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Comminution Energy Consumption of Biomass in Knife Mill and its Particle Size Characterization

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Abstract. *Current research is driven by the need to reduce the cost of ethanol production from biomass. Preprocessing research is focused on developing processes that would result in reduced bioconversion time, minimize enzymes usage, and/or maximize ethanol yields. Size reduction is an* *important preprocessing unit operation of biomass, which utilizes major portion of input energy. It changes the particle size, shape, and bulk density, and increases the total surface area of biomass and number of contact points for chemical reaction. Objectives of the present study were to chop switchgrass, wheat straw, and corn stover in knife mill and analyze the particle size distribution. Direct power inputs were determined for different knife mill screen openings from 12.7 to 50.8 mm, rotor speeds between 250 and 500 rpm, and mass feed rates from 1 to 11 kg/min. During the experiment, data were collected for determining effective and total specific energy for chopping. The chopped samples were analyzed for particle size distribution using ASABE sieve analyzer. For knife mill screen size of 25.4 mm a speed of 250 rpm gave the optimum performance. The optimum feed rates at these conditions were 7.6, 5.8, and 4.5 kg/min for switchgrass, wheat straw, and corn stover, respectively. The corresponding total specific energies were 27.3, 37.9, and 31.9 MJ/Mg and effective specific energies were 4.6, 5.4, and 0.9 MJ/Mg for switchgrass, wheat straw, and corn stover, respectively. Mathematical equations adequately fitted the total specific energy consumption and particle size distribution data. knife mill chopping of switchgrass/wheat straw/corn stover resulted in 'well-graded' 'strongly fine-skewed mesokurtic'/'fine-skewed mesokurtic'/'fine-skewed mesokurtic' particles with reduced size screens (12.7 to 25.4 mm) and 'well-graded' 'fine-skewed mesokurtic'/'strongly fine-skewed mesokurtic'/'fine-skewed mesokurtic' particles with increased size screen (50.8 mm).*

Keywords. Switchgrass, wheat straw, corn stover, knife mill, total specific energy, effective specific energy, particle size distribution

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) apart from wheat straw and corn stover. For efficient conversion of biomass to bioenergy, an optimized supply chain ensures timely supply of biomass with minimum costs (Kumar and Sokhansanj, 2007). Conversion of naturally occurring lignocellulosic materials to ethanol currently requires preprocessing to enhance the accessibility of reactive agents and to improve conversion rates and yields. According to one patent, agricultural biomass was prepared to approximately 1 to 6 mm by a disc refiner for ethanol production (US Patent 5 677 154, 1997). Such reduced particle sizes can be achieved by fine grinders (e.g. hammer mill, disc refiner, pin mill, chain mill). Long pieces of straw/stalk of biomass may not flow easily into grinders such as hammer and disc refiners. Hence, biomass needs to be preprocessed or chopped with a knife mill to accommodate bulk flow, densification, and uniformity of feed rate. For example, switchgrass reduced to approximately 25 mm in length using rotary shredder was fed to a hammer mill and subsequently to disc refiner for further size reduction (1-2 mm) for ethanol conversion process (Schell and Harwood, 1994). A shredder, knife cutter, or knife mill is often used for coarse size reduction (>50 mm) of stalk, straw, and grass feed stocks. 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). 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; Aden et al., 2002) and warrants improvement to raise the energy efficiency of biofuels. 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 renewable research trend is driven by the need to reduce the cost of biomass ethanol production. Preprocessing 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, wheat straw, and corn stover.

Energy demand for grinding depends on its initial particle size, moisture content, material properties, mass feed rate, and machine variables (Mani et al., 2004a). Performance of a grinding device is often measured in terms of energy requirement, geometric mean diameter, and resulting particle size distribution. Although not always explicitly stated, most studies reported total specific energy. Mani et al. (2002, 2004a) observed that energy requirement increased rapidly with decreasing particle size. They found that switchgrass required the highest effective specific energy (99 MJ/Mg) to grind using a laboratory hammer mill, whereas corn stover required less effective specific energy (40 MJ/Mg) for 3.2 mm screen using the same grinder. They indirectly estimated mechanical energy using a wattmeter to monitor an electric motor. In another study, about 1.3 to 2.5% of the total energy content of hardwood chips was required as total specific energy to shred them to 10 to 30 mesh (2.0 to 0.6 mm) size (Datta, 1981).

Himmel et al. (1985) observed that total specific milling energy of aspen wood chips, reduced to <6.4 and <12.7 mm particles, was respectively, 5 and 3 times greater than that required for corn cobs using a knife mill. They used an indirect method of measuring electric power with wattmeter and corrected with power factor, though motor efficiency was unaccounted. Austin and Klimpel (1964) noted that strain energy stored in the material before breaking was converted to energy, other than new surface development energy, such as propagated stress wave energy, kinetic energy of fragments, and plastic deformation energy. Fraction of total energy converted to surface energy will be extremely variable, depending on the operating conditions of mill. It should be noted that the theoretical analyses of size reduction primarily pertains to brittle failure of homogeneous materials, which is not representative of lignocellulosic biomass.

Past research was carried out with an aim to measure indirect energy. Balk (1964) used a wattmeter to relate hammer mill total specific energy with moisture content and feed rate of coastal bermudagrass. Moisture content and grind size influenced the specific energy. Datta (1981) reported that size reduction of hardwood chips to 0.2-0.6 mm required 72-144 MJ/Mg, whereas size reduction of particles to 0.15-0.3 mm required five times higher energy (360-720 MJ/Mg). Arthur et al. (1982) found that specific energy consumption of a tub grinder decreased from 2696 to 1181 MJ/Mg with an increase in screen size from 12.7 to 50.8 mm for rectangular wheat straw bales. They reported wheat straw grinding rate increased from 0.137 to 0.267 Mg/min with an increase in screen size from 12.7 to 50.8 mm. Also, they found that grinding rate increased with an increased tub rotational speed from 3.1 to 9.5 rpm. However, the rate of increase of grinding rate became less as the tub speed increased. Their indirect measurement of total specific energy was based on engine fuel consumption rate and did not take into account energy conversion by an internal combustion engine. Total specific energy to reduce the switchgrass to 100-200 mm length particles using a shredder was 30 MJ/Mg based on a wattmeter (Schell and Harwood, 1994). Samson et al. (2000) reported that total specific energy requirement of switchgrass hammer milling with 5.6 mm screen was 162 MJ/Mg. Jannasch et al. (2001) reported a wattmeter-measured total specific electric energy of 201 MJ/Mg for both 5.6 and 2.8 mm screen sizes for hammer mill grinding of switchgrass. Esteban and Carrasco (2006) estimated energy requirements of 307, 427, and 71 MJ/Mg for poplar chips, pine chips, and pine bark, respectively, in a hammer mill (1.5 mm screen) using ampere meter and vacuum discharge. Thus, most of the published energy values were based on indirect measures of total specific energy.

Knife mills worked successfully for shredding forages under various chop and machine conditions. Ige and Finner (1976) developed models to predict shear energy of alfalfa and corn stalks. Cadoche and López (1989) tested knife and hammer mills on hardwood chips, agricultural straw and corn stover. Effective specific energy demand to reduce hardwood chips to a particle size of 1.6 mm was 468 MJ/Mg for both hammer and knife mills. Hammer mill required more energy (414 MJ/Mg) than a knife mill (180 MJ/Mg) for 3.2 mm particle size. They observed that agricultural straw and corn stover required 6 to 36% of the effective specific energy required for wood. Total Specific energy of hammer mill grinding of corn increased from 17 to 46 MJ/Mg for an increase in hammer tip speed from 54 to 86 m/s for 6.4 mm-thick hammer (Agriculture Canada, 1971). High speed hammer mills with smaller diameter rotors are good for fine or hard to grind material. However, at high tip speeds, material moves around the mill parallel to the screen surface making the openings only partially effective. At slower speeds, material impinges on the screen at a greater angle causing greater amounts of coarser feed to pass through (Bargen et al., 1990). Operating speeds, mass feed rate, and screen size of knife mill seems to be critical to find appropriate effective specific energy demand for biomass size reduction.

Nominal biomass particle sizes produced by knife mill grinding depend on operating factors of the mill. Himmel et al. (1985) observed chopped wheat straw retention of 30 to 85% on 20 to 60 mesh size for knife mill screens ranging from 12.7 to 1.6 mm, respectively. They found that 50% of chopped aspen was retained at 6 to 14 mesh for 12.7 to 3.2 mm knife mill screens, respectively. Yang et al. (1996) fitted the particle size distribution data of alfalfa forage grinds from a hammer mill with a log-normal distribution equation. They found that median size and standard deviation were 238 µm and 166 µm, respectively. Mani et al. (2004a) determined sieve-based particle size distribution of hammer milled wheat and barley straws, corn stover, and switchgrass. Particle size distribution of corn stover grind from various 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) reported that geometric mean dimensions of actual biomass particles varied from 5x for particle length to 0.3x 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 provides information on knife mill total and effective specific energy requirement and particle size distribution due to various operating factors is available for switchgrass, wheat straw, and corn stover. Also, size reduction studies on knife mills equipped with direct measurement of mechanical input energy are scarce in the literature. Hence, first objective of this research was to determine the direct mechanical input energy for knife mill size reduction of switchgrass, wheat straw, and corn stover over a range of screen sizes, operating speeds, and mass feed rates. The second was to evaluate Rosin-Rammler particle size distribution mathematical function for sieve results obtained for chopped materials.

Materials and Methods

Biomass Test Material

Switchgrass (*Panicum virgatum* L.), wheat straw (*Triticum aestivum* L.), and corn stover (*Zea mays* L.) were harvested from Agricultural Experiment Station, The University of Tennessee, Knoxville during fall, 2005. Switchgrass and wheat straw had been harvested as hay allowed to dry in a swath prior to baling. Corn stover was also allowed to field dry after ear harvest. Switchgrass, wheat straw, and corn stover were stored indoors for three months before experiments. Switchgrass and wheat straw were manually removed from bales (1.00 × 0.45 × 0.35 m) for sample mass determinations. Corn stover was cut into about 150 mm long pieces with arborist pruners. Moisture contents of switchgrass, wheat straw, and corn stover were determined as about 9.0±0.5% wet basis following ASABE Standards for forages (ASABE Standards, 2006a) by oven drying the samples at 103±2ºC for 24 h.

Knife Mill and Operating Variables

A commercial 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 (Fig. 1) was used for chopping. The knife mill rotor had eight 75 mm-wide straight knife blades bolted to the rotor periphery. Length and thickness of single bevel edge blade were 600 and 12 mm, respectively. Knife blade lip angle was 45º. Blades cleared two stationary shear bars indexed at about the 10 o'clock and 2 o'clock angular positions. A uniform blade clearance of 3 mm was used. An interchangeable classifying screen was mounted in an arc of about 240º of angular rotation around the bottom side. Screen selections tested had opening diameters ranging from 12.7 to 50.8 mm (4 levels). An engine rated speed of 3600 rpm powered the knife mill at a speed of 507 rpm by using a V-groove pulley and belt drive system. Various engine throttle settings operated the knife mill at speeds ranging from 250 to 500 rpm (5 levels) to examine speed effects.

Mass Feed Control to Knife Mill

Weighed switchgrass, wheat straw, and corn stover samples were evenly distributed on a 6.1 m long inclined belt conveyor (Automated Conveyor Systems, Inc., West Memphis, Arkansas). Belt speed was adjusted to feed the sample into knife mill in 1 min. This arrangement provided a means to uniformly feed the test material into the knife mill at a measured rate. Sample feed rates ranged from 1 to 11 kg/min (10 levels). Maximum mass feed rates were determined in pre-tests and were usually influenced by knife mill screen opening size and rotor speed.

