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Knife grid size reduction to pre-process packed beds of high- and low-moisture switchgrass

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Abstract

A linear knife grid device was developed for first-stage size reduction of high- and low-moisture switchgrass (*Panicum virgatum* L.), a tough, fibrous perennial grass being considered as a feedstock for bioenergy. The size reduction is by a shearing action accomplished by forcing a thick packed bed of biomass against a grid of sharp knives. The system is used commercially for slicing forages for drying or feed mixing. No performance data or engineering equations are available in published literature to optimize the machine and the process for biomass size reductions. Tests of a linear knife grid with switchgrass quantified the combined effect of shearing stresses, packed bed consolidation, and frictional resistance to flow through a knife grid. A universal test machine (UTM) measured load–displacement of switchgrass at two moisture contents: 51%, and 9% wet basis; three knife grid spacings: 25.4, 50.8, and 101.6 mm; and three packed bed depths: 50.8, 101.6, and 152.4 mm. Results showed that peak load, ultimate shear stress, and cutting energy values varied inversely with knife grid spacing and directly with packed bed depth (except ultimate shear stress). Mean ultimate shear stresses of high- and low-moisture switchgrass were 0.68 ± 0.24, and 0.41 ± 0.21 MPa, mass-based cutting energy values were 4.50 ± 4.43, and 3.64 ± 3.31 MJ/dry Mg, and cutting energy based on new surface area, calculated from packed-circle theory, were 4.12 ± 2.06, and 2.53 ± 0.45 kJ/m^2, respectively. The differences between high- and low-moisture switchgrass were significant ($P < 0.05$), such that high-moisture switchgrass required increased shear stress and cutting energy. Reduced knife grid spacing and increased packed bed depths required increased cutting energy. Overall, knife grid cutting energy was much less than energy values published for rotary equipment. A minimum knife grid spacing of 25.4 mm appears to be a practical lower limit, considering the high ram force that would be needed for commercial operation. However, knife grid spacing from 50 to 100 mm and greater may offer an efficient first-stage size reduction, especially well suited for packaged (baled) biomass. Results of this research should aid the engineering design of size reduction equipment for commercial facilities.

Keywords: Switchgrass; Cutting energy; Biomass pre-processing; Knife grid; Size reduction

1. Introduction

Candidate biomass materials and individual processing steps need evaluation to develop sustainable renewable energy systems (Kumar and Sokhansanj, 2007). Some crops established for forage are now being considered for energy (Sanderson et al., 1996). The US Department of Energy and the Oak Ridge National Laboratory selected switchgrass, a perennial grass, as a model herbaceous energy crop due to high productivity; low demand on land fertility, water, and nutrients; and positive environmental benefits (McLaughlin, 1993). The value of switchgrass for bioenergy was developed over two decades of intensive agronomic research (McLaughlin and Kszos, 2005).

Size reduction of biomass is a pre-processing operation that increases bulk density, improves flow properties, generates new surface area (Drzymala, 1993), increases pore

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size, and increases rates of hydrolysis reactions (Schell and Harwood, 1994). Typical size reduction machines for biomass are hammer-, knife-, and disk-mills, and various choppers, chippers, and shredders (Yu et al., 2003). These machines are usually based on rotary action, with machine elements mounted on a shaft. Hammer-mills have the advantages of simple operation, rugged construction, and wide product particle size range (Lopo, 2002). A high-capacity tub grinder, commonly used with crop and forest biomass residues (Arthur et al., 1982), is essentially a hammer mill with rotary feed hopper. Size reduction is energy inefficient, at least with typical rotary machines, as only 0.06% to 1% of the energy is used in breaking and creating new surfaces (Mohsenin, 1986).

Knowledge of energy required to cut any fibrous material is limited. Neither a cutting theory nor a mathematical model for cutting fibrous materials has been reported (Dowgiallo, 2005). However, some studies examined specific biomass materials such as soybean stalks (Mesquita and Hanna, 1995), cotton stalks (El Hag et al., 1971), maize stalks (Prasad and Gupta, 1975), alfalfa stems (Prince et al., 1969), and hemp (Chen et al., 2004). These studies showed that cutting energy is related to maximum cutting force, stem shear strength, stem diameter, dry matter density, and moisture content. Mani et al. (2004) determined the grinding performance and physical properties of switchgrass, along with wheat and barley straws and corn stover. Switchgrass ultimate tensile and shear stress properties applicable to size reduction were recently determined (Yu et al., 2006).

Linear cutting of biomass, instead of rotary action, is an alternative action that may be applied either with or without impact. Biomass compression occurs before cutting (Chancellor, 1958), and is more pronounced in failure without impact. Cutting force of fibrous material is based on knife cutting speed, material, and knife geometry (Dowgiallo, 2005). Grid cutting of forages (alfalfa and timothy) is practiced commercially in Canada for drying or feed mixing. The grid is vertical and a pressure plate forces material horizontally through the knife grid. Current grid spacing is 400 mm. One issue is the lack of information to determine the minimum practical grid spacing and the associated forces to push switchgrass through the grid. Technologies that convert biomass into value-added products and to energy will likely require final particle sizes less than 400 mm.

The objective of the study was to determine the engineering performance characteristics of a linear knife grid for size reduction of switchgrass, especially at reduced knife grid spacings.

2. Methods

2.1. Linear knife grid size reduction device

Linear knife grid model size reduction device components (Fig. 1) were ram (pressure plate), feed block, knife grid, knife support block, and product block. A grid of orthogonal, interlocking knives was supported in grooves spaced at 25.4 mm intervals in the support block. Different knife sets were fabricated and knife grid spacings of 25.4, 50.8, and 101.6 mm were based on anticipated particle sizes as a first cut in sequential size reduction.

Inside cross-section dimensions of the feed, knife and product blocks were 203.2 by 203.2 mm and were made from 19.05 mm mild steel plates bolted together. Lateral clearance was 0.16 mm between ram and feed block. Knife material was A2 tool-steel. Knives were 3.18 mm thick plate, machined with a leading bevel angle of 30° (Womac et al., 2005).

2.2. Test sample

A uniform mixture of switchgrass varieties (Alamo, Kanlow, and Cave-in-Rock) was used at two moisture contents. Previous tests by Yu et al. (2006) found that differences in the mean ultimate tensile and shear strengths of Alamo and Kanlow switchgrass varieties are very small (8.3% and 12.7%, respectively). Similar differences were obtained between these two varieties and Cave-in-Rock variety. Therefore, an equal proportion mixture of the three switchgrass varieties (Alamo, Kanlow and Cave-in-Rock) was used in this study with each mixture being tested at moisture contents of $9.0 \pm 0.5\%$ and $51.5 \pm 4.1\%$ wet basis. Mixing was carried out after each mature switchgrass variety was mechanically raked. To obtain the low-moisture content sample (9.0% wet basis), the mixture was rectangular-baled and then stored indoors for three months. High-moisture samples (51.5% wet basis) were immediately tested after being collected from the field. The moisture content of the samples was evaluated using an oven method by subjecting 50 g of samples to a temperature of 103 °C for 24 h (ASAE Standards, 2003). Switchgrass samples about 195 mm long were cut to fit inside the feed block. Other physical dimensions (diameters) of switchgrass samples were not measured but the dimensional data of Yu (2004) were used in this study – because switchgrass sources were the same.

