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Direct measures of mechanical energy for knife mill size reduction of switchgrass, wheat straw, and corn stover

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ABSTRACT

Lengthy straw/stalk of biomass may not be directly fed into grinders such as hammer mills and disc refiners. Hence, biomass needs to be preprocessed using coarse grinders like a knife mill to allow for efficient feeding in refiner mills without bridging and choking. Size reduction mechanical energy was directly measured for switchgrass (*Panicum virgatum* L.), wheat straw (*Triticum aestivum* L.), and corn stover (*Zea mays* L.) in an instrumented knife mill. 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. Overall accuracy of power measurement was calculated to be ±0.003 kW. Total specific energy (kWh/Mg) was defined as size reduction energy to operate mill with biomass. Effective specific energy was defined as the energy that can be assumed to reach the biomass. The difference is parasitic or no-load energy of mill. Total specific energy for switchgrass, wheat straw, and corn stover chopping increased with knife mill speed, whereas, effective specific energy decreased marginally for switchgrass and increased for wheat straw and corn stover. Total and effective specific energy decreased with an increase in screen size for all the crops studied. 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 at increased feed rate. For knife mill screen size of 25.4 mm and optimum speed of 250 rpm, optimum feed rates were 7.6, 5.8, and 4.5 kg/min for switchgrass, wheat straw, and corn stover, respectively, and the corresponding total specific energies were 7.57, 10.53, and 8.87 kWh/Mg and effective specific energies were 1.27, 1.50, and 0.24 kWh/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 fine grinding operations and designing new mills.

1. Introduction

Lignocellulosic materials offer a fuel source to supplement fossil fuels. Conversion of naturally occurring lignocellulosic materials to ethanol currently requires pretreatment to enhance the accessibility of reactive agents and to improve conversion rates and yields. According to one patent, agricultural biomass was prepared to approximately 1–6 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, and chain mill). Long pieces of straw/stalk of biomass may not flow easily into grinders such as hammer mills and disc refiners. Hence, biomass needs to be processed or chopped with a knife mill to accommodate bulk flow and for uniformity of feed rate. For example, switchgrass reduced to approximately 25 mm in length using rotary shear shredder was fed to a hammer mill and subsequently to disc refiner for further size reduction (1–2 mm) for the 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.

The National Renewable Energy Laboratory indicated that size reduction required one-third of total energy inputs for biomass to ethanol conversion (Aden et al., 2002). Hence, size reduction of biomass is an energy-intensive process that warrants improvement to raise the energy efficiency involved in bio-fuels production. Energy consumption for grinding depends on its initial particle size, moisture content, material properties, mass feed rate, and machine variables (Mani et al., 2004). Performance of a grinding device is often measured in terms of energy consumption, geometric mean

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diameter/length, and resulting particle size distribution. Mani et al. (2002) observed that power requirement increased rapidly with decreasing particle size. About 1.3–2.5% of the total energy content of hardwood chips was required to shred them to 10–30 mesh (2.00–0.595 mm) size (Datta, 1981). 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 (Himmel et al., 1985). They adopted indirect method of measuring electric power with watt meter and corrected with power factor. 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 extremely brittle failure of homogeneous materials, which is not representative of lignocellulosic biomass.

A linear knife grid device was recently reported to offer an efficient first-stage size reduction (to create product dimensions of 50–100 mm and greater) for high- and low-moisture switchgrass. Mass based cutting energy values of high- and low-moisture switchgrass were 1.25 ± 1.23 and 1.01 ± 0.92 kWh/dry Mg, respectively (Igathinathane et al., 2008).