Instrumentation and Data Acquisition

Mechanical power input into the knife mill was directly monitored with a calibrated torque and speed sensor (± 0.05% accuracy) (Series 4200 PCB Piezotronics, Depew, NY) in driveshaft between the engine to the driver sheave using commercial S-flex shaft couplings. Torque and speed data streams were collected with an analog to digital signal processing module (National

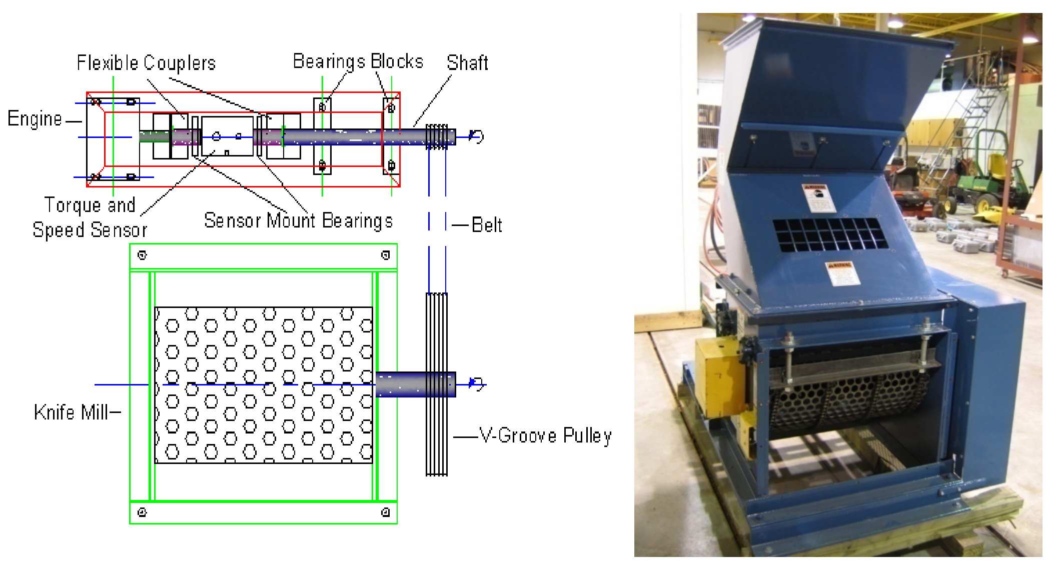

Figure 1. Overhead sectional view of knife mill and instrumentation set up and photo of knife mill.

Instruments, Austin, TX). Data were stored on a laptop computer using LabView data acquisition software (Version 8, Austin, TX). Maximum sampling rate of sensor was 5 MHz. Torque and speed raw data obtained through data acquisition system were analyzed using LabView Version 8 Fast Fourier Transform data analysis module to determine power spectra for torque and speed. Initially, collected torque and speed voltage data were converted to normal units using instrument specifications and calibration curve, respectively. The converted data were filtered using a 2nd-order Butterworth band-pass filter. Sensor sampling frequency was determined by sampling each channel from 1 to 24 kHz, and then examining the power spectra (Jeon et al., 2004), and then applying Nyquist sampling theorem (Proakis and Manolakis, 1992) to ensure sampling at least 2x the highest frequency that had appreciable power. Most of the torque and speed frequencies were in the order of 10 and 2 Hz, respectively, for all power spectra between 1 and 24 kHz sampling rates (Fig. 2 depicts 1 kHz samplings). A minimum sampling rate of 1 kHz was determined and used for experiments that examined mill operating speeds, screen sizes, and mass feed rates. In addition to continuous computer monitoring of a speed sensor, independent measures of knife mill speeds were taken with a handheld laser tachometer (± 0.05% accuracy). Overall accuracy of power was calculated to be ±0.003 kW.

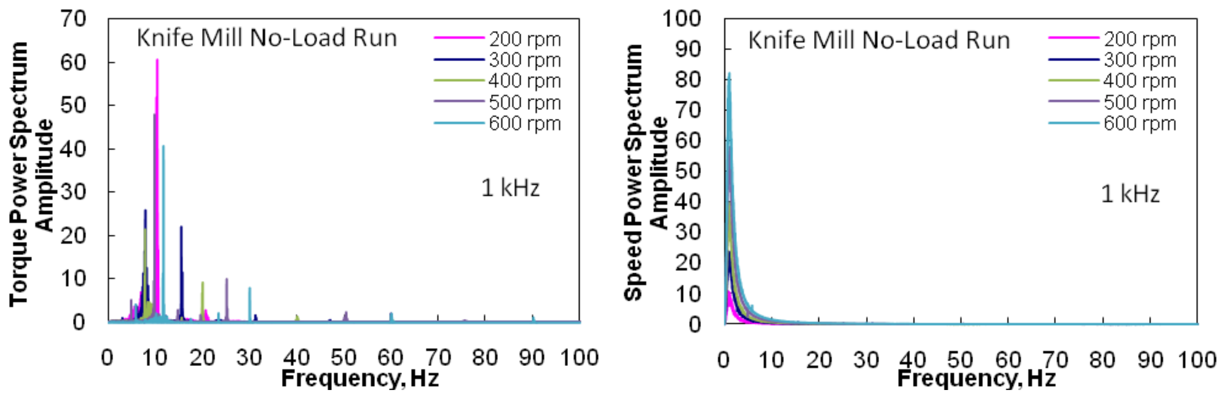

Figure 2. Power spectra of torque and speed for 1 kHz data acquisition sampling rates during no-load run of knife mill.

Test Procedure and Sample Collection

Initially, knife mill no-load run power consumption at different speeds from 200 to 600 rpm was determined for different sampling frequencies from 1 to 24 kHz and averaged. Test samples were weighed using a digital crane scale (±0.1 kg). While knife mill was running, conveyor dropped a continuous stream of test sample into knife mill hopper. Chopped mass passed down through classifying screen at the bottom and material was collected below the mill. All experiments were conducted once by integrating speed and torque data for 1 min using data acquisition system developed with high attention paid to sampling rate over typical range of system operation. Outlier data was identified through examination of results as a continuous function of screen sizes, operating speeds, and feed rates. Outlier experiments were repeated as test runs. 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.

Sieve Analysis

All samples after size reduction was subjected to particle size distribution analysis following ASABE standard S424.1 (ASABE Standards, 2006b). A sieve analyzer (Fig. 3) 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).

Figure 3. ASABE sieve analyzer.

Data Analysis

Total specific energy was determined in MJ/Mg from the mass feed rate data, torque and speed. Effective specific energy was determined by subtracting no-load energy from total energy (Cadoche and López, 1989; Himmel et al., 1985; Holtzapple et al., 1989). Regression (NLIN) and Generalized Linear Model (GLM) procedures (SAS, 2004) were used for regression fits and analyses. Total specific energy consumption was regressed as a function of screen size, mass feed rate, and rotor speed in second order polynomial equations. Total specific energy equations were optimized for finding optimum operating parameters of knife mill by determining the function minima values of energy using Non-Linear Programming (NLP) (SAS, 2004) and by maximization of coefficient of determination values. An energy utilization ratio was calculated as the ratio of effective specific energy to total specific energy.

Log-normal distribution plots of switchgrass, wheat straw, and corn stover between percent retained mass and geometric mean diameter of particles on each sieve, $\bar{X}_i$, were plotted on semi-log graph. Geometric mean diameter, X_{gm}, and geometric standard deviation, S_{gm}, were calculated based on mass fraction (ASABE Standards, 2006b).

Percent cumulative undersize mass as a function of nominal sieve aperture size was graphed on semi-log plot. Curves were characterized as well-graded, gap (step)-graded, or poorly-graded (Craig, 2004; Budhu, 2007). Cumulative undersize mass percentage data obtained through ASABE sieve analysis was regressed using Rosin-Rammler distribution equation (Rosin and Rammler, 1933). This equation was selected based on previous success with sieved materials (Allaire and Parent, 2003; Djamarani and Clark, 1997; Jaya and Durance, 2007; Perfect and Xu, 1998). Rosin-Rammler equation is as follows:

$$M_{cu} = 100\left[1 - e^{-\left(\frac{D_p}{a}\right)^b}\right]$$

where, M_{cu} is cumulative undersize mass, %; D_p is particle length, assumed equivalent to nominal sieve aperture size, mm; a is size parameter, or Rosin-Rammler geometric mean length, mm; and, b is distribution parameter, or Rosin-Rammler skewness parameter (dimensionless).

From this equation, particle sizes in mm corresponding to 10, 50, and 90% cumulative undersize mass (D_{10}, D_{50} (median diameter), and D_{90}, respectively) were evaluated to calculate mass relative span as an indicator of distribution width. It should be noted that median length is different from geometric mean length for skewed distribution (Hinds, 1982). The size D_{10} is also known as effective size (Craig, 2004). Mass relative span, RS_m, provides a dimensionless measure of particle size distribution width (Allais et al., 2006) and was determined as follows:

$$RS_m = (D_{90} - D_{10})/D_{50}$$

Another difference among particle size distributions may be skewness. Skewness measures degree of asymmetry of normal distribution curve and its sign denotes whether a curve has an asymmetrical tail on its left or right when distribution is plotted versus particle size. Inclusive graphic skewness and graphic kurtosis were calculated from procedure stated by Folk (1974).

Generally, uniformity index and size guide number of particle size distribution are determined using the procedure of Canadian Fertilizer Institute (CFI, 1982). Uniformity index is the ratio of particle sizes ‘small’ (D_5) to ‘large’ (D_{95}) in the product, expressed in percentage. Size guide number is the median dimension expressed in mm to the second decimal and then multiplied by 100 (CFI, 1982). These calculations are prone to positive and negative errors due to linear interpolation (Perfect and Xu, 1998). Due to this limitation, uniformity index was assessed from equation of Perfect and Xu (1998) from Rosin-Rammler equation. Median diameter of Rosin-Rammler equation multiplied by 100 gave size guide number. Coefficient of uniformity and coefficient of gradation of particle size distribution were evaluated as stayed by Craig (2004). Distribution geometric standard deviation of higher region (between D_{84} and D_{50}), geometric standard deviation of lower region (between D_{16} and D_{50}), and geometric standard deviation of the total region (between D_{84} and D_{16}) were determined as per Hinds (1982).

SAS ANOVA with Tukey analysis was performed on particle size distribution parameters data for mean separation. Pearson correlation coefficients among knife mill operating factors, geometric mean length, geometric standard deviation, Rosin-Rammler parameters, median length, effective length, mass relative span, uniformity index, size guide number, uniformity coefficient, and distribution standard deviation were determined using PROC CORR procedure in SAS (SAS, 2004). SAS Non-Linear Regression (NLIN) procedure and Generalized Linear Model (GLM) procedure (SAS, 2004) were used for all regression fits and analyses. Particle size distribution parameters were regressed as a function of screen size, mass feed rate, and rotor speed in second order polynomial equations after neglecting non-significant variables and their interactions. Statistical significance was set at $P < 0.05$ unless otherwise noted.

Results and Discussion

Knife Mill No-Load Power

No-load power consumption of knife mill increased curvilinear by 67% from 1.55±0.03 kW at 200 rpm to 7.78±0.05 kW at 600 rpm (Fig. 4). Increased power was attributed to increasing speed at essentially constant torque (11.98 to 12.70 N-m). Large knife mill bearings contributed to torque resistance.

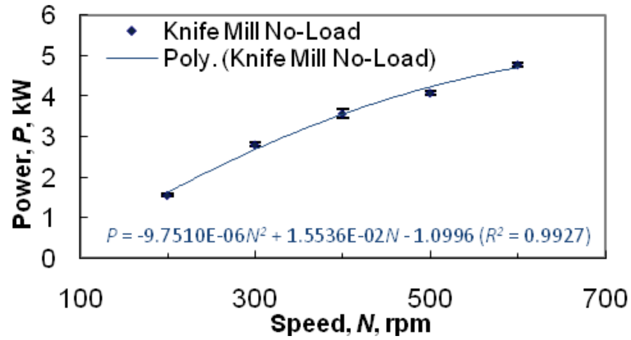

Figure 4. No-load power consumption of knife mill with speed.

Effect of Speed on Total and Effective Specific Energy

Mean total specific energy of switchgrass increased by 33% from 37.4±10.4 MJ/Mg with an increase in speed from 250 to 500 rpm for all screen sizes (12.7 to 50.8 mm) (Fig. 5). Increased total specific energy was partially attributed to no-load power increase with speed. Mean effective specific energy of switchgrass linearly decreased by 14% as knife mill speed increased from 250 to 500 rpm for all screen sizes, even though the no-load power consumption increased with speed (Fig. 4). The decreased effective specific energy with speed was attributed to less effort required in breakage of slightly brittle switchgrass with an increase in speed and also inertia of rotor. Also, at higher speeds, the chopped switchgrass might have passed off the bottom classifying screen of mill fast enough due to higher centrifugal force, which resulted in less accumulation of material in the mill and less friction between rotor and screen. It should be noted that total specific energy as size reduction energy expended for a particular mill design, whereas the effective specific energy is the energy that can be assumed to reach the biomass.

