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Assessing the specific energy consumption and physical properties of comminuted Douglas-fir chips for bioconversion

Yalan Liu[a,*], Jinwu Wang[b], Michael P. Wolcott[a]

[a] Composite Materials & Engineering Center, Washington State University, Pullman, WA 99164-1806, United States
[b] United State Department of Agriculture, Forest Service, Forest Products Laboratory, 35 Flagstaff Road, Orono, ME 04469-5793, United States

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ABSTRACT

Size reduction homogenizes the bulk biomass and facilitates downstream feedstock handling, transportation, and storage. Effects of feeding rate, mill-type (hammer and knife mill), screen size, and moisture content on comminution energy consumption of commercial Douglas-fir (*Pseudotsuga menziesii*) pulp chips were quantified. The resulting particles were characterized by geometric mean diameter, size distribution, aspect ratio and bulk density. We also employed scanning electron microscopy (SEM) to visualize the dominant fracture surface features. A linear regression was used to describe the relationship between specific energy consumption (SEC) and comminution ratio, which can be used for estimating SEC of various particle sizes of feedstock. Results demonstrated that with a screen size of 3.18 mm, the hammer mill consumed 141 kJ kg^{-1}, while the knife mill consumed 345 kJ kg^{-1}. Selecting the feeding rate, which allows the machine reach its rated power, can result in lowest total SEC. SEC also increased substantially with an increase in moisture content from 11% to 17% (fraction in total mass basis). Analysis of the particle morphology revealed that the dominant fracture mechanism was across lumen for hammer milling and along middle lamella for knife milling.

1. Introduction

Commercial operations for producing second-generation biofuels and bioproducts are currently focused on using lignocellulosic biomass for both biochemical and thermochemical conversion (Anex et al., 2010; Brown et al., 2013; Weimer, 2008). All processes, regardless of feedstock type, require comminution to convert the raw biomass into a feedstock suitable for industrial use (Bitra et al., 2009; Dukes et al., 2013; Tumuluru et al., 2014). To maximize usable net energy or energy return on investment of the resulting fuel (Gingerich and Hendrickson, 1993), a primary goal of any comminution system must be to minimize the energy that is expended in the process. In addition, processing systems should be designed to engineer biomass into feedstock particles to benefit downstream industrial processes for materials handling and treatment efficacy.

1.1. Particle morphology and performance

The particle size of the feedstock is one key parameter for successful gasification (McKendry, 2002). Utilizing small particle sizes increases gas yield and energy efficiency due to the large surface area and fast rate of heat transfer (Kumar et al., 2009). In biochemical processing, reducing the size of the feedstock improves overall conversion rate up to 50% by influencing biomass digestibility (Vidal et al., 2011), while total conversion of enzymatic hydrolysis increases as particle size decreases (Khullar et al., 2013).

Bulk density is an important factor for influencing transportation and storage costs and is highly dependent on particle size, size distribution, aspect ratio, and moisture content. Size reduction can increase the bulk density and particle surface area of the feedstock (Chevanan et al., 2010; Ghorbani et al., 2012; Miao et al., 2011). Kronbergs et al. (2012) found a nonlinear relationship between feedstock bulk density and screen size for hammer milling. Bulk density of the resulting feedstock was found to decrease as the opening diameter of the screen increased. Similarly, other researchers reported a power-law relationship between bulk density and the geometric mean diameter of the particle (Adapa et al., 2011; Lam et al., 2008). Bulk density has been found to increase with decreasing aspect ratio of wood particles (Gozdecki et al., 2011). But a high particle aspect ratio is favorable for particle ignition because oxygen can be easily transferred to the ignition point (Gera et al., 2002).

Particle morphology influences the conversion process through the resulting surface chemistry and surface area. By using different

* Corresponding author.
E-mail address: yalan.liu@wsu.edu (Y. Liu).

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refining techniques, the exposed fracture surface has been found to possess various compositions of lignin, cellulose and hemicellulose (Zhu, 2011).