Balk (1964) found that the specific energy required to hammermill coastal Bermudagrass was influenced by moisture content and grind size. Datta (1981) reported that size reduction of hardwood chips to 0.2–0.6 mm required 20–40 kWh/Mg, whereas size reduction of particles to 0.15–0.3 mm required five times higher energy (100–200 kWh/Mg). Arthur et al. (1982) found that specific energy consumption of a tub grinder used for rectangular wheat straw bales decreased from 749 to 328 kWh/Mg as the screen size increased from 12.7 to 50.8 mm. The authors also reported that grinding rate increased from 8.2 to 16.0 Mg/h when the screen size increased. Their indirect measurement of overall energy input rate was based on engine fuel consumption rate and did not take into account energy conversion by an internal combustion engine. Schell and Harwood (1994) found that the energy required to reduce the switchgrass to 100–200 mm length particles using a shredder was 8.2 kWh/Mg. Their energy estimation was based on electric energy measurement. Samson et al. (2000) reported that specific energy consumption of switchgrass hammer milling with 5.6 mm screen was 44.9 kWh/Mg. Jannasch et al. (2001) reported a specific electric energy consumption of 55.9 kWh/Mg for both 5.6 and 2.8 mm screen sizes during the hammer milling of switchgrass. Mani et al. (2002, 2004) found that the specific energy required to hammer mill switchgrass through a 3.2 mm screen was 27.6 kWh/Mg and was higher than that required to hammer mill corn stover (11.0 kWh/Mg). They indirectly estimated mechanical power using a wattmeter to monitor an electric motor. Esteban and Carrasco (2006) estimated mean energy requirements of 85.4, 118.5, and 19.7 kWh/Mg for poplar chips, pine chips, and pine bark, respectively, in a hammer mill containing 1.5 mm screen. They also estimated mechanical input energy into the mill from electric voltage and current input to a motor. Thus, most of the published energy values were based on indirect estimation of fuel or electric energy.

Knife mills worked successfully for shredding forages under various crop 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. Energy consumption to reduce hardwood chips to a particle size of 1.6 mm was 130 kWh/Mg for both hammer and knife mills whereas the hammer mill required more energy (115 kWh/Mg) than a knife mill (50 kWh/Mg) to reduce the size of the hardwood chips to 3.2 mm particle size. They observed that the energy required to grind agricultural straw and corn stover was about 6–36% of the energy to grind wood.

Published size reduction studies on knife mill equipped with direct measurement of mechanical input energy are scarce in the literature. Primary objective of this study was to determine the direct mechanical input energy for knife mill size reduction of switchgrass, wheat straw, and corn stover over a range of mill operating speeds, screen sizes, and mass feed rates. A secondary objective was to identify whether optimum operating conditions may lend to reduced energy expended for size reduction.

2. Methods

2.1. 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 ($1.00 \times 0.45 \times 0.35$ 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, 2006) by oven drying the samples at 103 ± 2 °C for 24 h.

2.2. 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 45°. 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 240° 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.

2.3. 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.

2.4. Instrumentation and data acquisition

Mechanical power input into the knife mill was directly monitored with a calibrated torque and speed sensor (±0.05% accuracy)

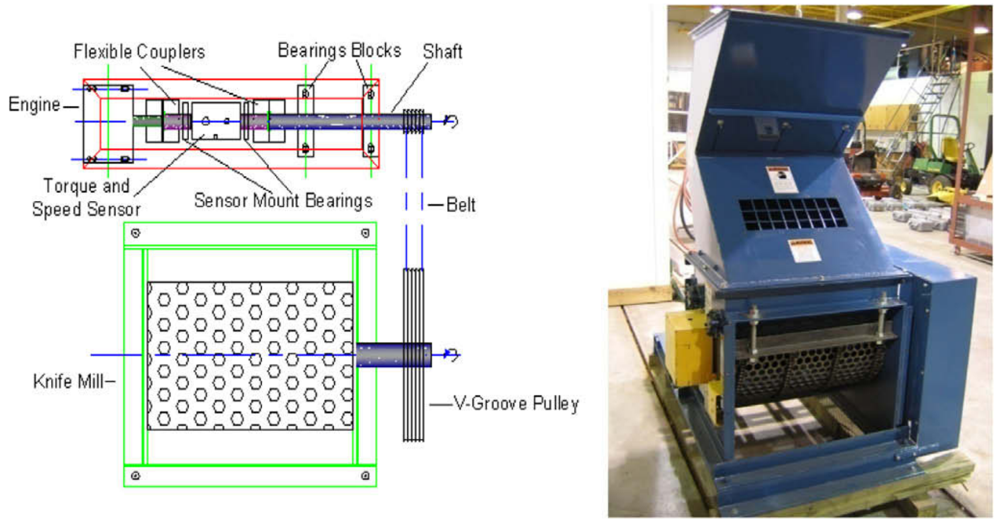

Fig. 1. Overhead sectional view of knife mill and instrumentation set up and photo of knife mill uniformly feed with a conveyor.