Mean total specific energy of wheat straw also increased by 39% from 47.8±21.9 MJ/Mg with an increase in speed from 250 to 500 rpm for all screen sizes (Fig. 6). Mean effective specific energy of wheat straw marginally increased by 10% from 18.4±13.2 MJ/Mg for same increase in speed for all screen sizes (Fig. 6). Total and effective specific energy increased by 10.8 MJ/Mg for wheat straw compared to switchgrass (Fig. 5). Increased total and effective specific energy may be attributed to difficulty in size reducing flexible, slippery, and less brittle wheat straw (ultimate tensile stress: 118.7 MPa (Kronbergs, 2000)) compared to switchgrass (ultimate tensile stress: 89.7 MPa (Yu et al., 2006)).

Mean total and effective specific energy of corn stover increased by 44 and 48% from 48.8±15.8 and 15.7±7.3 MJ/Mg, respectively, with an increase in speed from 250 to 500 rpm for all screen sizes (data not presented). During experimentation, continuous rotation of corn stover within the mill was observed at medium and higher speeds, which might have resulted in increased effective specific energy with an increase in speed. Both total and effective specific energy for corn stover chopping were less compared to wheat straw for same operating conditions. But, higher total specific energy and lower effective specific energy of corn stover chopping were observed compared to switchgrass. Mani et al. (2002, 2004a) also observed less effective specific energy for corn stover (39.6 MJ/Mg) compared to switchgrass (99.4 MJ/Mg) during hammer milling. Reduced total and effective specific energy consumption for corn stover was attributed to the fact that corn stover rind was very easily broken apart when dry. Overall, there was pronounced effect of speed on total and effective specific energy for size reduction of biomass materials studied.

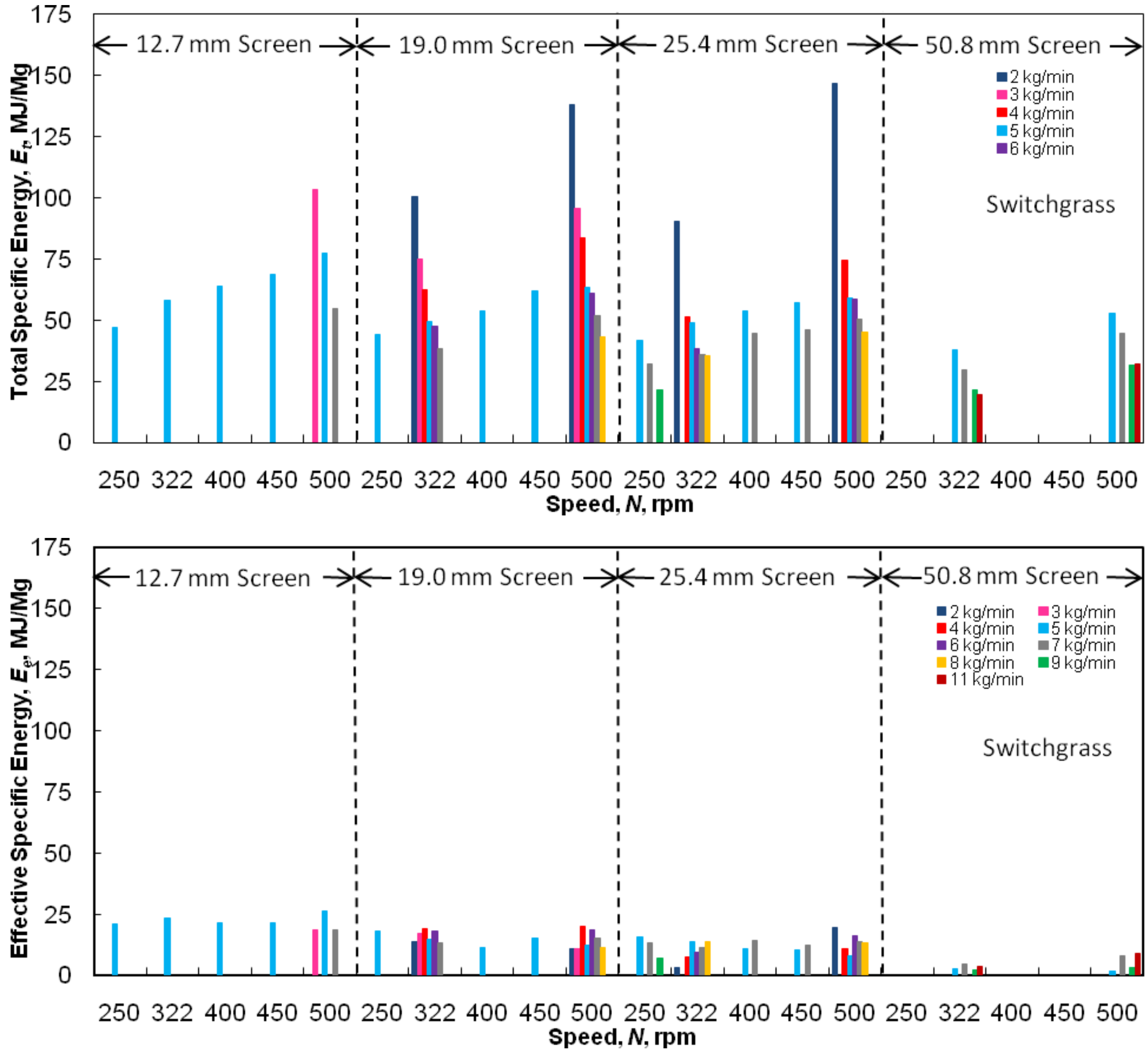

Figure 5. Total and effective specific energy of switchgrass with knife mill speed at various mass feed rates.

Effect of Screen Size on Total and Effective Specific Energy

Total specific energy decreased by 20, 23, and 25% and effective specific energy consumption decreased by 55, 68, and 78% with an increase in screen size from 12.7 to 50.8 mm for switchgrass (Fig. 7), wheat straw (data not presented), and corn stover (data not presented), respectively. Therefore, as screen size increased, specific energy decreased. Reduction of energy with screen size agrees with published results of alfalfa stem grinding reported by Sitkei (1986). Mani et al. (2002, 2004a) also reported a similar decreasing trend of specific energy with screen size increase for hammer milling of barley straw, switchgrass, wheat straw, and corn stover. Jannasch et al. (2001) reported a specific energy of 201.2 MJ/Mg for hammer mill screen sizes of 5.6 and 2.8 mm for switchgrass. Decrease in energy with increased screen opening size was due to formation of longer chopped material and less resistance to flow of the chopped material.

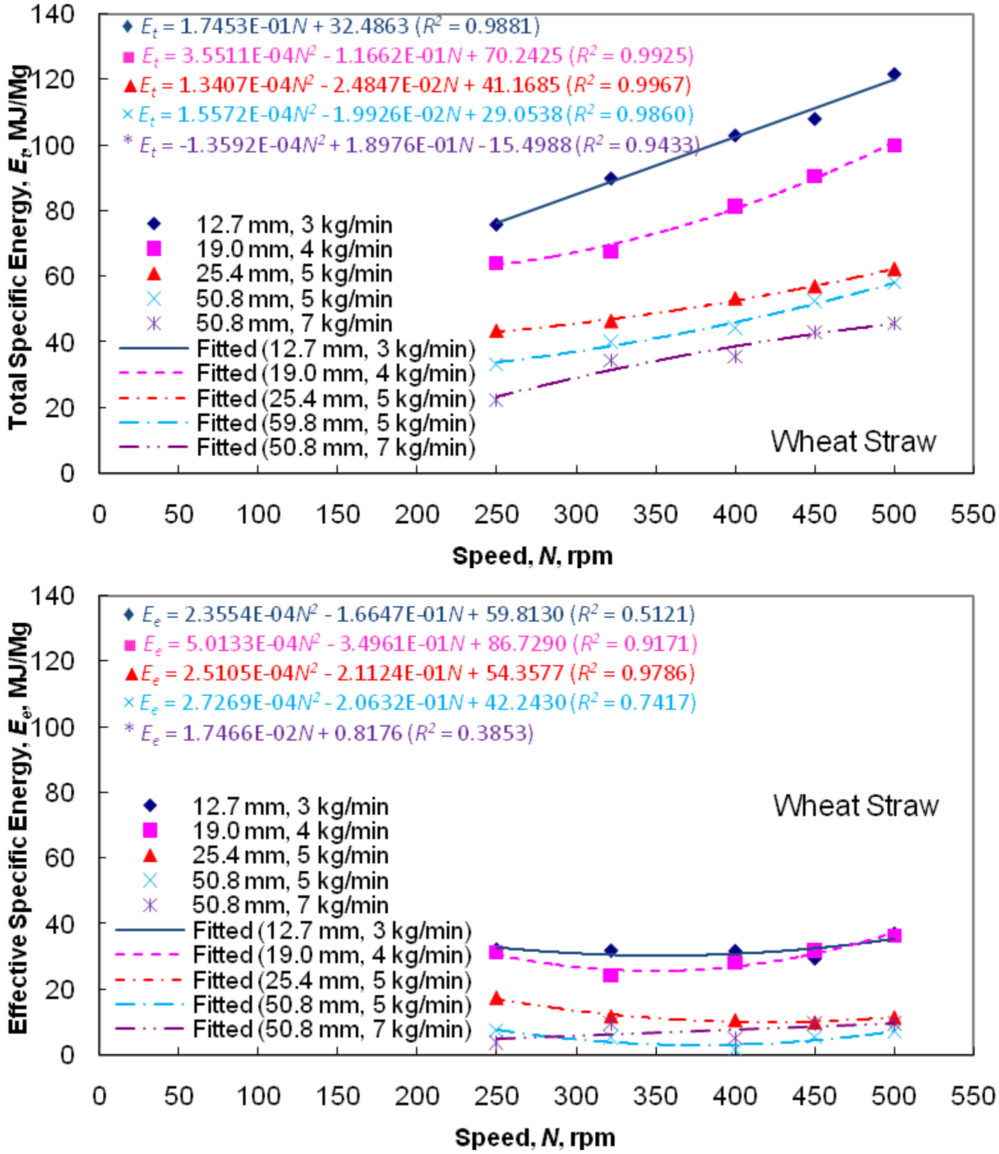

Figure 6. Total and effective specific energy of wheat straw with knife mill speed at selected screen sizes and corresponding mass feed rates.

Effect of Mass Feed Rate on Total and Effective Specific Energy

Total specific energy decreased gradually by 55, 49, and 75% with an increase in mass feed rate from 2 to 11 kg/min, 2 to 9 kg/min, and 2 to 7 kg/min for switchgrass (data not presented), wheat straw (data not presented), and corn stover (Fig. 8), respectively. Effective specific energy increased marginally by 11 and 4% for switchgrass and wheat straw, respectively, and decreased marginally by 7% for corn stover for same operating conditions. Decrease in total specific energy with feed rate was attributed to chopping of larger quantity of material in unit time and increased utilization by distributing material all along the full length of rotor. Hence, higher feed rates to be employed for lower total specific energy during biomass chopping.