2.3. Universal test machine

The linear knife grid ram was attached to a universal test machine (UTM) (Model 60 K, Measurement Technology, Inc. (MTI) Roswell, GA) that applied compressive load through a 222.41 kN load cell (Fig. 2). MTI software (32 bit Testing Application Programs, Version 1.15) was used to operate the machine, and to acquire and store load-displacement data (50–75 Hz).

Ram velocity of 50.8 mm/min and an upper load limit of 60% load capacity were used, though on a few occasions 80% capacity was used. To prevent contact between ram and knives, a vertical clearance of 3.18 mm was programmed for stopping the ram. Inner walls of the feed block were marked at levels of 50.8, 101.6, and 152.4 mm,

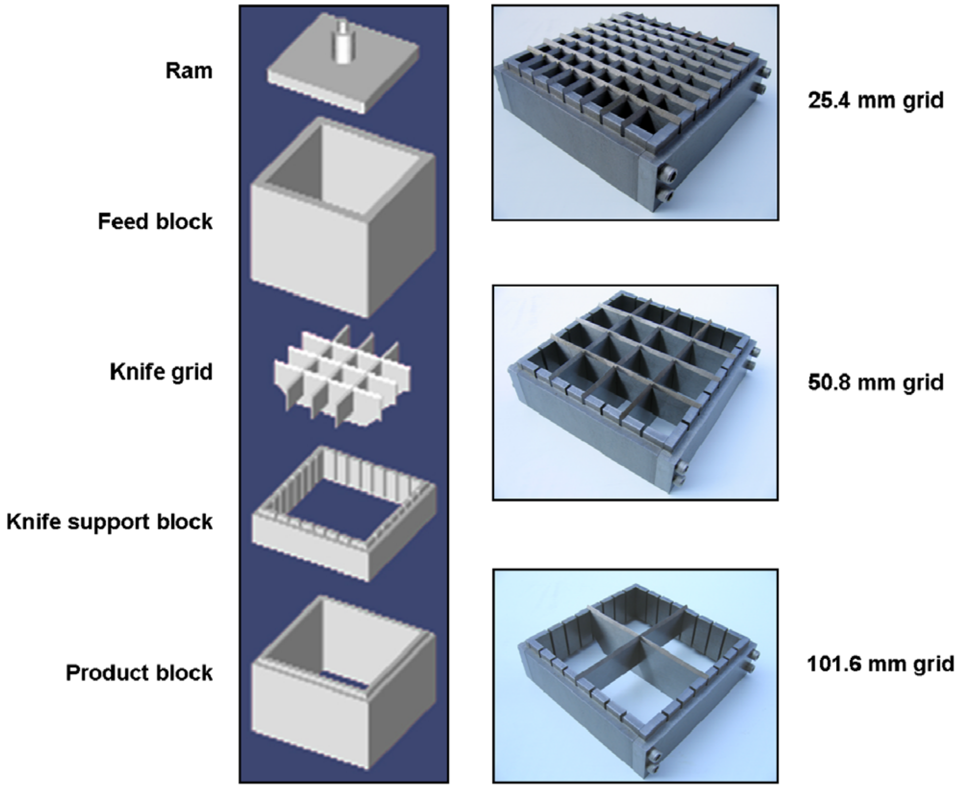

Fig. 1. Components of linear knife grid model cutting device and knives arrangement at various grid spacing.

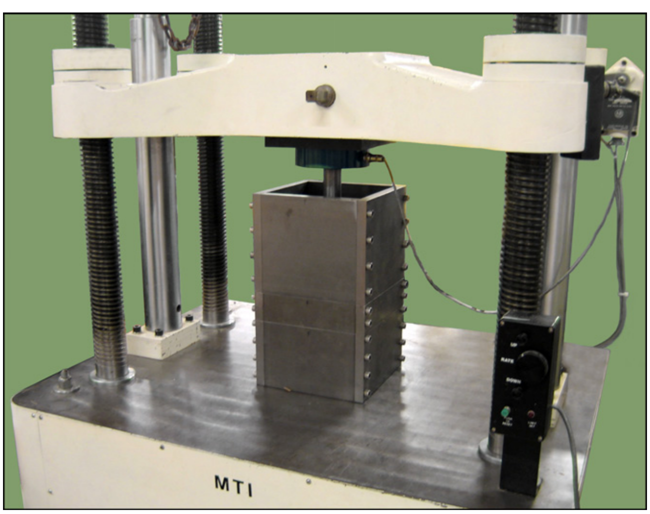

Fig. 2. Universal test machine with linear knife grid device.

measured from the plane of knife edges, to aid in sample filling to specified depths.

2.4. Test procedure

A test procedure was selected to resemble a commercial operation whereby refill loadings (and measurements) of a given treatment did not disturb the packed bed of material passing through the knife grid. In lieu of replications, emphasis was placed on performing tests with refills (4 or 5 refills) in a continuous fashion to best resemble commercial operation procedures. This allowed identification of outliers similar to that of a continuous function and maximized the examination of variables deemed important. Preliminary tests identified greater variance among refill number than replication of the same refill. These differences among refills were due to achieving steady-state accumulation of compressed input material as compared to first or second runs at a given configuration as residual material filled the knife grid.

Independent test variables included switchgrass moisture content (51%, and 9% wet basis), knife grid spacing (25.4, 50.8, and 101.6 mm), and packed bed depth (50.8, 101.6, and 152.4 mm). Tests were conducted on all combinations of variables.

Switchgrass was laid in the feed block to selected test depth (50.8, 101.6, and 152.4 mm, with an average depth variation of maximum 1.5 mm). Depth of the packed bed was measured before and after each test. Mass of product falling into the product block after each cycle of the ram was determined without disturbing the compressed packed bed retained in the knife grid.

A typical run consisted of loading of sample to specified depth, cutting of samples by downward movement of ram, withdrawing of ram for refill, collecting cut products and measuring their mass, and recording load–displacement data. Subsequent cutting operations were continued with refills and the procedure was conducted until four or five measurements were obtained for each test condition. After the final run, the uncut material was separated and the mass of cut switchgrass retained inside the knife grid was removed and measured. Sum of masses of inputs and cut products of all runs provided total input and cut product, respectively, for the analysis. Experimental runs with refills were not analyzed as replications in the strictest sense. However, the procedure best represented the behavior of a continuous commercial operation, and outliers could be observed. The physical process was similar for all runs and provided another basis to observe any potential irregularities.