(Series 4200 PCB Piezotronics, Depew, NY) in a 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 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 2× 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 and 4 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.

2.5. Test procedure

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.

2.6. Data analysis

Total specific energy was determined in kWh/Mg from the mass feed rate data, torque, and speed. Effective specific energy was determined by subtracting idle energy from total energy (Cadoche and López, 1989; Himmel et al., 1985; Holtzapple et al., 1989). SAS Non-Linear 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.

3. Results and discussion

3.1. Knife mill no-load power consumption

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. 3). Increased power was attributed to increasing speed at essentially constant torque (11.98–12.70 N-m). Large knife mill bearings contributed to torque resistance.

3.2. Effect of speed on total and effective specific energy

Mean total specific energy of switchgrass increased by 33% from 10.4 ± 2.9 kWh/Mg with an increase in speed from 250 to 500 rpm for all screen sizes (12.7–50.8 mm) (Fig. 4). 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 (Fig. 4), even though the no-load power consumption increased with speed (Fig. 3). 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

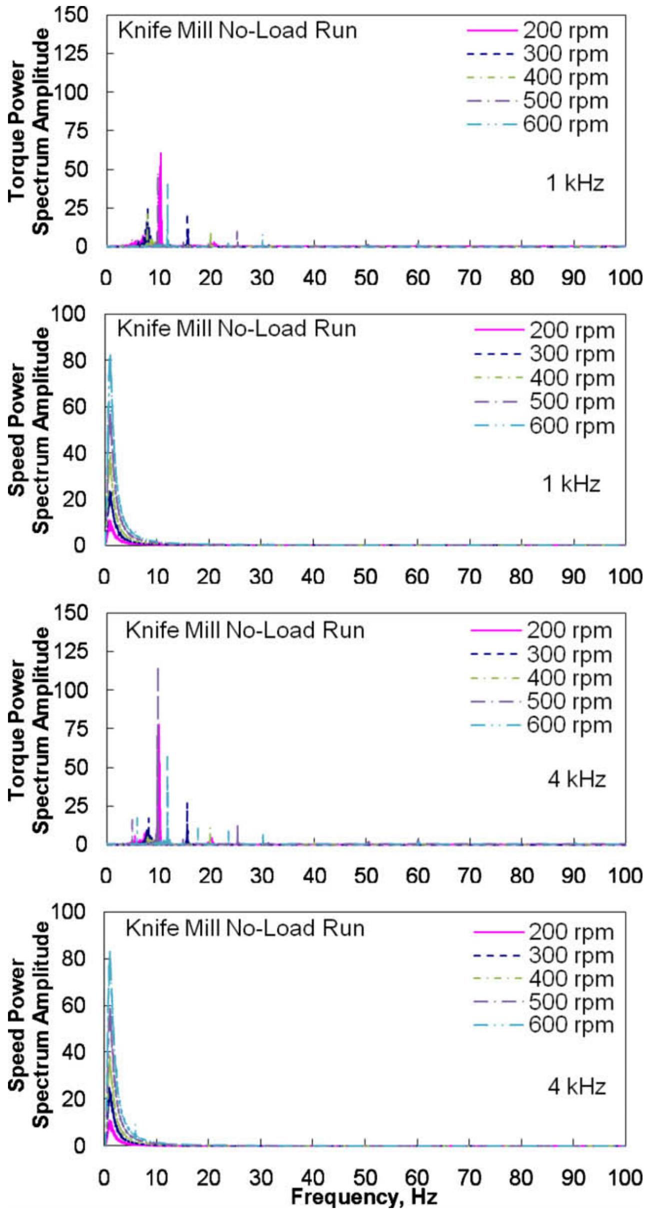

Fig. 2. Power spectra of torque and speed for 1 and 4 kHz data acquisition sampling during no-load run of knife mill.