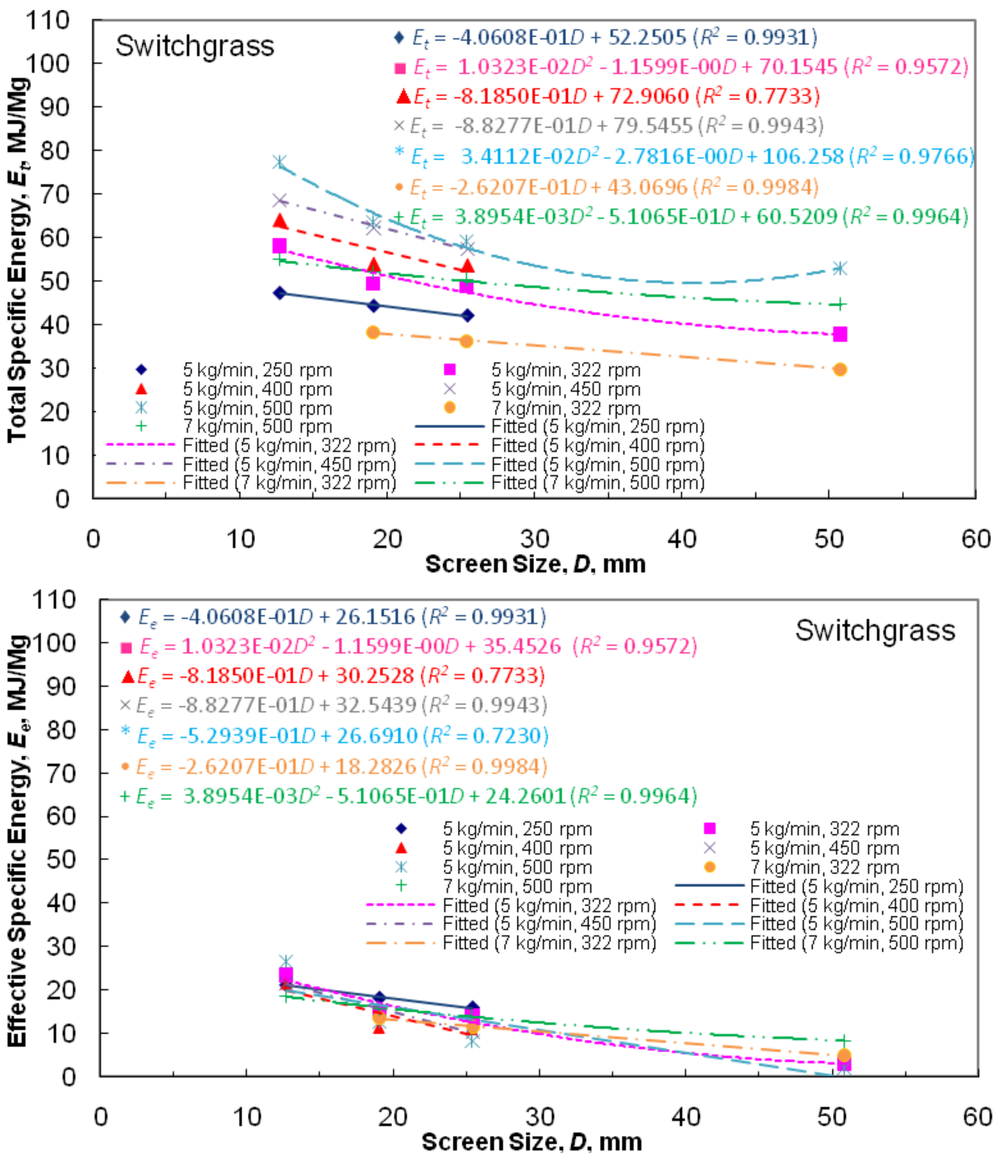

Figure 7. Total and effective specific energy of switchgrass with knife mill screen size at selected mass feed rates and corresponding screen sizes.

Energy Optimization

From energy consumption point of view, total specific consumption is important and it should be minimum for economical size reduction. Total specific energy of switchgrass depended mostly, in decreasing order of dependence, on mass feed rate, screen size, and speed (Table 1). Total specific energy of switchgrass as a function of knife mill operating conditions and their interactions was as follows:

$$E_t \text{ (Switchgrass)} = 89.7211 - 4.0558\text{E-}01\, D - 2.1676\text{E+}01\, F + 1.9641\text{E-}01\, N - 7.5973\text{E-}02\, DF - 1.6621\text{E-}02\, FN + 7.1018\text{E-}03\, D^2 + 1.8057\, F^2 \quad (R^2 = 0.9498)$$

where, E_t is total specific energy consumption, MJ/Mg; D is screen size, mm; F is mass feed rate, kg/min; and N is rotor speed, rpm.

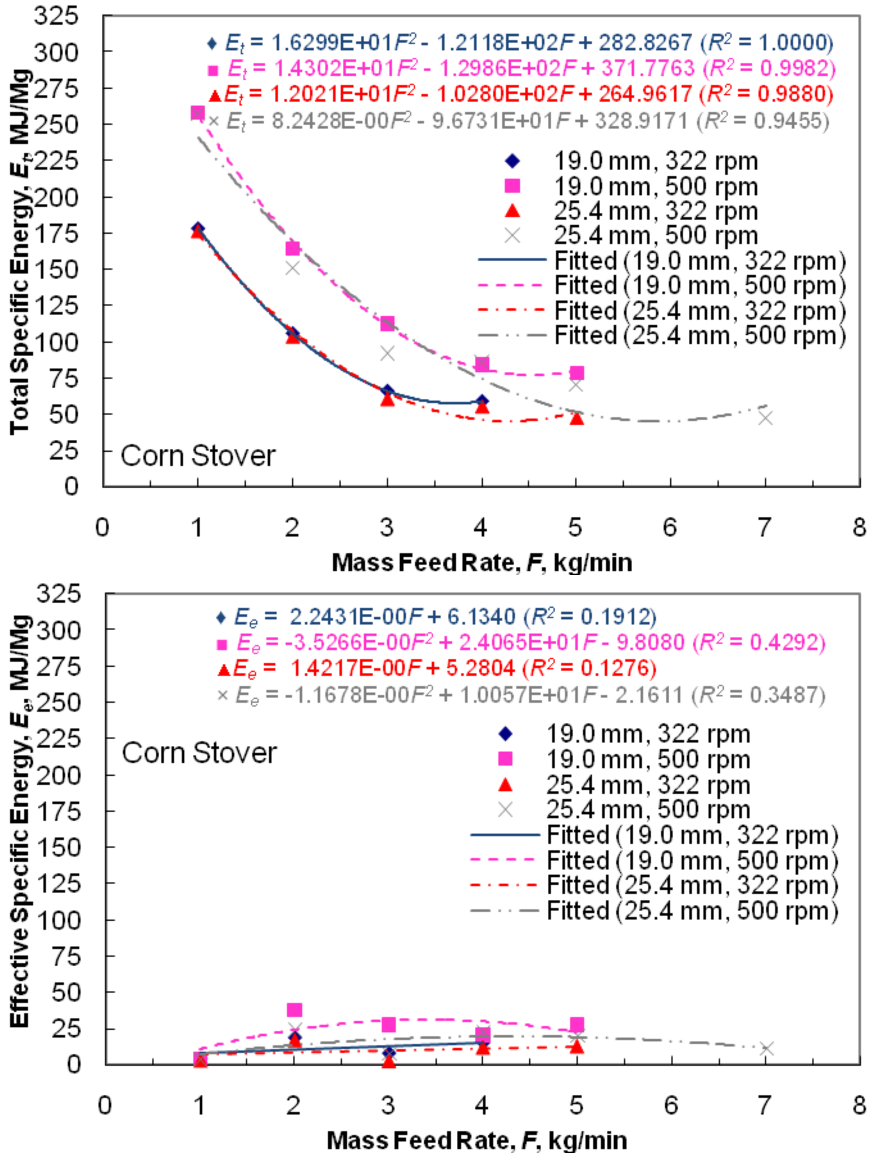

Figure 8. Total and effective specific energy of corn stover with knife mill mass feed rate at selected screen sizes and corresponding speeds sizes.

Total specific energy of wheat straw depended mostly on screen size, mass feed rate, and speed in decreasing order of dependence (Table 1). Total specific energy of wheat straw as a function of knife mill operating conditions and their interactions was as follows:

$$E_t \text{ (Wheat straw)} = 104.1702 - 1.6027\,D - 2.5668\text{E+01}\,F + 2.7442\text{E-01}\,N + 2.4403\text{E-01}\,DF - 3.1389\text{E-02}\,FN - 1.6304\text{E-04}\,ND + 1.7998\,F^2 \quad (R^2 = 0.9593)$$

Total specific energy of corn stover depended mostly on mass feed rate, speed, and screen size in decreasing order of dependence (Table 1). Total specific energy of corn stover as a function of knife mill operating conditions and their interactions was as follows:

$$E_t \text{ (Corn stover)} = 73.3809 - 1.8676\,D - 3.2109\text{E+01}\,F + 4.8437\text{E-01}\,N - 8.7142\text{E-01}\,DF - 8.8313\text{E-02}\,FN + 1.4267\text{E-03}\,\text{DN} + 7.9617\text{E-02}\,D^2 + 8.3691\,F^2 \quad (R^2 = 0.9599)$$

Above equations determined optimum screen size, speed, and mass feed rate. Optimum speed was 250 rpm for biomass chopping within the operating parameters tested. Optimized screen sizes for switchgrass, wheat straw, and corn stover were 51, 44, and 38 mm, respectively. Optimum screen sizes lesser than 50.8 mm for wheat straw and corn stover were attributed to 2^{nd}-order polynomial equations. For example, with nominal screen size of 25.4 mm, optimum feed rates were 7.6, 5.8, and 4.5 kg/min at optimized speed of 250 rpm for switchgrass, wheat straw, and corn stover, respectively. Corresponding total specific energies were 27.3, 37.9, and 31.9 MJ/Mg and effective specific energies were 4.6, 5.4, and 0.9 MJ/Mg for switchgrass, wheat straw, and corn stover, respectively, for the determined optimum operating parameters. Energy utilization ratios were calculated as 16.8, 14.3, and 2.8% for switchgrass, wheat straw, and corn stover, respectively. These results could not be compared with straw and corn stover size reduction by Cadoche and López (1989). They did not mention the speed and feed rate for the knife mill. However, the results of wheat straw and corn stover were comparable with Himmel et al. (1986). Switchgrass consumed less effective specific energy compared to wheat straw at optimum operating parameters of knife mill. However, total specific energy was highest for wheat straw followed by corn stover and switchgrass for optimum operating conditions. Higher total specific energy for wheat straw was attributed to its flexible and less brittle characters. Knife mill total specific energy was influenced by operating factors in the order of screen size, mass feed rate, speed, and biomass type, whereas, effective specific energy was controlled by screen size, biomass type, and speed in decreasing order (Table 2). Biomass type had least effect on total specific energy demand and pronounced effect on effective specific energy.

Table 1. Significant interactions of parameters on total specific energy.

Parameter	Mean sum square		
	Switchgrass	Wheat straw	Corn stover
Screen size	6429.96*	18222.30*	12718.15*
Mass feed rate	15639.73*	7782.80*	55670.89*
Speed	4633.94*	6272.54*	16432.14*
Screen size × Mass feed rate	1977.88*	2906.33*	5902.72*
Mass feed rate × Speed	776.94*	454.37*	799.93*
Speed × Screen size	17.94	40.08*	130.83*
Screen size × Screen size	123.80*	12.94	2311.77*
Mass feed rate × Mass feed rate	2161.80*	692.05*	10195.09*
Speed × Speed	0.77	4.48	2.27

* Parameter coefficient significant at 95% confidence level

Table 2. Significance test of knife mill variables on total and effective specific energy.

Parameter	Mean sum square	
	Total specific energy	Effective specific energy
Screen size	9896.34*	883.83*
Mass feed rate	6813.32*	20.27
Speed	2294.44*	49.89*
Material	283.83*	283.83*

* Parameter significant at 95% confidence level

Particle Size Analysis of Chopped Switchgrass, Wheat Straw, and Corn Stover

a. Size distribution

Switchgrass, wheat straw, and corn stover mass percent retained on each test sieve, *M*, in relation to geometric mean length of particles on each sieve followed log-normal distribution for all the knife mill screens (Fig. 9 for switchgrass). But, all the distribution curves showed positive skewness or fine skewed (a tail to the right on normal scale of X-axis) for all screen sizes from 12.7 to 50.8 mm. Skewness could well be viewed if abscissa of Fig. 9 is drawn on normal scale as shown by Womac et al. (2007). About 27/22/20, 15/13/13, 10/10/11, and 5/6/3% of switchgrass/wheat straw/corn stover contained particle size <1 mm for 12.7, 19.0, 25.4, and 50.8 mm screens, respectively, which indicated that further size reduction was required to make it more suitable for effective chemical reactions. Similar particle distribution trends were observed for hammer mill grinds of wheat, soybean meal, corn (Pfost and Headley, 1976), alfalfa (Yang et al., 1996), wheat straw (Himmel et al., 1985; Mani et al., 2004a), corn stover (Himmel et al., 1985), switchgrass, and barley straw (Mani et al., 2004a).