2.5. New surface area generated by cutting

New surface area generated by the knife cutting through the material filled to a specified packed bed depth was calculated based on the geometry of packed-circle theory (Weisstein, 2006) (Fig. 3). Although the whole switchgrass was comprised of grass-like leaves and stems, calculations were performed assuming a cylindrical shape since the small narrow leaves readily conformed to the outside diameter of stems. A cross-section of switchgrass internodes was observed as hollow, and corresponded with hollow cylinder geometry previously described (Yu et al., 2006). Number of hollow switchgrass stems arranged parallel in the feed block in a regular cubic packing order was calculated as

$$n = \frac{L}{d_o}\frac{D}{d_o} \tag{1}$$

where n is the number of packed stems; L is the length of the available area or length of the knife (m); D is the depth of the available area or packed bed depth (m); and d_o is the mean outer diameter of the switchgrass stem (m). By comparison, the number of stems n increases by 33% (1.33 n) when the stems are packed in a regular hexagonal packing order compared to a cubic packing order.

The total cross-sectional area of all the hollow cylindrical switchgrass stems using Eq. (1) will be:

$$s = n\frac{\pi}{4}(d_o^2 - d_i^2) \tag{2}$$

where s is the total area of packed stems (m^2); and d_i is the mean inner diameter of switchgrass stems (m). The mean

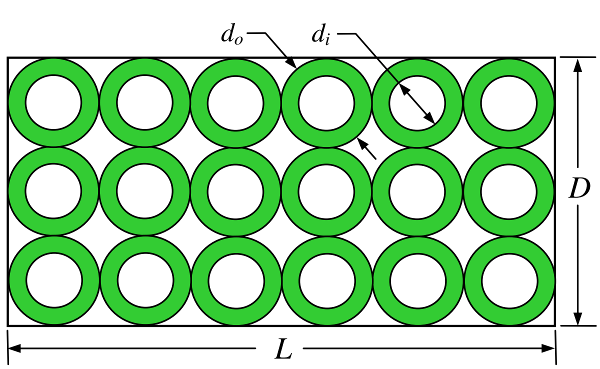

Fig. 3. Regular cubic packing of hollow cylindrical switchgrass inside feed block.

outside and inside diameters were obtained from data reported by Yu (2004). Based on the data for Alamo and Kanlow switchgrass varieties from this author, the mean outside diameter ($n = 863$) was 3.57 ± 0.59 mm while the wall thickness was 0.71 ± 0.18 mm at moisture contents between 17.9 and 35.4%, wet basis. The mean inside diameter was obtained by subtracting the wall thickness from the mean outside diameter. Small deviations in diameter could occur as the switchgrass lost or gained moisture to the levels used in this study.

Packing density indicates the use efficiency of area and is defined as the ratio of the total area occupied by the material and the available area. From Eq. (2) and packed bed geometry (Fig. 3):

$$\sigma = \frac{s}{LD} \tag{3}$$

where σ is packing density (dimensionless). Once the packing density σ was evaluated, the available area was calculated from Eq. (3) easily for other packed bed depth settings. The total new surface area generated by the knife grid while cutting switchgrass at any packed bed depth and knife grid spacing is expressed as

$$A = 2\sigma LDN_k \tag{4}$$

where A is new surface area generated by the knife grid (m^2); and N_k is the number of cutting knives of the knife grid perpendicular to the switchgrass, which varied with the knife grid spacing. The '2' in Eq. (4) represents the two new surface areas produced by a single cut of the knife.

Based on the considered mean outer diameter (3.57 mm), the number of layers of switchgrass for the first fill was evaluated as about 14, 28, and 43 that formed packed bed thicknesses of 50.8, 101.6, and 152.4 mm, respectively, irrespective of variety and moisture content. With the mean dimensions used in Eq. (4), the new surface area varied only with grid spacing and packed bed depths. The dimensionless mean packing density of switchgrass based on the three packed bed depths was 0.4994 ± 0.0002. A theoretical maximum value of 0.9069 was possible in the densest packing scenario (Weisstein, 2006); but hollowness of the switchgrass attributed to the observed smaller value for the switchgrass. Knife grid size reduction generated new surface area ranging from 0.019 to 0.424 m^2, with a mean value of 0.146 m^2.

It should be noted that the above calculation only considers perpendicular cutting across the switchgrass. This is a simplification because in commercial operations with random loading, the potential exists for cutting switchgrass at various angles. Variation from transverse or longitudinal cutting across switchgrass would create elliptical cross-sectional areas.

2.6. Data analysis

Mean and maximum ultimate shear stresses of a given packed bed depth and knife grid spacing were determined

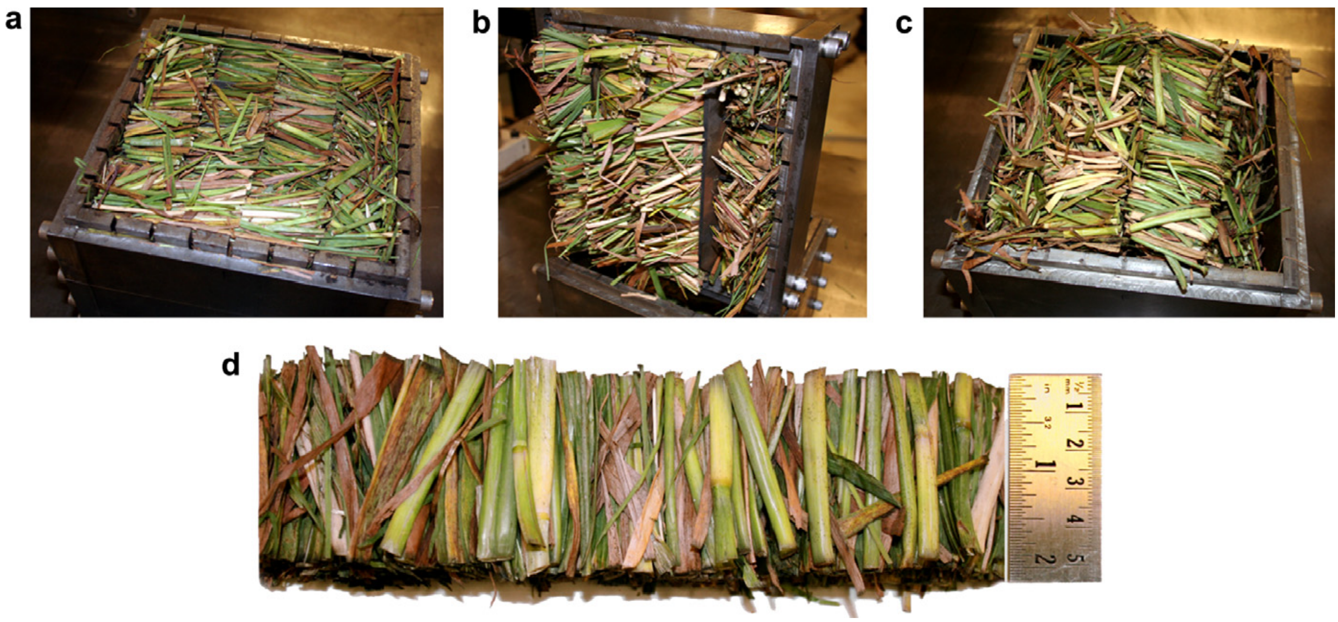

Fig. 4. Switchgrass size reduction at 50.8 mm knife grid spacing (a) top view of cut product embedded in knife grid (b) view from the underside of knife grid (c) cut products collected in product block and (d) cut products showing uniformity in length.

by considering all refill runs. Ultimate shear stresses were determined by dividing the load by the cross-sectional area of cut switchgrass ($A/2$, one-half of new surface area – Eq. (4)). Thus, ultimate shear stress calculations were consistent with those reported by Yu et al. (2006). Mean and maximum ultimate shear stresses and energies were calculated from the multiple refill runs.

