The rotor was powered by a 3 hp. motor with a rated speed of 3490 rpm. Twelve hammers were arranged alternately along the cubic frame encasing the central shaft. The mill used a removable perforated screen that extended 180 degrees around the lower section of the housing. Hammer mill screens with circular perforations of 25.4, 12.7, 6.4, and 3.2 mm were used. The feeding rate to the hammer mill was 1000 g/min. A vibratory feeder (Model 15A, Eriez Manufacturing Co., Erie, PA) was used when needed.

2.3. Method

Sieving and manual separation were performed to show the qualitative and quantitative variability of constituents of each sample as they were collected from field. The representative sample was passed through a sieve with a Mesh No. 7 (2.8 mm). The weight of the materials passed through the sieve was recorded. The remaining material on the sieve was divided visually and by hand into its constituents (e.g. stems, broken stems, and leaves) and the weight of each constituent was recorded.

The target moisture content for grinding was set at 10% (wet mass basis, *wb*). Samples were spread out on a canvas on the floor of the lab and left there for natural drying. The samples were dried to 10% in a large drying oven set at 40 °C in cases when the required 10% (*wb*) moisture content was not naturally achieved.

Corn stover and canola straw had long tangled stems. The stems, as received, blocked the inlet of the hammer mill during preliminary tests. They were precut by a chipper/shredder before feeding to the hammer mill. A representative sample of 2 kg was prepared. The 2 kg sample was fed to the hammer mill either manually or by using a vibratory feeder. For manual feeding, the sample was divided into ten portions of 200 g each. Each portion was fed into the grinder during a 2 min grinding cycle. For feeding with the vibratory feeder, the sample was fed into the grinder during the 2 min grinding cycle. Feeding rate was controlled by changing the feeder trough vibration speed.

The energy consumption of the hammer mill was recorded by using a data acquisition card connected to the LabVIEW interface. The data logging system consisted of a three-phase transducer to transform alternate current and voltage into DC signals. A data acquisition card (PCI DAS-08) received the instantaneous power consumption in W. Labview 8.2 software (National Instruments, Austin, Texas, USA) and a desktop computer acquired, stored and displayed the values [30]. The grinder's net power consumption was calculated by deducting parasitic power input P_E (J/s, power while running empty) from the total recorded power P (J/s). Specific energy consumption, E (J/g), was calculated by dividing net power input by feeding rate, F (g/s).

$$E = \frac{P - P_E}{F} \tag{4}$$

Size analysis is a crucial step to measure the fineness of ground particles. Ground particles were size analyzed by sieving. The stack of sieves for size analysis was wire meshed forming square holes ranging in size from 1 mm to 35 mm. The sieve shaker was W.S. Tyler Ro-Tap (Model RX-94, Canada). The fractions were weighed on an electronic balance with a precision of 0.01 g. d_{gw} (mm), geometric mean diameter of ground particles by mass, and S_{gw} (mm), geometric standard deviation, were calculated based on ASAE Standard S319.3 [31] using the weight fraction results from sieving.

2.4. Density of ground particles

A container 77 mm in diameter and 135 mm height was used to measure loose and tapped bulk density. The ground particles were poured freely into the container until the container was full. The excess particles were removed by striking excess material from the top. The weight of particles inside the container was recorded. Loose bulk density was calculated using the weight of particles and volume of the container.

For tapped density, the filled container was tapped down from a height of 50 mm. Each time, the empty volume that was created due to tapping was filled with particles. The procedure of tapping and filling was repeated until there was no empty volume generated (due to tapping). The weight of particles inside the container was recorded. The tapped density was calculated using the weight of particles and volume of the container. The Hausner ratio is defined as the ratio of tapped bulk density over loose bulk density. The ratio is a measure of the internal friction condition of moving powder [32]. Hausner ratio > 1.25 indicates high internal angle of friction and thus a poor flowability of the powder.

The volume of ground particles passed through 3.2 mm screen was measured in a gas (helium) comparison pycnometer (Quantachrome Instrument, Boynton Beach, FL). The displacing gas with a pressure of 15 psi penetrated into the pore spaces of the material to approximate the volume of the solid fraction of material. The particle density was calculated as the ratio of mass of the ground particles to volume (as measured in pycnometer).