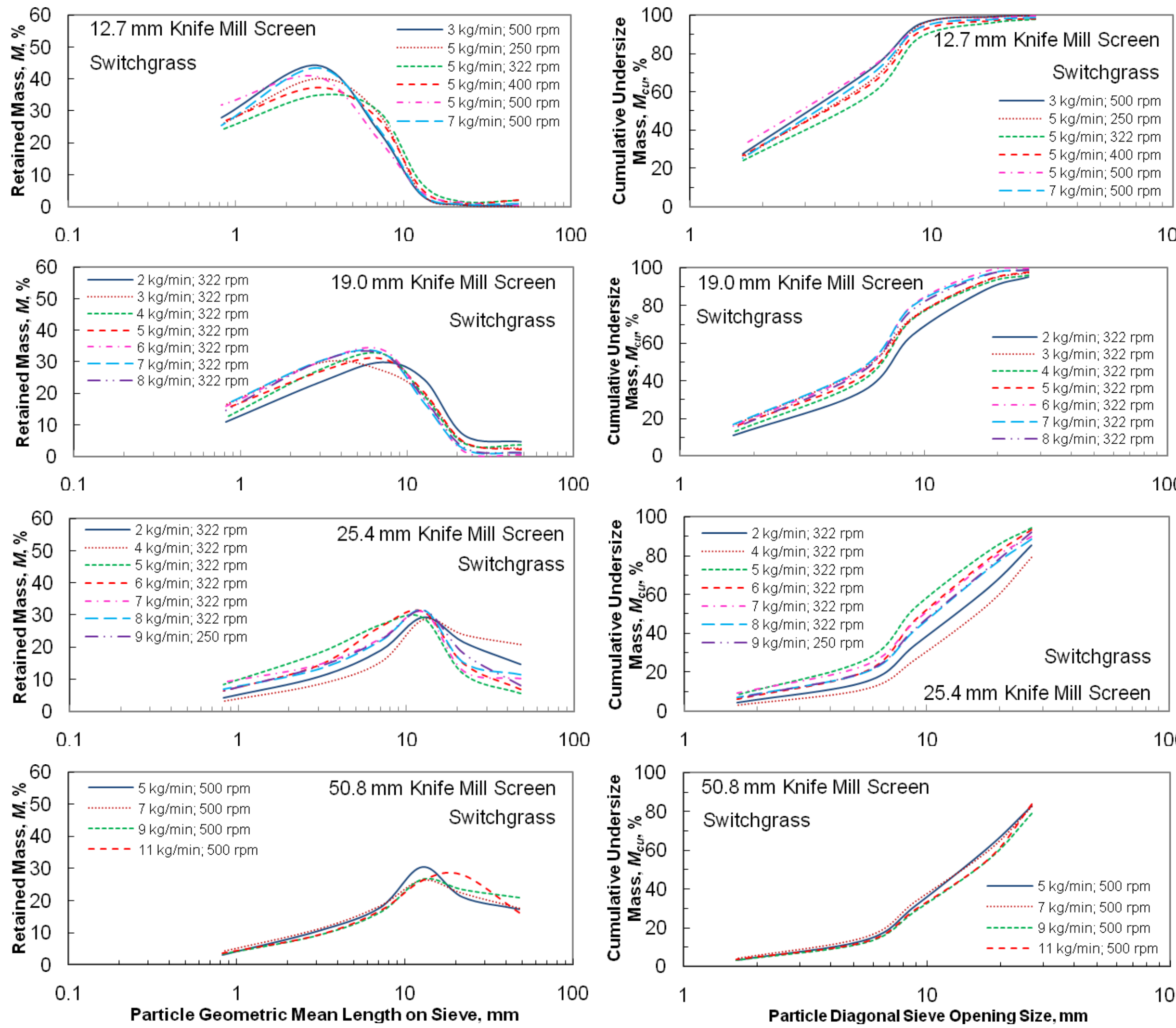

Figure 9. Log-normal distribution and cumulative percent undersize of chopped switchgrass.

b. Geometric mean diameter and geometric standard deviation

Geometric mean length, X_{gm}, of switchgrass/wheat straw/corn stover increased from 3.05±0.29 to 13.01±0.62 mm/3.46 ±0.20 to 10.87±0.90 mm/3.62±0.57 to 14.01±0.79 mm with an increase in knife mill screen size from 12.7 to 50.8 mm (Fig. 10). These coarse particles are suitable for boilers and ablative pyrolyzers (Lédé, 2003). Geometric mean length of switchgrass, wheat straw, and corn stover from ASABE sieve analysis results was less than the image analysis and micrometer readings measured by Yang (2007). ASABE sieve analysis gave an under sized geometric mean length due to slip down of lengthy particles on to lower sieves. Yang (2007) observed geometric mean length of 5x using image analysis and compared with micrometer readings. Geometric mean length was directly proportional to Rosin-Rammler size parameter (Table 3 for switchgrass), median length and effective size (Table 4 for wheat straw), and size guide number (Table 5 for corn stover). Mean separation of geometric mean length indicated significant difference (P < 0.05) in particle sizes between different screens (Table 3). Minimum significant difference (MSD) test across geometric mean length resulted in similar and coherent mean separations. In other words, geometric mean lengths of particles resulted from 12.7, 19.0, and 50.8 mm screens were uniform individually for all feed rates and speeds. Variation in knife mill screen size, speed, and mass feed rate had significant effect (P < 0.05) on geometric mean length (Table 3). A positive correlation was established between geometric mean length, X_{gm}, and knife mill screen size, D, and there was moderate and weak correlations with feed rate, F and knife mill speed, N, respectively (Table 6 for switchgrass).

Geometric standard deviation, S_{gm}, of switchgrass increased marginally from 2.5±0.1 to 2.7±0.1 with an increase in screen size from 12.7 to 25.4 mm and decreased to 2.6±0.1 for further increase to 50.8 mm (Fig. 10). But, it increased marginally from 2.09±0.05 to 2.54±0.11 for wheat straw with an increase in screen size from 12.7 to 50.8 mm (Fig. 10). However, geometric standard deviation increased slightly from 2.33±0.04 to 2.40±0.13 with an increase in screen size from 12.7 to 19.0 mm and then decreased to 2.21±0.31 for further increase to 50.8 mm (Fig. 10). For normal distribution curve, one standard deviation represents difference between size associated with a cumulative count of 84.1% and median (50% cumulative count) size (or between 50% cumulative size and 15.9% cumulative size) and standard deviation must always be greater than or equal to 1.0 (Hinds, 1982) (Table 3). Higher standard deviation than 1.0 represented wider distribution of particles. Geometric standard deviation of particles was similar for each screen individually with minor variations when feed rate and speed were altered. Hence, values of geometric mean length and standard deviation of each screen were averaged and they were represented as a function of screen size, D, with very high coefficient of determination (R^2 >0.85) (Fig. 10). Variation in knife mill screen size, speed, and mass feed rate had significant effect (P < 0.05) on geometric standard deviation (Table 3 for switchgrass). Geometric standard deviation of switchgrass/wheat straw/corn stover had weak/strong/moderate correlation with knife mill screen size, weak/moderate/weak correlation with feed rate, and weak/weak/weak correlation with speed (Table 6 for switchgrass).

Selection of knife mill screen size affected the characteristic shape of particle spectra curves (Fig. 9). Inclusive graphic skewness, GS_i, decreased with an increase in screen size (Table 4 for wheat straw). Screen sizes of 12.7, 19.0, and 25.4 mm yielded 'strongly fine-skewed' switchgrass particles (GS_i between +1.0 and +0.3) and 'fine-skewed' wheat straw and corn stover particles (GS_i between +0.3 and +0.1). However, 50.8 mm screen resulted in 'fine skewed' switchgrass and corn stover particles (GS_i : +0.3 to +0.1) and 'strongly fine-skewed' wheat straw particles (GS_i : +1.0 to +0.3) (Folk, 1974). Mean separation of skewness followed fairly similar grouping of relative span (Table 4 for switchgrass). Graphic kurtosis, K_g, of switchgrass and corn stover decreased with increase in screen size which indicated (data not presented). Uniformity index of switchgrass and corn stover particles increased with screen size

(Table 5 for corn stover). Increased uniformity had increased Rosin-Rammler distribution parameter and decreased mass relative span as screen size increased. Switchgrass, wheat straw, and corn stover particles from all screens were termed as ‘mesokurtic’, as kurtosis was within 0.90 and 1.11 (Folk, 1974). Mesokurtic distribution is a distribution with a same degree of peakedness about the mean as a normal distribution. Hence, knife mill chopping of switchgrass/wheat straw/corn stover resulted in ‘strongly fine-skewed mesokurtic’/’fine-skewed mesokurtic’/’fine-skewed mesokurtic’ particles with reduced size screens (12.7 to 25.4 mm) and ‘fine-skewed mesokurtic’/’strongly fine-skewed mesokurtic’/’fine-skewed mesokurtic’ particles with increased size screen (50.8 mm).

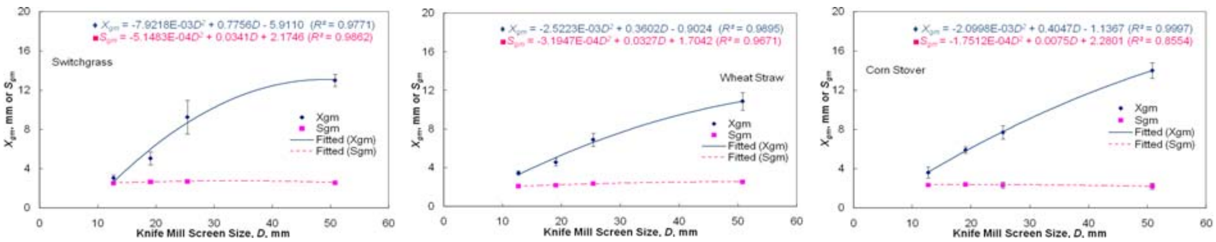

Figure 10. Variation in geometric mean length (X_{gm}) and geometric standard deviation (S_{gm}) of switchgrass, wheat straw, and corn stover chopped particles with knife mill screen size (error bars represent standard deviation from the mean).

c. Cumulative size distribution

Cumulative undersize mass percentage of switchgrass, wheat straw, and corn stover as a function of particle diagonal sieve opening size was not linear when plotted as log-probability graph (Fig. 9), which indicated bimodal distribution of particles (Hinds, 1982). Further, there was no optical and aerodynamic cutoff observed on log-log scale (not shown) as particles were lengthy in size. Optical and aerodynamic cutoff of size distribution means curving down of lower end and curving up of upper end of log-probability curve, respectively (Hinds, 1982). Switchgrass/wheat straw/corn stover coarse particles larger than 26.9 mm (large sieve) were about 2/1/0, 4/2/1, 10/6/3, and 16/15/12% for 12.7, 19.0, 25.4, and 50.8 mm screen sizes, respectively. Overall, cumulative trends for screen sizes from 12.7 to 50.8 mm were said to be ‘well-graded’(coefficient of gradation: 1 to 3) (Budhu 2007), even though the gap- or step-graded distribution was observed for 12.7 mm screen size for particles >10/10/12 mm, and a partial ‘poorly-graded’ distribution was observed for particles between 5.6 & 9.0/6.3 & 8.0/6.0 & 8.0 mm. In the present study, distribution curves showed effect of mixture of two log-normal distributions having two geometric standard deviations but of different median sizes for screen sizes tested. Rosin-Rammler equation fitted well the size-distribution data of switchgrass, wheat straw, and corn stover (R^2> 0.978) (Table 3 for switchgrass).

Particle Size Correlations

A direct consistent relation was observed among size-related parameters, namely, geometric mean length, X_{gm}, Rosin-Rammler size parameter, *a*, median length, D_{50}, effective size, D_{10}, and size guide number, N_{sg}, as screen size was the predominant knife mill operating factor. The moments method used for calculation of geometric mean length accounted for the variability in the fractions retained on each sieve. Sieve retained mass data were the basis for estimation of *a*, D_{50}, D_{10}, and N_{sg}. Hence, strong correlation was established among size-related parameters. A strong positive correlation existed among distribution-related parameters, namely, mass relative span, RS_m, uniformity coefficient, C_u, coefficient of gradation, C_g, and distribution geometric standard deviation, *GSD*, and also among Rosin-Rammler distribution parameter, b, and uniformity index, I_u. These two sets of distribution related parameters had negative correlation. Strong positive correlation among distribution-related parameters represented the shape of chopped switchgrass, wheat straw, and corn stover distribution curves without deviation. Parameters RS_m, C_u, C_g, and *GSD* were the measure of breadth of distribution and parameters *b* and I_u measured height of distribution. Also, size-related parameters had good correlation with distribution-related parameters.

Table 3. Estimated values of geometric mean length, geometric standard deviation, and parameters of Rosin-Rammler equation and its coefficient of determination for knife mill size reduction of switchgrass.