Cutting energy was integrated as area under the load–displacement curve. Calculated input energy included material compression, actual switchgrass cutting, and forcing the material through the knife grid – of which all was considered as cutting energy. Cutting energy was expressed in unit mass-basis (MJ/dry Mg) from cut product mass as well as unit new surface area generated (kJ/m^2) basis, and analyzed. Mass-based cutting energy was evaluated as (1) cumulative energy obtained from summing individual refill runs and dividing by product masses, and (2) maximum energy obtained from selecting the maximum energy and dividing by mean product masses of refill runs, of a particular experiment set. SAS macro mixed model analysis of

Table 1
Peak loads of switchgrass size reduction under different experimental settings with linear knife grid device

Moisture condition	Knife grid spacing (mm)	Packed bed depth (mm)	Peak load at refill runs (kN)				
			1	2	3	4	5
High-moisture	25.4	50.8	42.25	58.25	73.31	66.24	77.04
		101.6	72.07	102.04	117.03	142.44[a]	161.18[a]
		152.4	121.37	159.08[a]	162.78[a]	162.25[a]	163.55[a]
	50.8	50.8	13.38	21.46	24.94	28.60	26.23
		101.6	34.54	40.63	45.99	54.03	59.65
		152.4	53.34	74.13	78.76	87.83	–
	101.6	50.8	4.97	5.64	6.09	7.10	7.30
		101.6	6.66	6.89	6.98	7.02	6.95
		152.4	7.72	8.41	8.55	8.92	9.07
Low-moisture	25.4	50.8	23.75	46.64	68.22	68.56	63.15
		101.6	50.11	70.15	84.23	90.88	103.59
		152.4	88.77	85.32	110.99	116.39	131.42
	50.8	50.8	9.69	16.85	17.03	15.76	18.49
		101.6	15.26	17.73	17.95	19.58	–
		152.4	16.50	20.03	19.54	20.12	–
	101.6	50.8	4.07	4.33	4.26	3.64	–
		101.6	4.59	4.00	4.28	3.87	–
		152.4	4.02	4.25	4.63	4.71	–

[a] Above 60% of load cell capacity (133.45 kN).

variance (ANOVA) (Saxton, 2003) with log transformation and Tukey–Kramer ($P < 0.05$) mean separation was used for data analysis.

3. Results and discussion

3.1. Load–displacement characteristics of switchgrass

An example of switchgrass cut products in the knife grid is shown in Fig. 4. Peak loads increased with packed bed depth, and decreased with increase in knife grid spacing (Table 1). High-moisture switchgrass had greater peak loads than low-moisture switchgrass. The 60% load cell capacity limit (133.45 kN) was sometimes exceeded with knife grid spacing of 25.4 mm at depths ⩾101.6 mm (Table 1). Since the test of high-moisture material at 25.4 mm spacing is incomplete due to high loads, conclusions were not drawn on those test conditions.

Typical load–displacement of high- and low-moisture switchgrass showed smooth and initial consolidation (Fig. 5). Chancellor (1958) found that a packed bed of fibrous biomass against a sharp edge had compression prior to shearing. The exponential increase of load towards the point of rupture in Fig. 5 indicated the magnitude of force required to compress the material before initiating the cutting process. Undulations observed in the load–displacement curve, after the initial compression indicates the onset of shear. A momentary drop of loads in the region where cutting occurred was expected due to formation of failure planes, as evidenced by cut product. The peak loads for initial runs were generally observed to be of lower magnitude in comparison to the corresponding peak loads for

