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Knife mill operating factors effect on switchgrass particle size distributions

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ABSTRACT

Biomass particle size impacts handling, storage, conversion, and dust control systems. Switchgrass (*Panicum virgatum* L.) particle size distributions created by a knife mill were determined for integral classifying screen sizes from 12.7 to 50.8 mm, operating speeds from 250 to 500 rpm, and mass input rates from 2 to 11 kg/min. Particle distributions were classified with standardized sieves for forage analysis that included horizontal sieving motion with machined-aluminum sieves of thickness proportional to sieve opening dimensions. Then, a wide range of analytical descriptors were examined to mathematically represent the range of particle sizes in the distributions. Correlation coefficient of geometric mean length with knife mill screen size, feed rate, and speed were 0.872, 0.349, and 0.037, respectively. Hence, knife mill screen size largely determined particle size of switchgrass chop. Feed rate had an unexpected influence on particle size, though to a lesser degree than screen size. The Rosin–Rammler function fit the chopped switchgrass size distribution data with an $R^2 > 0.982$. Mass relative span was greater than 1, which indicated a wide distribution of particle sizes. Uniformity coefficient was more than 4.0, which indicated a large assortment of particles and also represented a well-graded particle size distribution. Knife mill chopping of switchgrass produced 'strongly fine skewed mesokurtic' particles with 12.7–25.4 mm screens and 'fine skewed mesokurtic' particles with 50.8 mm screen. Results of this extensive analysis of particle sizes can be applied to selection of knife mill operating parameters to produce a particular size of switchgrass chop, and will serve as a guide for relations among the various analytic descriptors of biomass particle distributions.

1. Introduction

Bio-based power, fuels, and products may contribute to worldwide energy supplies and economic development. Switchgrass is widely recognized as a leading crop for energy production (Greene, 2004). For efficient conversion of biomass to bioenergy, an optimized supply chain ensures timely supply of biomass with minimum costs (Kumar and Sokhansanj, 2007). Size reduction is an important energy intensive unit operation essential for bioenergy conversion process and densification to reduce transportation costs. Biomass size reduction process changes the particle size and shape, increases bulk density, improves flow-properties, increases porosity, and generates new surface area (Drzymala, 1993). However, physical- and flow-properties of biological materials are highly dependent on particle size and distribution (Ortega-Rivas, 2003). Fine corn flour particle size was found to improve hydrolysis yields (Naidu and Singh, 2003). Corn stover particle size reduction and separation to various size fractions affected pretreatment and hydrolysis processes (Chundawat et al., 2006). Higher surface area increases number of contact points for chemical reactions (Schell and Harwood, 1994), which may require grinding to a nominal particle size of about 1 mm (US Department of Energy, 1993). Size reduction alone can account for one-third of the power requirements of the entire bioconversion to ethanol (US Department of Energy, 1993). Particle size analyses characterize the input and output materials of size reduction operations that usually produce a range of particle sizes or distribution, within a given sample.

Current research is driven by the need to reduce the cost of biomass ethanol production. Pretreatment research is focused on developing processes that would result in reduced bioconversion time, reduced enzyme usage and/or increased ethanol yields (Silverstein et al., 2007). Efficient size reduction emphasizes delivery of suitable particle size distributions, though information to predict particle size distributions is lacking for most of the newly considered biomass sources such as switchgrass.

Nominal biomass particle sizes produced by knife mill chopping depend on screen size of the mill. Himmel et al. (1985) observed chopped wheat straw retention of 30–85% on 20–60 mesh size

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for knife mill screens ranging from 12.7 to 1.6 mm, respectively. They found that 50% of chopped aspen was retained at 6–14 mesh for 12.7–3.2 mm knife mill screens, respectively.

Particle size distribution of hammer-milled alfalfa forage grinds were fitted with a log-normal distribution equation (Yang et al., 1996). They found that median size and standard deviation were 238 and 166 μm, respectively. Mani et al. (2004a) determined sieve-based particle size distribution of wheat and barley straws, corn stover, and switchgrass and established relationships for bulk density with geometric mean particle size. Particle size distribution of corn stover grind from different hammer mill screens depicted positive skewness in distribution (Mani et al., 2004b). In actual practice, measured geometric mean length of biomass particles using sieve analysis is less than the actual size of the particles (Womac et al., 2007). They reported that geometric mean dimensions of actual biomass particles varied from 5× for particle length to 0.3× for particle width for knife milled switchgrass, wheat straw, and corn stover when compared to geometric mean length computed from American Society of Agricultural and Biological Engineers (ASABE) sieve results. Geometric mean dimensions of switchgrass were accurately measured using an image analysis technique as verified with micrometer measurements (Yang et al., 2006). However, sieves have a long history and acceptance in various industries and provide a standardized format for measuring particle sizes, even with published values of offset.