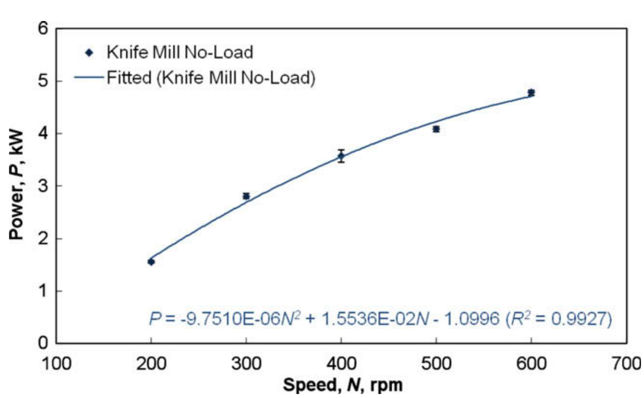

Fig. 3. No-load power consumption of knife mill with speed.

between rotor and screen. It should be noted that total specific energy as size reduction energy expended for a particular mill design,

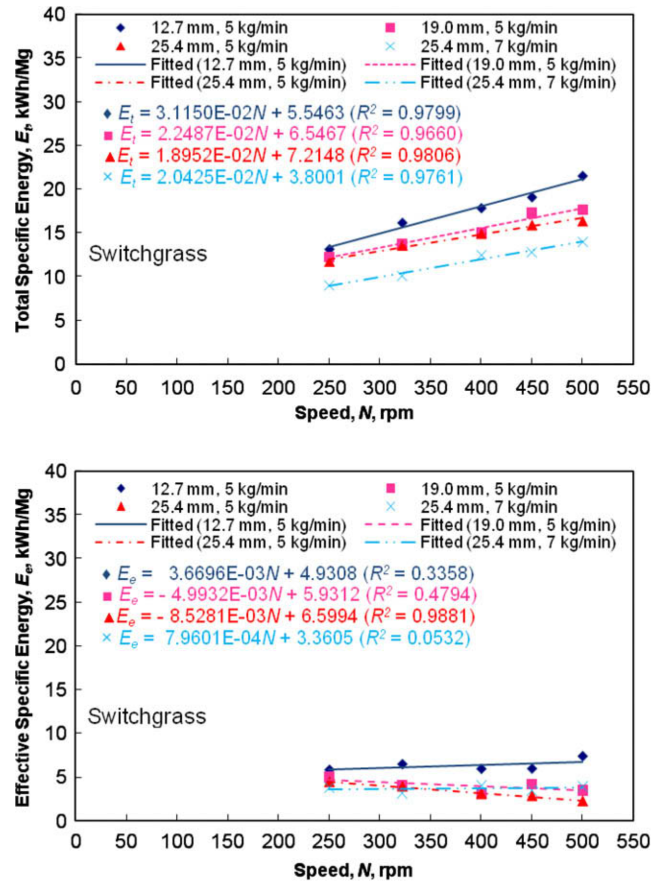

Fig. 4. Total and effective specific energy of switchgrass with knife mill speed at selected screen sizes and corresponding mass feed rates.

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 13.28 ± 6.08 kWh/Mg with an increase in speed from 250 to 500 rpm for all screen sizes (Fig. 5). Mean effective specific energy of wheat straw marginally increased by 10% from 5.12 ± 3.67 kWh/Mg for same increase in speed for all screen sizes (Fig. 5). Total and effective specific energy increased by 3 kWh/Mg for wheat straw compared to switchgrass (Fig. 4). 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 13.55 ± 4.38 and 4.35 ± 2.02 kWh/Mg, respectively, with an increase in speed from 250 to 500 rpm for all screen sizes (Fig. 6). 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, 2004) also observed less effective specific energy for corn stover (11.0 kWh/Mg) compared to switchgrass (27.6 kWh/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.