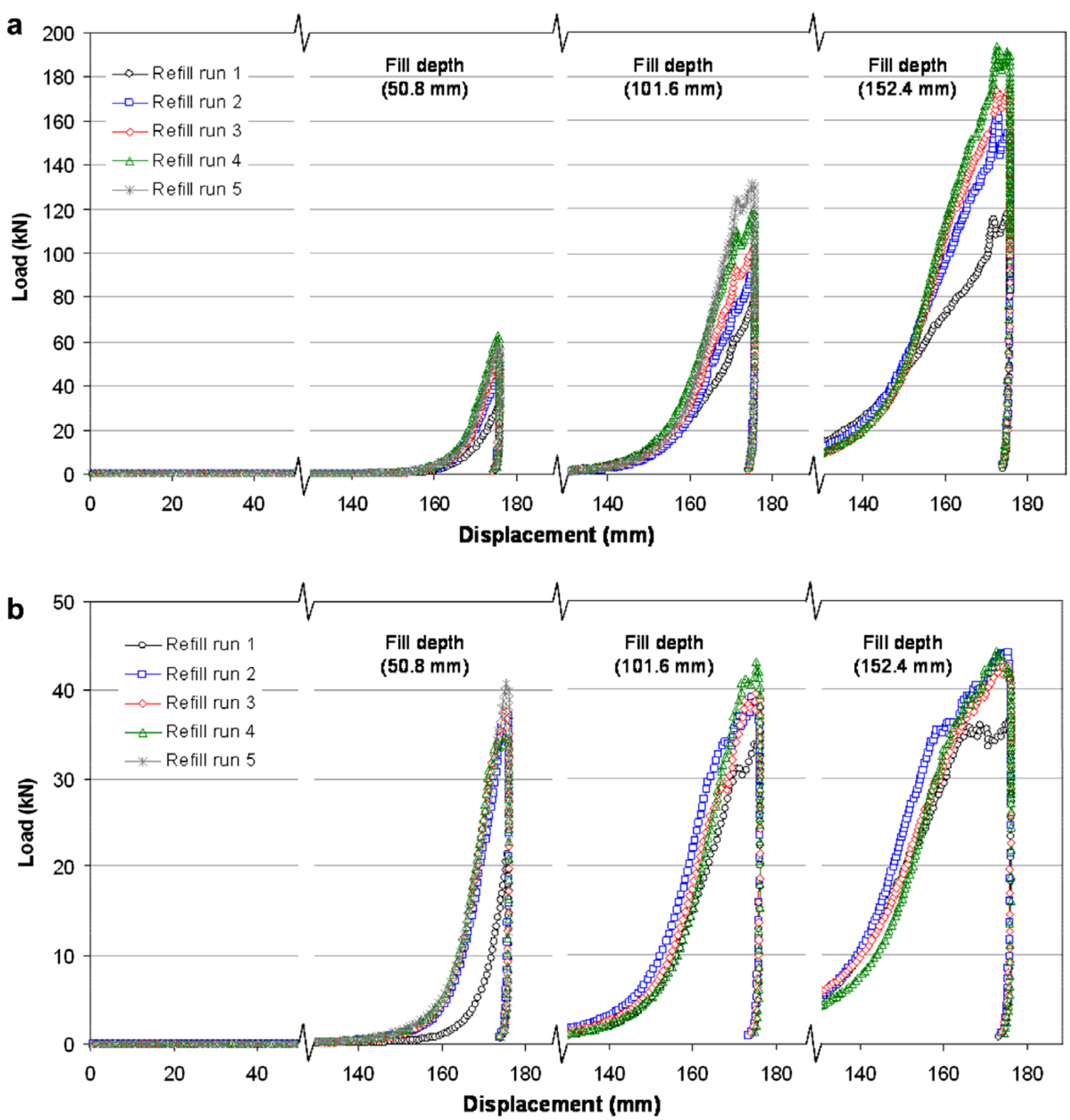

Fig. 5. A typical load–displacement characteristics of (a) high-moisture switchgrass (b) low-moisture switchgrass with a knife grid spacing of 50.8 mm.

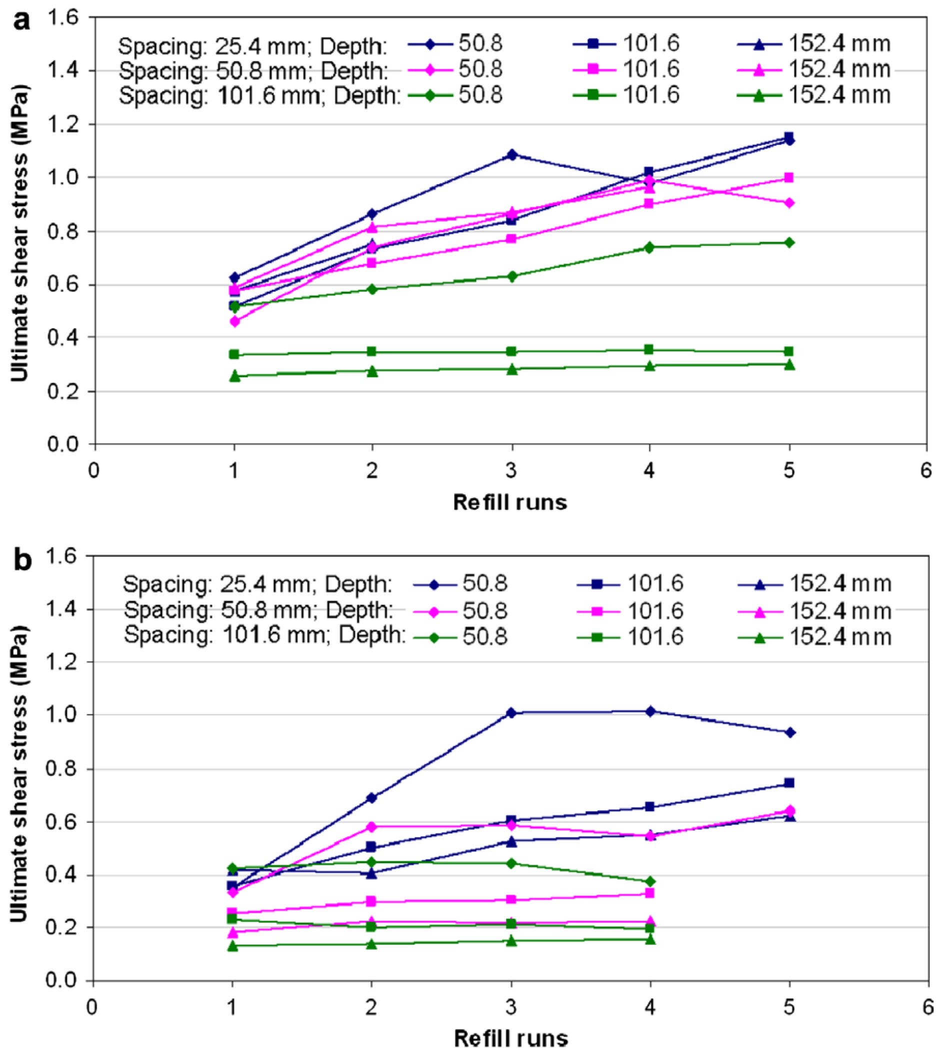

Fig. 6. Ultimate shear stress of individual refill runs for (a) high-moisture and (b) low-moisture switchgrass at various knife grid spacing and packed bed depths.

refill runs. This is because the clean knife grid is free of packed switchgrass and therefore offers less resistance than subsequent runs. Material was retained in the knife grid since the knife blade thickness reduced cross-sectional area.

Convergence of load–displacement curves for refill runs may indicate that subsequent refill during continuous operation would follow a similar trend. Similar trends were observed with the 25.4 and 101.6 mm knife grid spacing (not shown). Variation of peak loads among the packed bed depths was greater for the high-moisture switchgrass than for low-moisture switchgrass.

3.2. Ultimate shear stress and cutting energy of switchgrass refill runs

Ultimate shear stresses of high-moisture and low-moisture switchgrass varied inversely with knife grid spacing (Fig. 6). High-moisture switchgrass results were slightly closer grouped than low-moisture switchgrass. Reduced knife grid spacing increased stresses, because the passage clearances through the knife grid gave increased restriction to flow of material (i.e. knife–blade thickness was greater percentage of cross-sectional path). At a given knife grid spacing, ultimate shear stresses increased as packed bed depth increased.

Cutting energy reduced as grid spacing increased, because of fewer cuts (Fig. 7). Cutting energy was proportional to packed bed depth and was attributed to increased quantity of material, which increased with packed bed depth. Tests with knife grid spacing of 101.6 mm produced cutting energy results that were somewhat constant for both high- and low-moisture switchgrass (Fig. 7).