1.2. Assessing energy consumption in processing

Although size reduction improves feedstock uniformity and downstream conversion efficacy, it is an energy-intensive process. The energy consumption is commonly expressed as specific energy consumption (SEC), i.e. electrical or mechanical energy consumed per unit of mass. The total SEC can be computed by integrating the area under the power consumption curve with respect to time. This data is typically collected using a wattmeter and normalized to the total consumed energy using the mass of processed material. In turn, the net SEC is obtained by subtracting the idle energy consumption from total SEC (Mani et al., 2004; Repellin et al., 2010).

The measured SEC depends on many variables, including material characteristics (species, moisture content, feedstock original size, etc.), grinding mechanism, equipment design, and operational parameters (feeding rate). Specifically, the feedstock composition and grinding mechanism influence the SEC through both physical properties and fracture modes. For instance, the grinding energy of beech (*Fagus* spp.) was found to be 3060 kJ kg^{-1}, which is higher than spruce (*Picea* spp.) of 2700 kJ kg^{-1} at a given screen size 0.5 mm (Repellin et al., 2010). Energy consumption has been found to be strongly affected by moisture content, because the moisture of the cell wall significantly influences the toughness property and shear strength of the biomass (Annoussamy et al., 2000; Glass and Zelinka, 2010). When moisture content increases from 7 to 9% to 11–13% (fraction in total mass basis), the SEC of both hammer mill and knife mill increased (Mani et al., 2004; Miao et al., 2011).

Processing method also has a strong influence on SEC. Schell and Harwood (1994) reported that a disk mill consumed five times more energy than a hammer mill and produced particles with a larger size distribution. In addition, the energy consumption of a knife mill was found to be 2–3 times higher than that of a hammer mill with the same screen size (1 mm and 2 mm) and the same feedstock when milling grasses (miscanthus and switchgrass). Knife-milled grindings also resulted in higher bulk density at the same screen size (Miao et al., 2011).

In addition, screen size used to classify material on these milling machines influence the resulting particle sizes and therefore, the required energy consumption. The electric energy required to produce poplar and aspen particles of 0.85 mm in length is over five times higher than that for producing 2 mm long particles (Holtzapple et al., 1989). Many studies showed that high energy was required for fine grinding of both hard wood chips and agricultural biomass materials (Datta, 1981; Fang et al., 1997; Himmel et al., 1985; Mani et al., 2004; Martin and Behnke, 1984). Other studies demonstrated that the energy consumption of knife milling decreased as screen size increases (Mani et al., 2004; Zhang et al., 2012). In addition, SEC of a forage chopper and a hammer mill could be represented using a power-law relationship with screen size (Adapa et al., 2011). Energy consumption also varies with operational parameters e.g. rotating speed and feeding rate, due to its influence on equipment efficiency. Total SEC has been found to decrease with a second-order polynomial function as feeding rate increases (Bitra et al., 2009).

While delineating energy requirements and product attributes for comminution processes for biomass, the specific objectives of this study are to investigate the:

1. Effects of feeding rate, mill type, screen size and moisture content on SEC of the comminution process for softwood chips, specifically Douglas-fir (*Pseudotsuga menziesii)*.
2. The relation between SEC and physical properties (geometric mean diameter, aspect ratio and bulk density) and fracture surface morphology of the resulted grindings.

2. Material and methods

2.1. Wood chip preparation

Douglas-fir pulp chips were acquired from Vaagen Brothers Lumber Inc. located at Colville, Washington, in November 2012. The trees were about 80 years old and harvested from west of the Cascade Crest to the Pacific Ocean area. The lumber was chipped into pulp chips at a green state. The initial moisture content of chips was 51% (fraction in total mass basis). The received chips were screened into three portions over a gyratory screen (Model 580, Serial 4095-76, Black Clawson, Everett, WA), with the accepted chips passing a 25.4 mm top deck and retained on a 4.75 mm bottom deck. The accepted chips were air dried at ambient temperature to a moisture content of approximately 13% and subsequently stored in environmental moisture conditioner room (at a moisture level of 11%) before use.

2.2. Specific energy consumption of comminution

Chips were ground with a hammer mill (Prater, 14.9 kW) using one of five screen sizes (11.11, 6.35, 3.18, 1.59 and 0.79 mm) and a knife mill (Nelmor, 3.7 kW) with one of four screen sizes (9.53, 6.35, 4.76 and 3.18 mm). A 5 kg sample of Douglas-fir chips was manually fed into the hammer mill at a predetermined feed rate, and each test was performed in triplicate. In comparison to the hammer mill, the knife mill required a lower feeding rate to achieve the rated power consumption. Therefore, a 2 kg material sample was adopted. The test order was randomized to eliminate the confounding effects of screen size and potential knife wear.