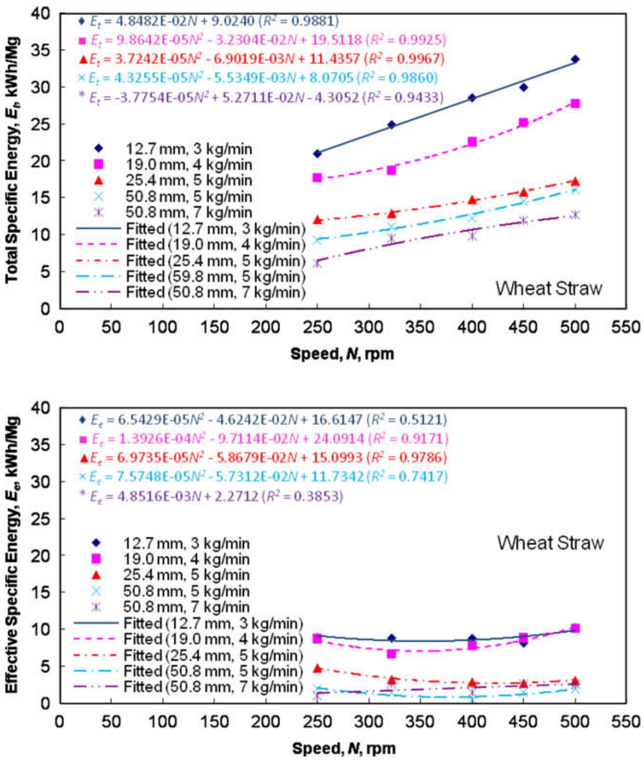

Fig. 5. Total and effective specific energy of wheat straw with knife mill speed at selected screen sizes and corresponding mass feed rates.

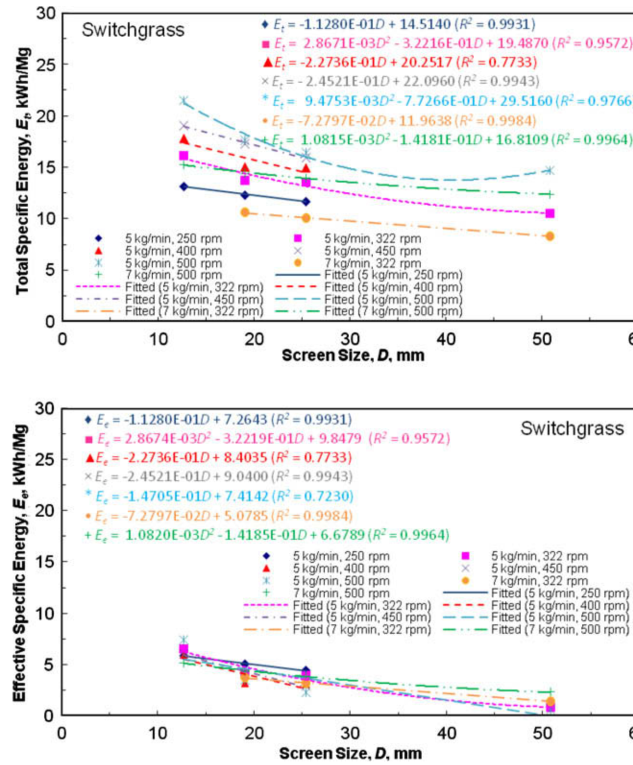

Fig. 7. Total and effective specific energy of switchgrass with knife mill screen size at selected mass feed rates and corresponding speeds.

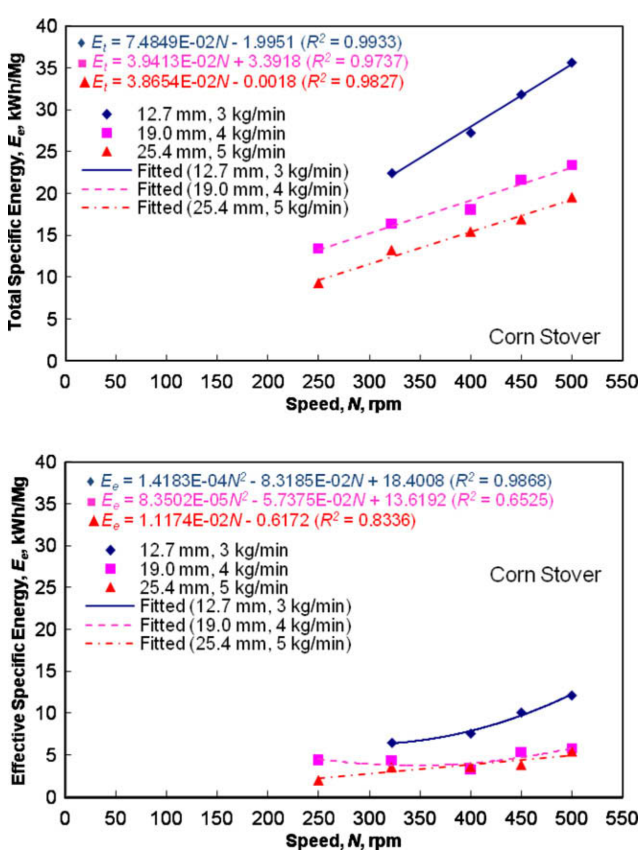

Fig. 6. Total and effective specific energy of corn stover with knife mill speed at selected screen sizes and corresponding mass feed rates.