Finding acceptable mathematical functions to describe particle size distribution data may extend the application of empirical data. Rosin and Rammler (1933) stated their equation as a universal law of size distribution valid for all powders, irrespective of the nature of material and the method of grinding. Among at least three common size distribution functions (log-normal, Rosin–Rammler and Gaudin–Schuhmann) tested on different fertilizers, the Rosin–Rammler function was the best function based on an analysis of variance (Allaire and Parent, 2003; Perfect and Xu, 1998). Also, particle size distributions of alginate–pectin microspheres were well-fit with the Rosin–Rammler model (Jaya and Durance, 2007).

Little published data provide information on knife mill particle size distribution of switchgrass due to various knife mill operating factors. Hence, the objective of this research was to evaluate Rosin–Rammler particle size distribution mathematical function and other analytic descriptors of particle distributions for standardized forage sieve results obtained for chopped switchgrass prepared with a knife mill operated at various mill operating factors.

2. Methods

2.1. Biomass test material

Switchgrass (*Panicum virgatum* L.; *Cultivar*. Alamo) had been harvested as hay and allowed to dry in a swath prior to baling and then bales were stored indoors for three months. Switchgrass bales (1.00 × 0.45 × 0.35 m) were manually de-stringed for sample mass determinations. Moisture content of switchgrass was 9.0 ± 0.5% wet basis measured using ASABE Standard S358.2 for forages (ASABE Standards, 2006a) by oven drying the samples at 103 ± 2 °C for 24 h.

2.2. Knife mill and operating variables

A commercially-available knife mill (H.C. Davis Sons Mfg. Co., Inc., Bonner Springs, KS) with a 400 mm diameter rotor powered with a gasoline engine rated at 18 kW was used for switchgrass chopping. The knife mill rotor had eight 75 mm-wide straight knife blades bolted to its periphery. Length and thickness of single bevel edge blade were 600 and 12 mm, respectively. Knife blade tip angle was 45°. Blades cleared two stationary shear bars indexed at about 10 o'clock and 2 o'clock angular positions. A uniform blade clearance of 3 mm was used. Knife mill was equipped with an interchangeable classifying screen that was mounted in an arc on the bottom side of rotor. Screens enclosed about 240° of sector angle around the rotor. Screen selections tested had opening diameters ranging from 12.7 to 50.8 mm. Engine rated speed of 3600 rpm using a V-belt drive system gave knife mill speed of 507 rpm. Various engine throttle settings operated the knife mill at speeds ranging from 250 to 500 rpm to examine speed effects. In addition to continuous monitoring with a speed sensor (Series 4200 PCB Piezotronics, Depew, NY, USA), independent measures of knife mill speeds were taken with a handheld laser photo tachometer (±0.05% accuracy).

2.3. Mass feed control to knife mill and sample collection

Weighed switchgrass samples (±50 g accuracy) were evenly distributed on a 6.1 m long inclined belt conveyor (Automated Conveyor Systems, Inc., West Memphis, Arkansas, USA). Belt speed was adjusted to feed the switchgrass in 1 min. This arrangement provided a means to uniformly feed switchgrass sample into knife mill at a measured rate. Sample feed rates ranged from 2 to 11 kg/min. Maximum mass feed rates were determined in pre-tests and were usually controlled by knife mill screen opening size and rotor speed. Chopped switchgrass passed down through knife mill screen at bottom and was collected below the screen. Collected sample was mixed thoroughly and a representative sample of about 1 kg was bagged in polyethylene bags for analysis of particle size distribution using ASABE sieve analyzer.

2.4. Sieve analysis

Each switchgrass sample after size reduction was subjected to particle size distribution analysis following ASABE standard S424.1 (ASABE Standards, 2006b). A sieve analyzer (Fig. 1) was constructed with two stacks of sieves to balance weight of complex elliptical motion of masses. First stack contained two sieves (19.0 and 12.7 mm nominal opening size) and a pan. The counter balancing second stack contained three sieves (6.30, 3.96, and 1.17 mm nominal opening size) and a pan. Diagonal sieve opening sizes were 26.90, 18.00, 8.98, 5.61, and 1.65 mm. After the particles had been sieved by first stack, particles in first pan were transferred to second stack of sieves for remaining separation pass while the first stack was engaged for next sample. Particles from each sieve were collected and weighed using an electronic top pan balance (±0.01 g accuracy). The sieve was operated for 10 min (Yang, 2007).

2.5. Data analysis

Log-normal distribution plots of switchgrass between percent retained mass and geometric mean length of particles on each sieve, $\overline{X_i}$, were graphed with semi-log scale. Geometric mean length and geometric standard deviation were calculated based on mass fraction using the following equations (ASABE Standards, 2006b):

$$X_{gm} = \ln^{-1}\left[\frac{\Sigma(M_i \ln \overline{X_i})}{\Sigma M_i}\right] \quad (1)$$

$$S_{gm} = \ln^{-1}\left[\frac{\Sigma(M_i(\ln \overline{X_i} - \ln X_{gm})^2)}{\Sigma M_i}\right]^{1/2} \quad (2)$$

where, X_{gm} is geometric mean length, mm; S_{gm} is geometric standard deviation (dimensionless) (Hinds, 1982); X_i is diagonal of sieve