3.3. Mean and maximum ultimate shear stress of switchgrass

Maximum ultimate shear stresses were about 25% greater than mean stresses (Fig. 8). On average, the mean and maximum ultimate shear stresses were 0.68 ± 0.24 and 0.83 ± 0.34 MPa, for high-moisture switchgrass and 0.41 ± 0.21 and 0.49 ± 0.29 MPa, for low-moisture

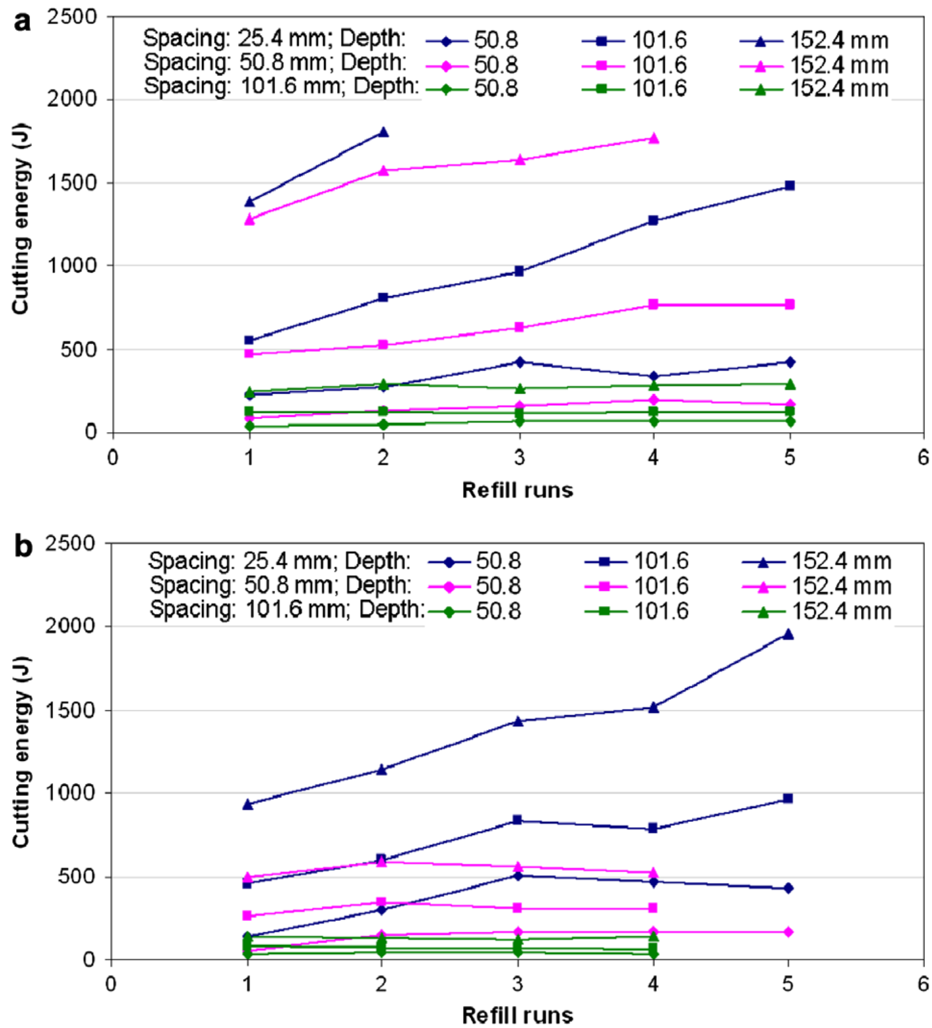

Fig. 7. Cutting energy of individual refill runs for (a) high-moisture and (b) low-moisture switchgrass at various knife grid spacing and packed bed depths.

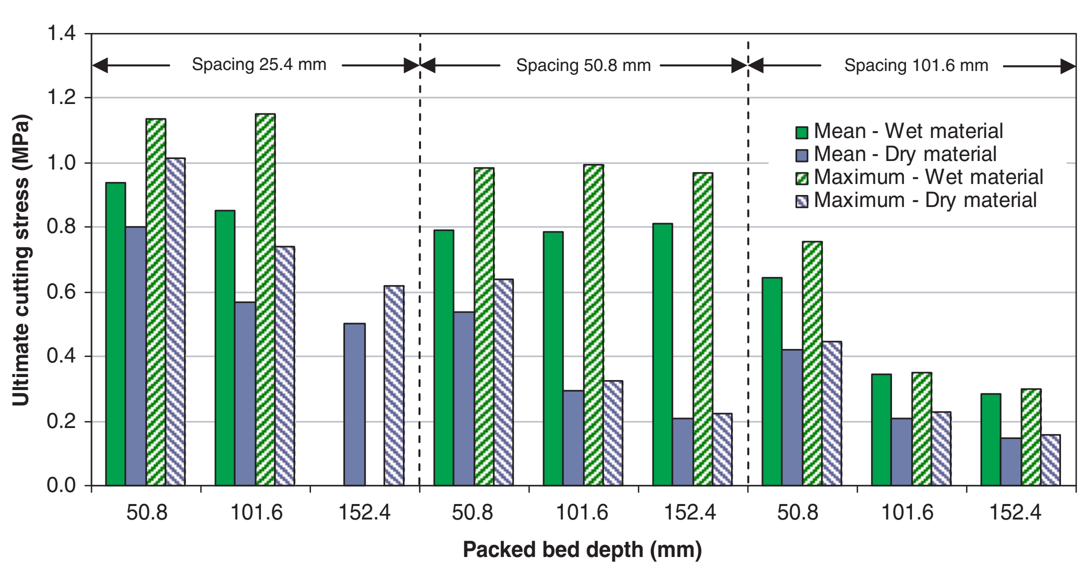

Fig. 8. Overall ultimate shear stress of high- and low-moisture switchgrass at various knife grid spacing and packed bed depths.

switchgrass. These results indicate that high-moisture switchgrass would require a more robust-design, commercial linear knife grid than one for low-moisture switchgrass.

3.4. Mass-basis cutting energy

Cutting energy calculated on a moisture-free mass-basis varied to a greater extent for high-moisture switchgrass compared to low-moisture switchgrass (Fig. 9), over the range of knife grid spacing and packed bed depths. Cutting energy for high- and low-moisture switchgrass, per dry Mg of cut products, reduced with increased knife grid spacing and increased proportional with packed bed depth. High-moisture switchgrass consistently required more cutting energy per unit mass than low-moisture switchgrass. This result contrasts the results by Yu et al. (2006) and Womac et al. (2005) that showed moisture content had little effect on ultimate shear stress on single stems of switchgrass. Results of the knife grid tests were likely affected by the additional complexity of compression prior to entry into the knife grid, and by frictional and compressive forces to move material through the knife grid. Tests by Yu et al. (2006) and Womac et al. (2005) directly applied a cutting edge to switchgrass, whereas tests conducted herein applied force through a packed bed. Packing the bed may have included a consolidation process, not only among switchgrass pieces, but also within a given piece of switchgrass during air and moisture expulsion.