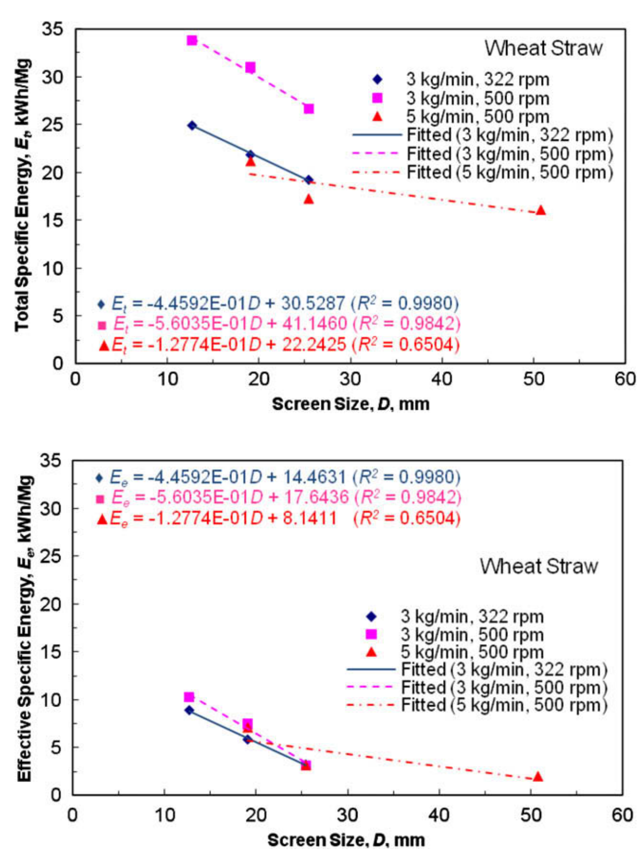

Fig. 8. Total and effective specific energy of wheat straw with knife mill screen size at selected mass feed rates and corresponding speeds.

3.3. 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 (Fig. 8), and corn stover (Fig. 9), 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, 2004) 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 55.9 kWh/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.

3.4. 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 (Fig. 10), wheat straw (Fig. 11), and corn stover (Fig. 12), 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.

3.5. 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:

$$\begin{aligned} E_t\ (\text{Switchgrass}) = {} & 24.9225 - 1.1266\text{E-}01\ D - 6.0211\ F \\ & + 5.4557\text{E-}02\ N - 2.1104\text{E-}02\ DF \\ & - 4.6170\text{E-}03\ FN + 1.9727\text{E-}03\ D^2 \\ & + 5.0158\text{E-}01\ F^2 (R^2 = 0.9498) \end{aligned}$$

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

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:

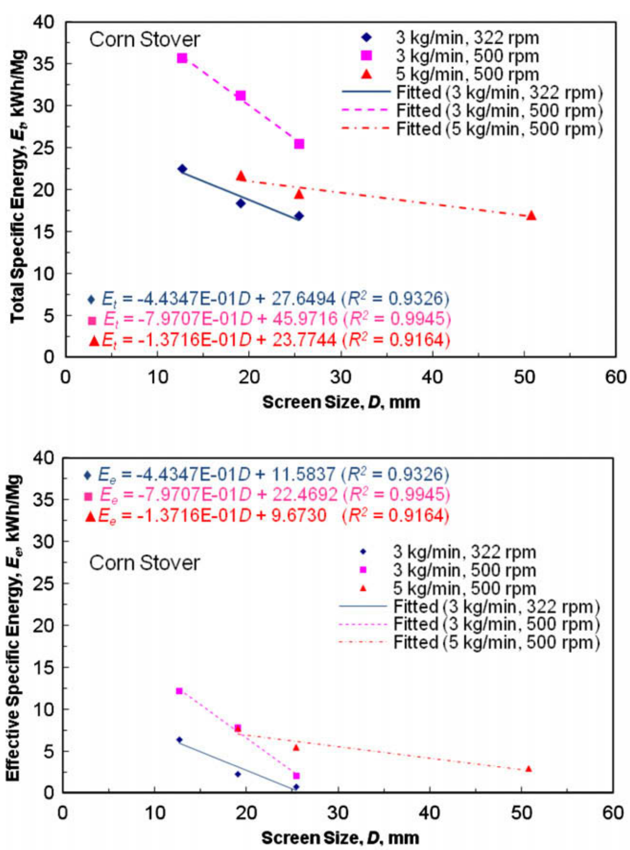

Fig. 9. Total and effective specific energy of corn stover with knife mill screen size at selected mass feed rates and corresponding speeds.