Mass Feed Rate, *F*, kg/min	Mill Speed, *N*, rpm	Geometric Mean Length, X_{gm}, mm[§]	Geometric Standard Deviation, S_{gm}[§]	Rosin-Rammler Size Parameter, *a*, mm[§]	Rosin-Rammler Distribution Parameter, *b*[§]	Coefficient of Determination, R^2
			Knife Mill Screen Size = 12.7 mm			
3	500	2.77 r	2.37 b	4.29 s	1.23 abcdefgh	0.993
5	250	3.00 qr	2.40 ab	4.73 s	1.26 abcdefgh	0.984
5	322	3.49 opqr	2.69 ab	5.49 qrs	1.18 defgh	0.982
5	400	3.17 qr	2.65 ab	4.94 s	1.16 efgh	0.985
5	450	3.30 pqr	2.52 ab	5.08 rs	1.29 abcdefgh	0.990
5	500	2.65 r	2.51 ab	4.11 s	1.09 h	0.994
7	500	2.99 qr	2.47 ab	4.60 s	1.25 abcdefgh	0.993
			Knife Mill Screen Size = 19.0 mm			
2	322	6.24 jklm	2.72 ab	9.62 mn	1.31 abcdefgh	0.990
2	500	6.29 jkl	2.78 ab	9.75 mn	1.24 abcdefgh	0.991
3	322	4.77 lmnopq	2.78 ab	7.62 op	1.20 cdefgh	0.994
3	500	5.33 lmn	2.69 ab	8.24 nop	1.31 abcdefgh	0.992
4	322	5.41 lmn	2.66 ab	8.20 nop	1.37 abcdefgh	0.987
4	500	5.55 lmn	2.66 ab	8.61 mnop	1.30 abcdefgh	0.992
5	250	4.39 nopqr	2.66 ab	7.04 pq	1.26 abcdefgh	0.993
5	322	5.04 lmnop	2.70 ab	7.98 nop	1.29 abcdefgh	0.989
5	400	5.34 lmn	2.63 ab	8.25 nop	1.37 abcdefgh	0.990
5	450	4.70 lmnopq	2.45 ab	7.26 opq	1.53 ab	0.992
5	500	4.20 nopqr	2.78 ab	6.80 pqr	1.14 gh	0.992
6	322	4.45 mnopqr	2.50 ab	7.03 pq	1.47 abcde	0.988
6	500	4.21 nopqr	2.77 ab	6.82 pqr	1.15 fgh	0.993
7	322	4.45 mnopqr	2.58 ab	7.01 pq	1.38 abcdefgh	0.988
7	500	5.21 lmno	2.57 ab	8.03 nop	1.43 abcdefg	0.992
8	322	4.70 lmnopq	2.54 ab	7.30 opq	1.43 abcdefg	0.990
8	500	5.77 klmn	2.65 ab	8.97 mno	1.37 abcdefgh	0.991
			Knife Mill Screen Size = 25.4 mm			
2	322	11.86 cd	2.62 ab	17.42 e	1.45 abcdefg	0.997
2	500	8.39 fgh	2.84 ab	12.97 ghijk	1.26 abcdefgh	0.990
4	322	14.19 a	2.56 ab	20.25 a	1.52 ab	0.997
4	500	9.43 efg	2.71 ab	14.22 fgh	1.34 abcdefgh	0.992
5	250	9.35 fgh	2.58 ab	13.89 fghi	1.38 abcdefgh	0.993
5	322	7.63 ghij	2.68 ab	11.74 kl	1.36 abcdefgh	0.994
5	400	8.97 fgh	2.65 ab	13.44 fghijk	1.40 abcdefg	0.995
5	450	8.19 fghi	2.72 ab	12.59 hijk	1.35 abcdefgh	0.993
5	500	8.77 fgh	2.63 ab	13.10 ghijk	1.44 abcdefg	0.994
6	322	8.85 fgh	2.57 ab	13.22 ghijk	1.45 abcdefg	0.993
6	500	11.22 de	2.86 ab	17.33 e	1.29 abcdefgh	0.996
7	250	7.55 hijk	2.80 ab	11.82 jkl	1.27 abcdefgh	0.995
7	322	8.65 fgh	2.89 a	13.57 fghij	1.29 abcdefgh	0.994
7	400	6.46 ijkl	2.81 ab	10.40 lm	1.23 bcdefgh	0.994
7	450	9.20 fgh	2.65 ab	13.86 fghi	1.35 abcdefgh	0.993

7	500	9.83 ef	2.78 ab	15.05 f	1.33 abcdefgh	0.995
8	322	9.70 ef	2.76 ab	14.76 fg	1.37 abcdefgh	0.996
8	500	8.32 fgh	2.52 ab	12.38 ijk	1.47 abcd	0.991
9	250	9.43 efg	2.64 ab	14.31 fgh	1.42 abcdefg	0.996
			Knife Mill Screen Size = 50.8 mm			
5	322	13.59 abc	2.54 ab	19.69 ab	1.47 abcd	0.991
5	500	12.79 abcd	2.55 ab	18.36 bcde	1.48 abcd	0.999
7	322	13.04 abcd	2.77 ab	19.60 abc	1.38 abcdefgh	0.997
7	500	12.38 abcd	2.50 ab	17.85 cde	1.50 abc	0.997
7	500	12.40 abcd	2.70 ab	18.47 abcde	1.38 abcdefgh	0.996
9	322	13.50 abc	2.55 ab	19.58 abc	1.47 abcd	0.991
9	500	13.92 ab	2.62 ab	20.18 ab	1.46 abcdef	0.997
11	500	13.32 abc	2.54 ab	19.28 abcd	1.54 a	0.993
n†		153	153	153	153	
SEM†		0.40	0.03	0.40	0.01	
CV†		5.79	5.79	5.79	5.79	
MSD†		1.83	0.50	1.83	0.31	
			Mean sum square			
Screen size		183.438*	0.064*	374.455*	0.084*	
Speed		1.472*	0.008*	2.784*	0.008*	
Mass feed rate		1.820*	0.008*	3.042*	0.005*	

§ Means with same letters in each column are not significantly different at $P < 0.05$ using Tukey's studentized range (HSD) test. Different letters within a value represent a significant difference.

† n – Number of observations; SEM – Square error mean; CV – Critical value; MSD – Minimum significant difference

* Significantly different at $P < 0.05$

Table 4. Median length, effective size, mass relative span, inclusive graphic skewness, and graphic kurtosis for knife mill size reduction of wheat straw using different screens.

Mass Feed Rate, F, kg/min	Mill Speed, N, rpm	Median Length, D_{50}, mm§	Effective Size, D_{10}, mm§	Mass Relative Span, RS_m§	Inclusive Graphic Skewness, GS_i§	Graphic Kurtosis, K_g§
			Knife Mill Screen Size = 12.7 mm			
3	250	4.34 kl	1.53 efgh	1.59 fghijkl	0.19 ghijklmn	0.97 cdefg
3	322	4.09 l	1.33 gh	1.72 cdefghijkl	0.22 defghijk	0.97 cdefg
3	400	4.56 kl	1.71 defgh	1.50 ghijkl	0.17 hijklmn	0.96 defg
3	450	4.13 l	1.41 fgh	1.64 efghijkl	0.20 fghijklm	0.97 cdefg
3	450	4.48 kl	1.52 efgh	1.66 defghijkl	0.21 fghijklm	0.97 cdefg
3	500	3.85 l	1.26 h	1.71 cdefghijkl	0.22 efghijkl	0.97 cdefg
			Knife Mill Screen Size = 19.0 mm			
2	322	5.37 hijkl	2.07 bcdefgh	1.45 hijkl	0.16 ijklmn	0.96 defg
2	500	6.19 ghijk	2.52 abcdefgh	1.37 ijkl	0.14 jklmn	0.96 fg
3	322	5.60 hijkl	2.33 abcdefgh	1.33 jkl	0.13 klmn	0.96 fg
3	500	5.19 jkl	1.99 cdefgh	1.46 hijkl	0.16 ijklmn	0.96 defg
4	250	6.32 ghijk	2.88 abcd	1.20 l	0.09 n	0.96 g
4	322	5.49 hijkl	2.34 abcdefgh	1.30 kl	0.12 lmn	0.96 g
4	400	5.54 hijkl	2.35 abcdefgh	1.30 kl	0.12 lmn	0.96 g
4	450	5.47 hijkl	2.31 abcdefgh	1.31 jkl	0.12 klmn	0.96 g
4	500	5.30 ijkl	2.08 abcdefgh	1.42 hijkl	0.15 ijklmn	0.96 efg
5	500	5.65 hijkl	2.40 abcdefgh	1.30 kl	0.12 lmn	0.96 g
			Knife Mill Screen Size = 25.4 mm			
2	322	8.55 ef	2.15 abcdefgh	2.16 abcde	0.31 abcde	1.00 abcdefg
2	500	7.27 fghi	3.19 abc	1.25 kl	0.11 mn	0.96 g
3	322	7.35 fgh	1.99 cdefgh	2.03 abcdefg	0.29 abcdefg	0.99 abcdefg

3	500	8.08 fg	2.00 cdefgh	2.18 abcd	0.32 abcd	1.00 abcdefg
4	322	8.77 ef	2.49 abcdefgh	1.95 abcdefgh	0.27 abcdefg	0.99 abcdefg
4	500	7.85 fg	2.47 abcdefgh	1.78 cdefghijk	0.23 cdefghij	0.97 cdefg
5	250	7.73 fg	3.22 abc	1.33 jkl	0.13 klmn	0.96 fg
5	322	7.28 fghi	2.83 abcde	1.43 hijkl	0.15 ijklmn	0.96 defg
5	400	7.75 fg	2.27 abcdefgh	1.90 bcdefghi	0.26 bcdefgh	0.98 bcdefg
5	450	7.74 fg	2.65 abcdefg	1.64 efghijkl	0.20 fghijklm	0.97 cdefg
5	500	6.27 ghijk	2.41 abcdefgh	1.46 hijkl	0.16 ijklmn	0.96 defg
7	500	7.06 fghij	2.14 abcdefgh	1.84 cdefghij	0.25 cdefghi	0.98 cdefg
			Knife Mill Screen Size = 50.8 mm			
5	250	13.10 ab	3.36 ab	2.12 abcde	0.31 abcde	1.00 abcdefg
5	322	11.23 bcd	2.49 abcdefgh	2.39 ab	0.36 ab	1.02 ab
5	400	11.83 abcd	2.95 abcd	2.18 abc	0.32 abcd	1.00 abcd
5	450	12.97 abc	3.19 abc	2.20 abc	0.32 abc	1.00 abc
5	500	12.08 abcd	2.70 abcdef	2.37 ab	0.35 ab	1.02 ab
7	250	12.70 abc	3.37 ab	2.06 abcdef	0.29 abcdef	0.99 abcdefg
7	322	10.99 cd	2.75 abcde	2.17 abc	0.32 abcd	1.00 abcde
7	400	13.51 a	3.41 a	2.15 abcd	0.31 abcde	1.00 abcdef
7	450	11.40 bcd	3.09 abc	2.03 abcdef	0.29 abcdefg	0.99 abcdefg
7	500	10.28 de	2.23 abcdefgh	2.43 a	0.36 a	1.02 a
9	500	11.67 abcd	2.94 abcd	2.15 abcd	0.31 abcde	1.00 abcdef
n†		117	117	117	117	117
SEM†		0.50	0.23	0.04	0.001	0.0002
CV†		5.63	5.62	5.63	5.63	5.63
MSD†		2.00	1.35	0.54	0.10	0.04
			Mean sum square			
Screen size		105.385*	2.93*	1.33*	0.06*	0.004*
Speed		0.945*	0.41*	0.07*	0.003*	0.0002*
Mass feed rate		0.413*	0.11*	0.06*	0.003*	0.0002*

§ Means with same letters in each column are not significantly different at $p<0.05$ using Tukey's studentized range (HSD) test. Different letters within a value represent a significant difference.
† n – Number of observations; SEM – Square error mean; CV – Critical value; MSD – Minimum significant difference
* Significantly different at $P < 0.05$

Table 5. Uniformity index, size guide number, uniformity coefficient, coefficient of gradation and distribution geometric standard deviation of particle size distribution for size reduction of corn stover using different screens.