On average, the mean and maximum mass-based cutting energy for high-moisture switchgrass were 4.50 ± 4.43 and

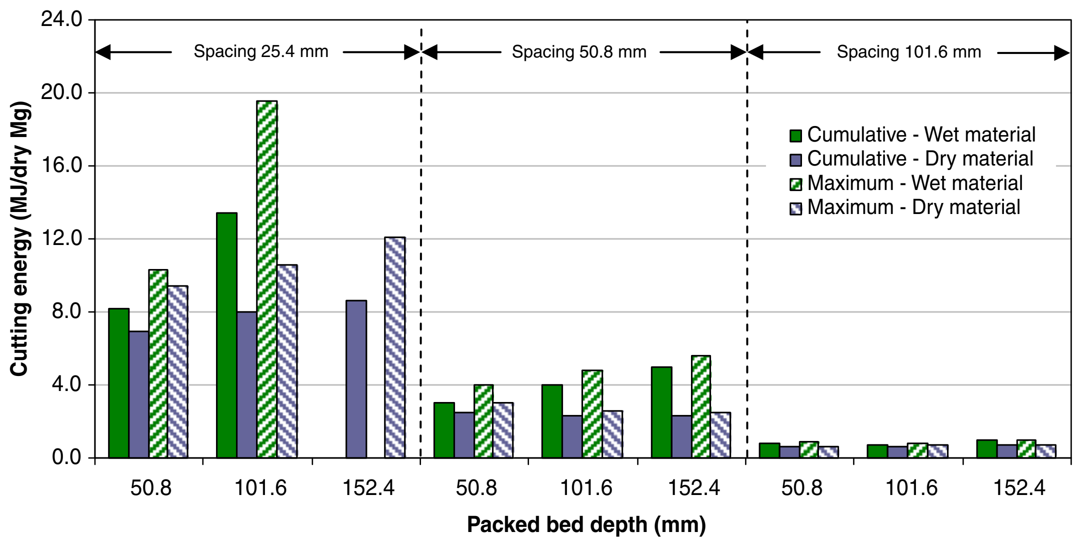

Fig. 9. Overall mass-based cumulative and maximum cutting energies of all refills runs of high- and low-moisture switchgrass at various knife grid spacing and packed bed depths.

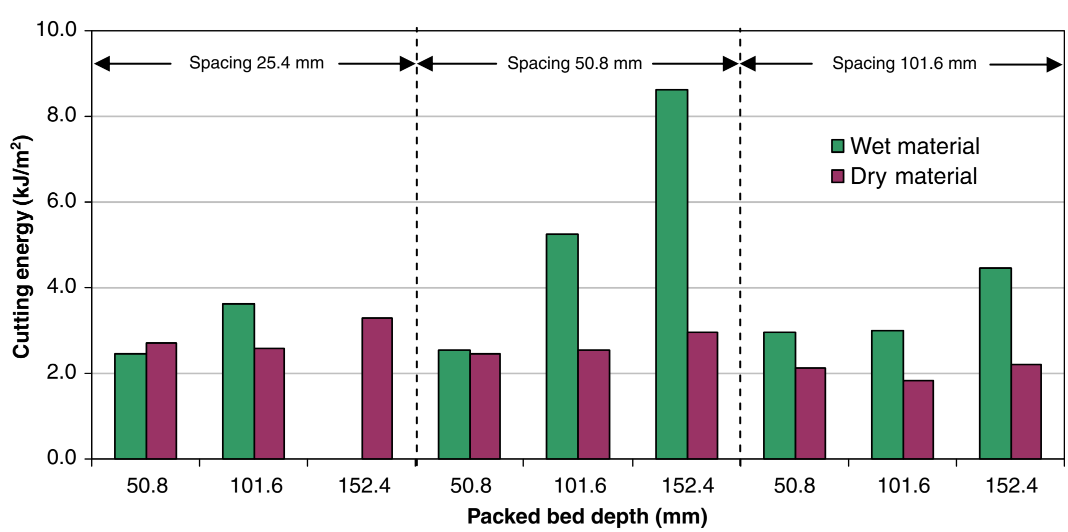

Fig. 10. New surface area-based cutting energy of high- and low-moisture switchgrass at various knife grid spacing and packed bed depths.

5.87 ± 6.41 MJ/dry Mg, and for low-moisture switchgrass were 3.64 ± 3.31 and 4.72 ± 4.64 MJ/dry Mg, respectively. Published results indicate 53.6 MJ/Mg for switchgrass chopped from bales to 25–100 mm size (Jannasch et al., 2005), and 84.6 MJ/Mg using a hammer mill to produce 3.2 mm particles (Mani et al., 2002). The linear knife grid appears to hold promise as an energy–efficient means of size reduction.

3.5. New surface area-basis cutting energy

New surface area-based cutting energy of high- and low-moisture switchgrass increased with increase in packed bed depth (Fig. 10). The high-moisture switchgrass at a knife grid spacing of 50.8 mm showed the largest increase of all test conditions (Fig. 10). The overload condition barring the data use for wet material with the 25.4 mm knife grid spacing was similar to the trend with wet material at a spacing of 50.8 mm. Cutting energy based on new surface area generated was considered specific energy, and the moisture conditions should minimally affect new surface area generated. For a 1 m^2 knife grid device with the studied knife grid spacing of 25.4, 50.8, and 101.6 mm and possible commercial grid spacing of 200, 250, and 400 mm the number of knives (both directions) required will be 76, 38, 18, 8, 6, and 4 with ratio of knife length to grid spacing will be 2992, 748, 177, 40, 24, and 10, respectively. Energy based on new surface area generated and ratio of knife length to grid spacing may serve as good factors to scale up the linear knife grid size for commercial use.

Mean values of cutting energies based on new surface area generated for high- and low-moisture switchgrass were 4.12 ± 2.06 and 2.53 ± 0.45 kJ/m^2, respectively. Womac et al. (2005) reported mean specific cutting energies of 78.0 and 95.2 kJ/m^2 for dry switchgrass, based on single stem cutting using a modified Warner Bratzler shear testing procedure, for knife bevel angles of 30° and 45°, respectively. New areas generated by knife grids at various spacing considered were 2650–59126 times greater than the new area from single stem cutting. The generated surface area was the major source of the difference observed in new area-based energy (kJ/m^2) between the methods, although the actual energy required for cutting switchgrass with knife grid (36–1956 J; Fig. 7) was much greater than that required for single stems (<2.0 J). Energy expended into the packed bed may account for differences. New area-based energy being the ratio of actual energy to new area generated makes the value small for knife grid. Differences may also be attributed to different cutting blade geometries; straight knife edges with knife grid (Fig. 1) and inverted V-shape knife with Warner Bratzler device. These examples illustrate the issues of scaling from a single stem to a packed bed failure, since blade geometry, switchgrass consolidation, and knife grid resistance to flow all affect the relation between cutting single stems and packed beds of switchgrass.