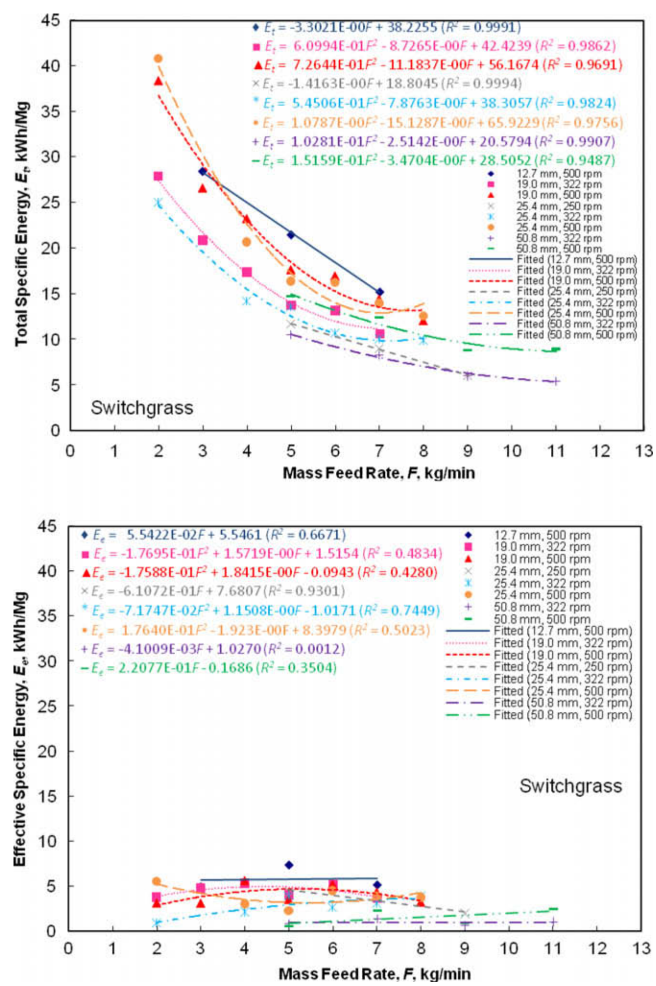

Fig. 10. Total and effective specific energy of switchgrass with knife mill mass feed rate at selected screen sizes and corresponding speeds.

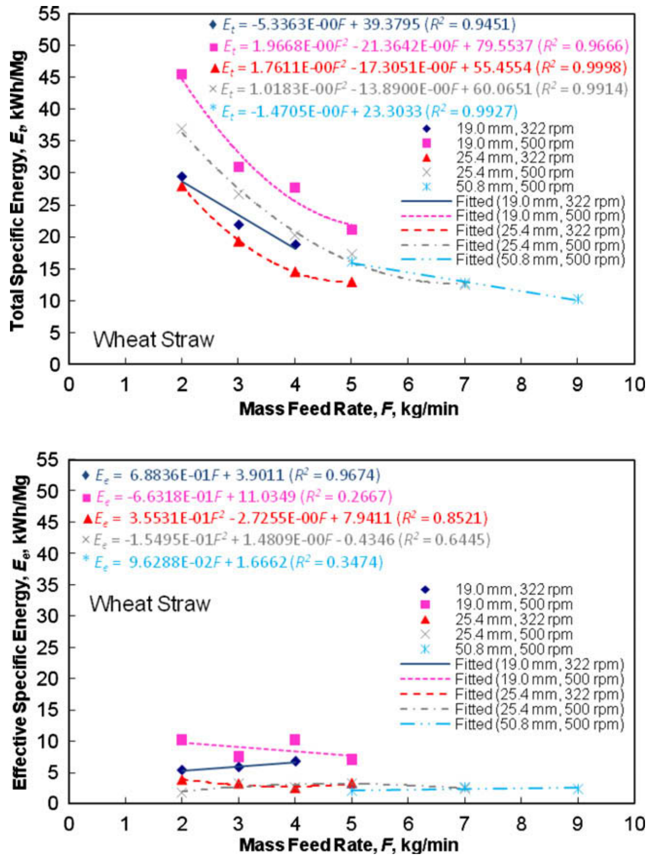

Fig. 11. Total and effective specific energy of wheat straw with knife mill mass feed rate at selected screen sizes and corresponding speeds.