Mass Feed Rate, F, kg/min	Mill Speed, N, rpm	Uniformity Index, I_u, %§	Size Guide Number, N_{sg}§	Uniformity Coefficient, C_u§	Coefficient of Gradation, C_g§	GSD_1	GSD_2	GSD_{12}
				Knife Mill Screen Size = 12.7 mm				
3	322	15.02 abcd	569 kl	2.94 ghij	1.15 fghi	1.62	1.99	1.80
3	400	5.17 j	389 m	5.39 a	1.24 a	2.13	2.93	2.50
3	450	5.89 ij	394 m	5.00 a	1.23 a	2.06	2.79	2.40
3	500	8.86 hij	441 lm	3.97 b	1.19 b	1.86	2.41	2.12
				Knife Mill Screen Size = 19.0 mm				
1	322	12.55 cdefgh	820 efghij	3.25 cdefghij	1.16 cdefgh	1.70	2.12	1.90
1	500	13.80 abcdef	761 fghij	3.08 defghij	1.15 defghi	1.66	2.05	1.84
2	322	10.70 efgh	783 efghij	3.56 bcdef	1.18 bcde	1.77	2.25	2.00
2	500	10.62 fgh	718 ijk	3.58 bcde	1.18 bcde	1.77	2.26	2.00
3	322	11.44 defgh	757 ghij	3.43 bcdefg	1.17 bcdefg	1.74	2.20	1.95
3	500	10.14 fgh	700 jk	3.67 bcd	1.18 bcd	1.79	2.29	2.03
4	250	12.12 cdefgh	794 efghij	3.32 cdefghi	1.17 bcdefg	1.71	2.15	1.92
4	322	10.35 fgh	713 ijk	3.63 bcde	1.18 bcde	1.79	2.28	2.02

4	400	12.57 cdefgh	728 hijk	3.25 cdefghij	1.16 cdefgh	1.70	2.12	1.90
4	450	12.12 cdefgh	723 ijk	3.32 cdefghi	1.17 bcdefg	1.71	2.15	1.92
4	500	11.71 cdefgh	685 jk	3.39 bcdefg	1.17 bcdefg	1.73	2.18	1.94
5	500	11.30 defgh	713 ijk	3.45 bcdefg	1.17 bcdef	1.75	2.21	1.96
			Knife Mill Screen Size = 25.4 mm					
1	500	17.88 a	944 cde	2.66 j	1.13 i	1.55	1.87	1.70
2	322	11.84 cdefgh	878 cdefghi	3.36 bcdefgh	1.17 bcdefg	1.73	2.17	1.93
2	500	14.17 abcdef	917 cdefg	3.04 efghij	1.15 efghi	1.65	2.03	1.83
3	322	15.72 abc	934 cdef	2.86 ghij	1.14 ghi	1.60	1.96	1.77
3	500	11.18 defgh	900 cdefgh	3.48 bcdefg	1.17 bcdef	1.75	2.21	1.97
4	322	13.18 bcdefg	942 cde	3.16 defghij	1.16 defghi	1.68	2.09	1.87
4	500	9.32 ghi	813 efghij	3.85 bc	1.19 bc	1.83	2.37	2.08
5	250	12.60 cdefgh	1040 c	3.25 cdefghij	1.16 cdefgh	1.70	2.12	1.90
5	322	13.91 abcdef	1030 c	3.07 defghij	1.15 defghi	1.66	2.05	1.84
5	400	14.84 abcde	920 cdefg	2.96 fghij	1.15 fghi	1.63	2.00	1.80
5	450	16.90 ab	1010 cd	2.75 hij	1.14 hi	1.58	1.91	1.73
5	500	14.01 abcdef	854 defghij	3.06 efghij	1.15 efghi	1.65	2.04	1.84
7	500	14.15 abcdef	938 cde	3.04 efghij	1.15 efghi	1.65	2.03	1.83
			Knife Mill Screen Size = 50.8 mm					
5	322	15.08 abcd	1643 a	2.93 ghij	1.15 fghi	1.62	1.99	1.79
5	500	13.89 abcdef	1562 ab	3.07 defghij	1.16 defghi	1.66	2.05	1.84
7	322	13.22 bcdefg	1547 ab	3.16 defghij	1.16 defghi	1.68	2.08	1.87
7	500	15.13 abcd	1592 ab	2.93 ghij	1.15 fghi	1.62	1.98	1.79
9	500	17.09 ab	1436 b	2.73 ij	1.14 hi	1.57	1.90	1.73
n†		102	102	102	102			
SEM†		2.22	3938.3	0.05	0.0001			
CV†		5.55	5.55	5.55	5.55			
MSD		4.14	174.2	0.63	0.03			
			Mean sum square					
Screen size		38.93*	1094658.7*	1.76*	0.0027*			
Speed		0.52	10143.7*	0.08*	0.0001*			
Mass feed rate		6.14*	5110.0*	0.12*	0.0004*			

§ Means with same letters in each column are not significantly different at $p<0.05$ using Tukey's studentized range (HSD) test. Different letters within a value represent a significant difference.
† n – Number of observations; SEM – Square error mean; CV – Critical value; MSD – Minimum significant difference
* Significantly different at $P < 0.05$

Particle Size Regression Analysis

All size related parameters (X_{gm}, a, D_{50}, D_{10}, and N_{sg}) depended strongly on screen size, D, and moderately on mass feed rate, F, and speed, N ($P < 0.05$) (Table 7). Hence, insignificant independent variables and their interactions of second-order polynomial equations were verified for $P < 0.05$ and discarded (Table 8). Size-related parameters X_{gm}, a, D_{50}, D_{10}, and N_{sg} had high R^2 values for second order polynomial equations as functions of knife mill operating factors. Distribution-related parameters (S_{gm}, b, RS_m, I_u, C_u, C_g, and GSD) were predicted with moderate R^2 value. Switchgrass chop of specific particle size and distribution statistics can now be produced by calculating the knife mill operating factors from polynomial equations (Table 8). Particle size- and distribution-critical applications could utilize these equations and prepare switchgrass, wheat straw, and corn stover chop with control over knife mill speed, mass flow rate, and screen size.

Table 6. Pearson correlation coefficients for knife mill size reduction of switchgrass.

Parameter	Screen Size, D, mm	Mass Feed Rate, F, kg/min	Speed, N, rpm	Geometric Mean Length, X_{gm}, mm	Geometric Standard Deviation, S_{gm}	Rosin-Rammler Size Parameter, a, mm	Rosin-Rammler Distribution Parameter, b	Median Diameter, D_{50}, mm	Effective Size, D_{10}, mm	Mass Relative Span, RS_m	Uniformity Index, I_u, %	Size Guide Number, N_{sg}	Uniformity Coefficient, C_u	Coefficient of Gradation, C_g	Distribution Standard Deviation (Higher), GSD_1	Distribution Standard Deviation (Lower), GSD_2	Distribution Standard Deviation (Total), GSD_{12}
D	1.000																
F	0.486 (3E-4)	1.000															
N	0.124 (0.381)	0.0527 (0.711)	1.000														
X_{gm}	0.872 (<10^{-4})	0.349 (0.011)	0.037 (0.796)	1.000													
S_{gm}	-0.042 (0.770)	-0.164 (0.247)	-0.032 (0.824)	0.096 (0.500)	1.000												
a	0.863 (<10^{-4})	0.348 (0.012)	0.030 (0.835)	0.998 (<10^{-4})	0.143 (0.311)	1.000											
b	0.605 (<10^{-4})	0.411 (0.003)	-0.042 (0.766)	0.661 (<10^{-4})	-0.416 (0.002)	0.642 (<10^{-4})	1.000										
D_{50}	0.868 (<10^{-4})	0.357 (0.009)	0.028 (0.841)	0.999 (<10^{-4})	0.112 (0.429)	0.999 (<10^{-4})	0.666 (<10^{-4})	1.000									
D_{10}	0.876 (<10^{-4})	0.393 (0.004)	0.026 (0.853)	0.989 (<10^{-4})	-0.022 (0.878)	0.982 (<10^{-4})	0.754 (<10^{-4})	0.988 (<10^{-4})	1.000								
RS_m	-0.582 (<10^{-4})	-0.386 (0.005)	0.071 (0.617)	-0.654 (<10^{-4})	0.370 (0.007)	-0.639 (<10^{-4})	-0.992 (<10^{-4})	-0.661 (<10^{-4})	-0.740 (<10^{-4})	1.000							
I_u	0.610 (<10^{-4})	0.418 (0.002)	-0.033 (0.818)	0.661 (<10^{-4})	-0.430 (0.002)	0.641 (<10^{-4})	0.999 (<10^{-4})	0.665 (<10^{-4})	0.756 (<10^{-4})	-0.986 (<10^{-4})	1.000						
N_{sg}	0.868 (<10^{-4})	0.357 (0.009)	0.028 (0.841)	0.999 (<10^{-4})	0.112 (0.429)	0.999 (<10^{-4})	0.666 (<10^{-4})	1.000 (<10^{-4})	0.988 (<10^{-4})	-0.661 (<10^{-4})	0.665 (<10^{-4})	1.000					
C_u	-0.571 (<10^{-4})	-0.373 (0.006)	0.082 (0.563)	-0.647 (<10^{-4})	0.349 (0.011)	-0.634 (<10^{-4})	-0.984 (<10^{-4})	-0.655 (<10^{-4})	-0.730 (<10^{-4})	0.999 (<10^{-4})	-0.976 (<10^{-4})	-0.655 (<10^{-4})	1.000				
C_g	-0.587 (<10^{-4})	-0.390 (0.004)	0.067 (0.638)	-0.656 (<10^{-4})	0.378 (0.006)	-0.640 (<10^{-4})	-0.994 (<10^{-4})	-0.663 (<10^{-4})	-0.743 (<10^{-4})	1.000 (<10^{-4})	-0.989 (<10^{-4})	-0.663 (<10^{-4})	0.997 (<10^{-4})	1.000			
GSD_1	-0.581 (<10^{-4})	-0.384 (0.005)	0.072 (0.610)	-0.653 (<10^{-4})	0.367 (0.007)	-0.638 (<10^{-4})	-0.991 (<10^{-4})	-0.660 (<10^{-4})	-0.739 (<10^{-4})	1.000 (<10^{-4})	-0.985 (<10^{-4})	-0.660 (<10^{-4})	0.999 (<10^{-4})	1.000 (<10^{-4})	1.000		
GSD_2	-0.577 (<10^{-4})	-0.380 (0.005)	0.076 (0.594)	-0.651 (<10^{-4})	0.361 (0.009)	-0.637 (<10^{-4})	-0.989 (<10^{-4})	-0.659 (<10^{-4})	-0.736 (<10^{-4})	1.000 (<10^{-4})	-0.982 (<10^{-4})	-0.659 (<10^{-4})	1.000 (<10^{-4})	0.999 (<10^{-4})	1.000 (<10^{-4})	1.000	
GSD_{12}	-0.579 (<10^{-4})	-0.382 (0.005)	0.074 (0.602)	-0.652 (<10^{-4})	0.364 (0.008)	-0.638 (<10^{-4})	-0.990 (<10^{-4})	-0.659 (<10^{-4})	-0.737 (<10^{-4})	1.000 (<10^{-4})	-0.983 (<10^{-4})	-0.659 (<10^{-4})	0.999 (<10^{-4})	0.999 (<10^{-4})	1.000 (<10^{-4})	1.000 (<10^{-4})	1.000

Table 7. Significant interactions of parameters on second order polynomial equations for knife mill size reduction of switchgrass, wheat straw, and corn stover