Table 2
Mean separation of linear knife grid operating properties for switchgrass size reduction

Mechanical property	Moisture condition		Knife grid spacing (mm)			Packed bed depth (mm)		
	High	Low	25.4	50.8	101.6	50.8	101.6	152.4
Mean ultimate shear stress (MPa)	0.642 ± 0.076 a	0.358 ± 0.052 b	0.717 ± 0.101 a	0.505 ± 0.076 a	0.305 ± 0.059 b	0.665 ± 0.087 a	0.448 ± 0.072 ab	0.371 ± 0.073 b
Maximum ultimate shear stress (MPa)	0.768 ± 0.093 a	0.412 ± 0.063 b	0.911 ± 0.128 a	0.594 ± 0.093 a	0.329 ± 0.069 b	0.791 ± 0.107 a	0.531 ± 0.088 ab	0.427 ± 0.087 b
Cumulative cutting energy–mass based (MJ/dry Mg)	3.283 ± 0.173 a	2.268 ± 0.133 b	9.338 ± 0.371 a	3.035 ± 0.187 b	0.716 ± 0.090 c	2.398 ± 0.169 b	2.768 ± 0.180 ab	1.742 ± 0.212 a
Maximum cutting energy–mass based (MJ/dry Mg)	3.989 ± 0.245 a	2.711 ± 0.187 b	12.632 ± 0.554 a	3.575 ± 0.263 b	0.788 ± 0.122 c	2.988 ± 0.241 a	3.323 ± 0.256 a	3.582 ± 0.295 a
Mean cutting energy based on new surface (kJ/m^2)	3.910 ± 0.174 a	2.494 ± 0.129 b	3.204 ± 0.200 a	3.591 ± 0.189 a	2.646 ± 0.162 a	2.535 ± 0.159 b	2.975 ± 0.172 ab	4.037 ± 0.224 a

Data represent mean estimate of property ± standard deviation and mean separation letter group (SAS macro %manova (Saxton, 2003) with log transformation and Tukey–Kramer ($P < 0.05$). Different letters within a mechanical property represent a significant difference.

3.6. Mean separation analysis

Mean and maximum ultimate shear stresses, mass-basis cutting energy, and new surface area-basis cutting energy of high-moisture switchgrass were significantly ($P < 0.05$) greater than those for low-moisture switchgrass (Table 2). Knife grid spacing caused significant differences in all properties, except mean cutting energy based on new surface area. Material packed bed depth caused significant differences in all properties except maximum cutting energy based on cut products.

4. Conclusions

Tests of a linear knife grid with switchgrass quantified the combined effect of shearing stresses, packed bed consolidation, and frictional resistance to flow through a knife grid. A minimum knife grid spacing of 25.4 mm appears to be a practical lower limit, considering the high ram force that would be needed for commercial operation. However, knife grid spacing from 50 to 100 mm and greater may offer an efficient first-stage size reduction, especially well suited for packaged (baled) biomass. Future tests should consider operating effects of a commercial-scale linear knife grid.

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References

Arthur, J.F., Kepner, R.A., Dobie, J.B., Miller, G.E., Parsons, P.S., 1982. Tub grinder performance with crop and forest residues. Transactions of ASAE 25, 94–1488.

ASAE standards, 2003. Moisture measurement–forages ASAE S358. In: ASAE Standards 2003. American Society of Agricultural Engineers, St. Joseph, Michigan, 2 February 03, p. 595.

Chancellor, W.J., 1958. Energy requirement for cutting forage. Agricultural Engineering 39, 633–636.

Chen, Y., Gratton, J.L., Liu, J., 2004. Power requirements of hemp cutting and conditioning. Biosystems Engineering 87, 417–424.

Dowgiallo, A., 2005. Cutting force of fibrous materials. Journal of Food Engineering 66, 57–61.

Drzymala, Z., 1993. Industrial briquetting-fundamentals and methods. Studies in mechanical engineering, vol. 13. Warszawa: PWN-Polish Scientific Publishers.

El Hag, H.E., Kunze, O.R., Wilkes, L.H., 1971. Influence of moisture, dry-matter density and rate of loading on ultimate strength of cotton stalks. Transactions of the ASAE 13, 713–716.

Kumar, A., Sokhansanj, S., 2007. Switchgrass (*Panicum vigratum* L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Bioresource Technology 98, 1033–1044.

Jannasch, R.Y., Quan, Samson, R., 2005. A process and energy analysis of pelletizing switchgrass. Resource Efficient Agricultural Production (REAP-Canada). <www.reapcanada.com> (Accessed November 2005).

Lopo, P., 2002. The right grinding solution for you: roll, horizontal or vertical. Feed Management 53, 6–23.

Mani, S., Tabil, L.G., Sokhansanj, S., 2002. Grinding performance and physical properties of selected biomass. ASAE Paper No. 026175. St. Joseph, Michigan: ASABE.

Mani, S., Lope, L.G., Tabil, G., Sokhansanj, S., 2004. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass and Bioenergy 27, 339–352.

McLaughlin, S.B., 1993. New switchgrass biofuels research program for the southeast. In: Proceeding 1992, Annual Automotive Technol. Dev. Contractor's Coordinating Meeting, 2–5 November 1992, Dearborn, MI, pp. 111–115.

McLaughlin, S.B., Kszos, L.A., 2005. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass and Bioenergy 28, 515–535.

Mesquita, C.M., Hanna, M.A., 1995. Physical and mechanical properties of soybean crops. Transactions of the ASAE 38, 1655–1658.

Mohsenin, N., 1986. Physical Properties of Plant and Animal Materials. Gordon and Breach publishers Inc., Amsterdam, The Netherlands.

Prasad, J., Gupta, C.P., 1975. Mechanical properties of maize stalk as related to harvesting. Journal of Agricultural Engineering Research 20, 79–87.

Prince, R.P., Bartok Jr., J.W., Bradway, D.W., 1969. Shear stress and modulus of elasticity of selected forages. Transactions of the ASAE 12, 426–429.

Sanderson, M.A., Reed, R.L., McLaughlin, S.B., Wullschleger, S.D., Conger, B.V., Parrish, D.J., Wolf, D.D., Taliaferro, C., Hopkins, A.A., Ocumpaugh, W.R., Hussey, M.A., Read, J.C., Tischler, C.R., 1996. Switchgrass as a sustainable bioenergy crop. Bioresource Technology 56, 83–93.

Saxton, A.M., 2003. Mixed Model ANOVA Analysis Macro. University of Tennessee, Knoxville, TN, 4574–37996.

Schell, D.J., Harwood, C., 1994. Milling of lignocellulosic biomass: results of pilot-scale testing. Applied Biochemistry and Biotechnology 45/46, 68–159.

Weisstein, E.W., 2006. Circle packing. In MathWorld. Champaign, Ill.: Wolfram Research, Inc. <http://mathworld.wolfram.com/CirclePacking.html> (Accessed November 2006).

Womac, A.R., Yu, M., Igathinathane, C., Ye, P., Hayes, D., Narayan, S., Sokhansanj, S., Wright, L., 2005. Shearing characteristics of biomass for size seduction. ASAE Paper No. 056058. St. Joseph, Michigan: ASABE.

Yu, M., Womac, A.R., Pordesimo, L.O., 2003. Review of biomass size reduction technology. ASAE Paper No. 036077. St. Joseph, Michigan: ASABE.

Yu, M., 2004. Ultimate strength characteristics of switchgrass stem cross-sections at representative processing conditions. Unpublished Masters Thesis, Department of Biosystems Engineering and Soil Science, The University of Tennessee, Knoxville.

Yu, M., Womac, A.R., Igathinathane, C., Ayers, P.D., Buschermohle, M.J., 2006. Switchgrass ultimate stresses at typical biomass conditions available for processing. Biomass and Bioenergy 30, 214–219.