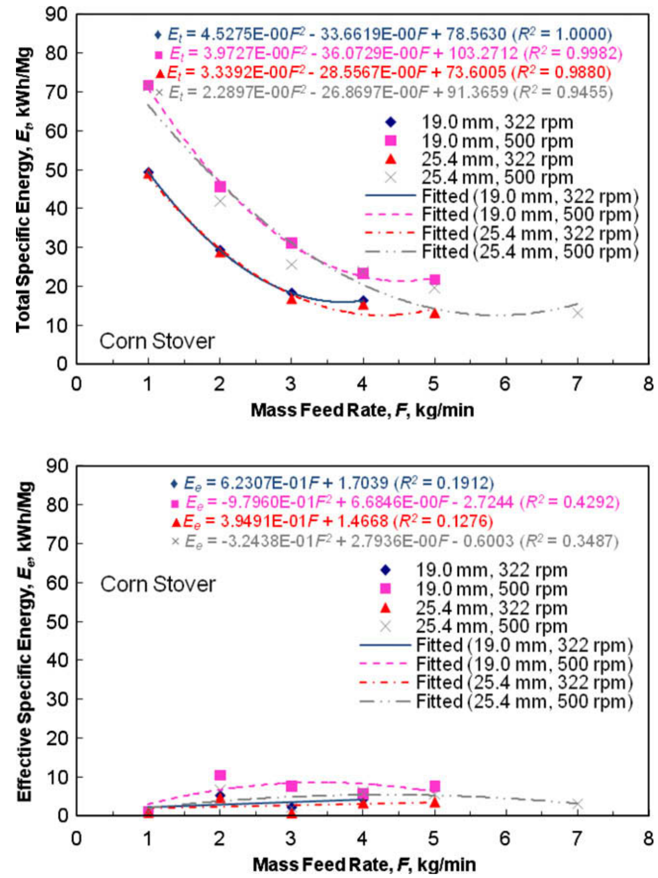

Fig. 12. Total and effective specific energy of corn stover with knife mill mass feed rate at different screen sizes and corresponding speeds.

$$E_t\ (\text{Wheat straw}) = 28.9362 - 4.4518\text{E-}01\ D - 7.1300\ F + 7.6229\text{E-}02\ N + 6.7786\text{E-}02\ DF - 8.7191\text{E-}03\ FN - 4.5290\text{E-}05\ ND + 4.9996\text{E-}01\ F^2 (R^2 = 0.9593)$$

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:

$$E_t\ (\text{Corn stover}) = 20.3836 - 5.1879\text{E-}01\ D - 8.9192\ F + 1.3455\text{E-}01\ N - 2.4206\text{E-}01\ DF - 2.4531\text{E-}02\ FN + 3.9630\text{E-}04\ DN + 2.2116\text{E-}02\ D^2 + 2.3247\ F^2 (R^2 = 0.9599)$$

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 50.80 mm for wheat straw and corn stover were attributed to 2nd-order polynomial equations. For example, with nominal screen size of 25.40 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 7.57, 10.53, and 8.87 kWh/Mg and effective specific energies were 1.27, 1.50, and 0.24 kWh/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. (1985). 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	496.14*	1406.04*	981.34*
Mass feed rate	1206.77*	600.52*	4295.59*
Speed	357.56*	483.99*	1267.91*
Screen size × mass feed rate	152.61*	224.25*	432.31*
Mass feed rate × speed	59.95*	35.06*	61.72*
Speed × screen size	1.38	3.09*	10.09*
Screen size × screen size	9.55*	1.00	178.38*
Mass feed rate × mass feed rate	166.81*	53.40*	786.69*
Speed × speed	0.06	0.35	0.18

* 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	763.61*	68.27*
Mass feed rate	525.72*	1.56
Speed	177.04*	3.85*
Material	21.90*	21.90*

* Parameter significant at 95% confidence level.

4. 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 25.40 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 7.57, 10.53, and 8.87 kWh/Mg and effective specific energies were 1.27, 1.50, and 0.24 kWh/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.

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