Parameter	Mean sum square								
	D	F	N	$D{\cdot}F$	$F{\cdot}N$	$N{\cdot}D$	D^2	F^2	N^2
					Switchgrass				
X_{gm}	480.43*	4.560*	3.341*	5.308*	0.937*	1.528*	60.23*	1.547*	0.081
S_{gm}	0.001	0.020*	0.001	0.020	0.017	4E-06	0.172	0.005	0.003
a	948.40*	8.653*	7.902*	14.482*	0.851	3.207*	145.864*	2.328*	0.188
b	0.232*	0.011*	0.009*	0.004*	0.014*	0.001	0.033*	0.013*	0.013*
D_{50}	597.215*	4.355*	5.139*	7.989*	0.937	1.875	85.832*	1.888*	0.039
D_{10}	53.75*	0.096	0.485*	0.319*	0.355*	0.121	5.548*	0.390	0.015
RS_m	0.845*	0.034*	0.051*	0.028*	0.043*	0.007	0.166*	0.049*	0.048
I_u	35.60*	1.847*	1.118*	0.427	2.172*	0.152	4.442*	1.961*	1.967
N_{sg}	5973125*	43270*	51374*	79975*	9444	18682	857912*	18906*	388
C_u	8.836*	0.327*	0.637*	0.352*	0.426*	0.092	1.972*	0.526*	0.500*
C_g	0.008*	3E-04*	5E-04*	2E-04*	4E-04*	1E-04	0.002*	5E-04*	5E-04*
GSD_1	0.294*	0.012*	0.018*	0.010*	0.015*	0.003	0.059*	0.017*	0.017*
GSD_2	1.099*	0.043*	0.072*	0.039*	0.055*	0.010	0.228*	0.064*	0.062*
GSD_{12}	0.586*	0.023*	0.037*	0.020*	0.029*	0.005	0.119*	0.034*	0.033*
					Wheat Straw				
X_{gm}	289.65*	1.033*	0.798*	1.784*	0.274*	0.017	4.104*	0.549*	0.092
S_{gm}	1.002*	0.028*	0.015*	0.043*	0.049*	2E-06	0.026*	2E-04	4E-07
a	604.07*	2.887*	0.103	2.009*	1.552*	0.720*	2.069*	1.619*	0.059
b	2.305*	0.038*	0.195*	0.039*	0.008	7E-04	0.036*	0.006	0.009
D_{50}	310.90*	1.045*	0.448*	1.795*	0.978*	0.375*	2.399*	0.851*	0.026
D_{10}	6.540*	0.016	0.805*	0.648	0.052	0.032	1.220*	0.028	0.004
RS_m	3.246*	0.087*	0.194*	0.025	5E-04	0.004	0.038*	0.012	0.002
I_u	430.55*	6.636*	3.999	8.236*	22.48*	30.38*	5.401	6.710*	5.731
N_{sg}	3110215*	10468*	11591*	17719*	1469	115	24827*	3031	674
C_u	24.09*	0.756*	0.172	0.147	1.258*	0.418*	0.223*	0.136	0.051
C_g	0.035*	0.001*	2E-04	3E-04	0.002*	0.001*	3E-04*	3E-04	2E-04
GSD_1	1.058*	0.029*	0.007	0.008	0.054*	0.026*	0.010*	0.007	0.004
GSD_2	3.590*	0.104*	0.025	0.026	0.185*	0.078*	0.033*	0.022	0.011
GSD_{12}	2.009*	0.057*	0.014	0.015	0.103*	0.046*	0.018*	0.013	0.007
					Corn Stover				
X_{gm}	300.46*	0.318*	2.480*	1.826*	0.150*	0.310*	0.341*	0.780*	0.004
S_{gm}	0.107*	0.004	0.021*	0.009*	0.006*	2E-04	1E-04	0.055*	0.019*
a	444.81*	0.912*	6.130*	4.925*	0.015	0.479*	2.142*	0.478*	0.155
b	0.371*	0.003	0.003	0.029*	0.010	0.039	0.208*	0.108*	0.024
D_{50}	321.81*	0.608*	4.159*	3.462*	1E-04	0.488*	2.148*	0.740*	0.026
D_{10}	58.48*	0.069*	0.514*	0.461*	0.022	0.245*	0.940*	0.750*	0.088
RS_m	0.379*	0.004	0.007	0.060*	0.014	0.033*	0.268*	0.076*	0.002
I_u	72.31*	0.488	0.262	5.301*	2.345	7.035	38.92*	20.67*	3.999
N_{sg}	3216781*	6049*	38237*	34774*	23.26	4229*	21406*	6591*	845.23
C_u	2.449*	0.033	0.050	0.499*	0.110	0.182	1.925*	0.391*	0.002
C_g	0.004*	4E-05	6E-05	0.001*	2E-04	3E-04	0.003*	0.001*	2E-05
GSD_1	0.120*	0.001	0.002	0.021*	0.005	0.010	0.087*	0.022*	1E-04
GSD_2	0.391*	0.005	0.007	0.071*	0.017	0.030	0.291*	0.069*	7E-05
GSD_{12}	0.223*	0.003	0.004	0.039*	0.010	0.018	0.164*	0.040*	1E-04

* Parameter coefficients significant at 95% confidence level

Table 8. Parameter coefficients of second order polynomial equations for knife mill size reduction of switchgrass, wheat straw, and corn stover.

Parameter	Constant	D	F	N	$D \cdot F$	$F \cdot N$	$N \cdot D$	D^2	F^2	N^2	R^2
					Switchgrass						
X_{gm}	-4.560	0.979	-1.074	-3.610E-3	-6.217E-3	1.408E-3	-2.195E-4	-8.785E-3	4.624E-2	-	0.882
S_{gm}	2.694	-	-9.326	-	-	-	-	-	-	-	0.027
a	-10.205	1.403	-0.690	3.592E-2	-4.575E-3	-	2.020E-4	1.377E-2	5.574E-2	-	0.886
b	0.847	2.172E-2	-5.210E-2	1.555E-3	-1.033E-2	8.447E-5	-	-1.603E-4	4.783E-3	-2.726E-6	0.514
D_{50}	-6.432	1.026	-0.541	-1.342E-3	-5.834E-3	-	-	-1.045E-2	4.968E-2	-	0.884
D_{10}	-2.190	0.267	-	-6.956E-4	-6.757E-4	4.043E-5	-	-2.640E-3	-	-	0.856
RS_m	3.248	-4.761	9.413E-2	-2.913E-3	2.123E-3	-1.517E-4	-	3.780E-4	-9.285E-3	-	0.504
I_u	0.185	0.234	-0.314	1.533E-2	-	1.035E-3	-	-2.628E-3	-2.845E-5	-	0.488
N_{sg}	-643.40	102.55	-54.047	-0.134	-0.586	-	-	-1.045	4.972	-	0.884
C_u	8.515	-0.162	0.301	-9.305E-3	7.043E-3	-4.792E-4	-	1.331E-3	-3.038E-2	1.645E-5	0.497
C_g	1.330	-4.620E-3	9.374E-3	-2.893E-4	2.084E-4	-1.520E-5	-	3.641E-5	-9.151E-4	5.090E-7	0.506
GSD_1	2.685	-2.829E-2	5.535E-2	-1.718E-3	1.258E-3	-8.920E-5	-	2.264E-4	-5.485E-3	3.024E-6	0.503
GSD_2	4.009	-5.552E-2	0.107	-3.307E-3	2.449E-3	-1.712E-4	-	4.483E-4	-1.063E-2	5.829E-6	0.501
GSD_{12}	3.283	-4.024E-2	7.796E-2	-2.419E-3	1.782E-3	-1.255E-4	-	3.236E-4	-7.751E-3	4.262E-6	0.502
					Wheat Straw						
X_{gm}	-1.623	0.407	8.083E-3	2.483E-3	-1.193E-2	-1.053E-3	-	-2.244E-3	7.412E-2	-	0.953
S_{gm}	2.026	3.623E-2	-9.894E-2	-8.265E-4	-9.302E-4	-2.328E-4	-	-2.566E-4	-	-	0.849
A	0.229	0.378	0.373	-	-2.217E-2	-1.821E-3	2.082E-4	-9.390E-4	9.432E-2	-	0.955
b	2.132	3.079E-3	4.982E-2	-8.105E-4	-4.413E-4	-	-	-3.120E-4	-	-	0.564
D_{50}	-1.791	0.310	0.743	5.458E-3	-2.173E-2	-2.733E-3	1.637E-4	-1.025E-3	0.106	-	0.959
D_{10}	0.679	0.146	-	-1.677E-3	-	-	-	-1.733E-3	-	-	0.710
RS_m	1.222	3.302E-3	-4.907E-2	8.114E-4	-	-	-	3.141E-4	-	-	0.665
I_u	12.657	- 0.480	4.368	-	-5.605E-2	-9.263E-3	1.157E-3	-	0.195	-	0.559
N_{sg}	72.194	38.196	-7.754	-0.209	-0.155	-	-	-0.245	-	-	0.955
C_u	3.247	6.413E-2	-0.604	-	-	1.087E-3	-1.179E-4	7.674E-4	-	-	0.688
C_g	1.162	2.755E-3	-2.631E-2	-	-	5.017E-5	-5.822E-6	3.223E-5	-	-	0.653
GSD_1	1.698	1.453E-2	-0.137	-	-	2.570E-4	-2.920E-5	1.699E-4	-	-	0.667
GSD_2	2.121	2.609E-2	-0.246	-	-	4.545E-4	-5.089E-5	3.066E-4	-	-	0.674
GSD_{12}	1.898	1.976E-2	-0.187	-	-	3.470E-4	-3.914E-5	2.317E-4	-	-	0.671
					Corn Stover						
X_{gm}	-0.189	0.304	0.668	-1.688E-3	-2.556E-2	-1.402E-3	1.459E-4	3.964E-4	7.590E-2	-	0.981
S_{gm}	3.369	-6.558E-3	-	-4.279E-3	9.256E-4	1.512E-4	-	-	-1.260E-2	4.418E-6	0.445
a	1.700	0.537	0.152	-6.036E-3	-2.122E-2	-	4.649E-5	-1.766E-3	4.301E-2	-	0.982
b	0.977	5.172E-2	-	-	-4.914E-3	-	-	-2.992E-4	1.773E-2	-	0.489
D_{50}	1.254	0.463	6.072E-2	-5.659E-3	-2.178E-2	-	5.839E-5	-1.480E-3	5.832E-2	-	0.979
D_{10}	0.322	0.200	-0.104	-3.308E-3	-1.592E-2	-	5.884E-5	-4.843E-4	6.463E-2	-	0.950
RS_m	2.583	-6.179E-2	-	-	3.993E-3	-	-	5.087E-4	-1.427E-2	-	0.496
I_u	0.808	0.708	-	-	-6.972E-2	-	-	-3.897E-3	0.252	-	0.487
N_{sg}	117.05	46.294	6.450	-0.548	-2.128	-	5.837E-3	-0.152	5.613	-	0.978
C_u	6.005	-0.168	-	-	9.082E-3	-	-	1.527E-3	-3.228E-2	-	0.488
C_g	1.269	-6.443E-3	-	-	4.302E-4	-	-	5.192E-5	-1.540E-3	-	0.497
GSD_1	2.279	-3.530E-2	-	-	2.189E-3	-	-	2.981E-4	-7.812E-3	-	0.495
GSD_2	3.189	-6.496E-2	-	-	3.847E-3	-	-	5.631E-4	-1.372E-2	-	0.493
GSD_{12}	2.698	-4.861E-2	-	-	2.947E-3	-	-	4.159E-4	-1.051E-2	-	0.494

\- represents non-significant coefficient dropped from equation

Conclusions

Knife mill no-load power consumption increased with speed. Overall accuracy of power measurement was ±0.003 kW. Total specific energy consumption of knife mill increased with speed for chopping switchgrass, wheat straw, and corn stover. However, effective specific energy decreased with speed for switchgrass and it increased for wheat straw and corn stover. Total and effective specific energy were greater in case of wheat straw compared to switchgrass. Corn stover resulted in reduced total and effective specific energy compared to wheat straw for same operating conditions, but higher total specific energy and lesser effective specific energy compared to switchgrass. Total and effective specific energy decreased with increase in screen size for switchgrass, wheat straw, and corn stover. Total specific energy decreased with increase in mass feed rate, but effective specific energy increased for switchgrass and wheat straw, and decreased for corn stover. Total specific energy was affected mainly by screen size, mass fee rate, and speed. For knife mill screen size of 25.4 mm and optimum rotor speed of 250 rpm, optimum feed rates were 7.6, 5.8, and 4.5 kg/min and the corresponding total specific energies were 27.3, 37.9, and 31.9 MJ/Mg and effective specific energies were 4.6, 5.4, and 0.9 MJ/Mg for switchgrass, wheat straw, and corn stover, respectively. Energy utilization ratios were calculated as 16.8, 14.3, and 2.8% for switchgrass, wheat straw, and corn stover, respectively. These data will be useful for preparing the feed material for subsequent grinding with hammer mill.

Rosin-Rammler equation fitted well the size-distribution data of switchgrass, wheat straw, and corn stover (R^2> 0.978). knife mill chopping of switchgrass/wheat straw/corn stover resulted in ‘well-graded’ ‘strongly fine-skewed mesokurtic’/’fine-skewed mesokurtic’/’fine-skewed mesokurtic’ particles with reduced size screens (12.7 to 25.4 mm) and ‘well-graded’ ‘fine-skewed mesokurtic’/’strongly fine-skewed mesokurtic’/’fine-skewed mesokurtic’ particles with increased size screen (50.8 mm). Size-related parameters (geometric mean length, X_{gm}, Rosin-Rammler size parameter, a, median size, D_{50}, effective size, D_{10}, and size guide number, N_{sg}) were fit as a function of knife mill screen size, D, feed rate, F, and mill speed, N. Analysis of particles will lead to the selection of knife mill operating parameters to produce a particular chop.

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