A Fluke 1735 Power Logger (Fluke Corporation, Everett, WA) was used to measure the electrical energy consumption of the hammer mill and knife mill and recorded as the realized power (i.e., the active power used by the motor) during the grinding process. An additional minute of data was collected before and after the grinding process to establish a machine baseline for net power consumption calculations. The total SEC was obtained by integrating the area under the power demand curve for the grinding time and dividing by the total oven-dried mass of wood that was ground in the session. Net SEC consumption was calculated by the following equation (Mani et al., 2004; Repellin et al., 2010).

$$Net\ \ SEC = \frac{Total\ \ energy - Idle\ energy}{(sample\ \ mass)\,/\,(1 + MC)} \tag{1}$$

2.3. Chip and particle characterization

2.3.1. Particle size and distribution

After milling, the resulting particles were sieved with a Ro-Tap Shaker (The W. S. Tyler Company, Cleveland, Ohio) for 10 min to analyze the size distribution and geometric mean diameter following ASAE Standard S319.4 FEB (2008). The geometric mean diameter (X_{gw}) and standard deviation (S_{gw}) were then calculated.

2.3.2. Moisture content measurement

The moisture content of the Douglas-fir wood chips and resulted grindings was determined according to ASAE Standard S358.2 FEB03 (2006) for five replicate samples and expressed as a fraction in total mass. Three initial moisture content values were selected for the energy consumption comparison: 13%, 17%, and 23%. To achieve these levels, the air-dried chips were rehydrated to 17% and 23% levels by evenly spraying water on the chips and subsequently storage in plastic bags for one week to allow equilibration. Before grinding, the moisture content of wood chips was confirmed to be 16.5% and 23.2%. A 6.35 mm screen was used to examine the influence of moisture content on the SEC of hammer and knife milling.

2.3.3. Aspect ratio

The aspect ratio of the ground wood particles was measured through image analysis of optical micrographs. Wood particles were placed on a black background platform and digital images were acquired through a stereomicroscope (Wild M-4A with Fluorescent Ring Light). Images of particles form each sieve were assessed with a digital image analysis software (Rasband, W.S., Image J, U. S. National Institutes of Health, Bethesda, Maryland, USA, 1997–2014) and expressed as the weighted average aspect ratio according to size distribution results.

2.3.4. Bulk density

Bulk density of hammer-and knife-milled grindings was determined in accordance with ASTM E873-82 DEC (2006) using a 7079 cm^3 wooden cubic container. The difference between the filled and empty mass of the container was used to compute the bulk density using the following equation:

$$\text{Bulk density (BD)} = \frac{(\text{Mass of container and sample}) - (\text{Mass of container})}{(\text{Volume of container})(1 + MC)} \quad (2)$$

Bulk density was corrected to the oven-dried mass. This measurement has been repeated five times to obtain the reported mean value and standard deviation.

2.3.5. Morphology

Images of fracture surface were obtained through SEM (FEI Quanta 200F, field emission gun, high vacuum, ETD detectors, FEI Company, Hillsboro, Oregon, USA) after sputter coating with gold.

3. Results and discussion

3.1. Geometric mean diameter and size distribution

Table 1 presents the moisture content, geometric mean diameter and bulk density of the resulting grindings. The geometric mean diameter of wood chips prior to grinding were 10.36 mm. For a given screen size, the hammer mill produced finer grindings than knife mill. This finding is supported by comparing the cumulative frequency distributions of the particles produced with each process for a 6.35 mm and 3.18 mm screen (Fig. 1(a)).

3.2. Bulk density

The grinding process increased the bulk density of the resulting particles. The inverse relationship of bulk density and geometric mean diameter of the particles fits a power-law function for both hammer mill and knife mill particles (Fig. 1(b)). Similarly, a power-law relationship was reported by Lam et al. (2008) for scissor cutting particles of wheat straw and switchgrass biomass. Since the hammer mill produced finer particles than the knife mill at a given screen size, these smaller particle sizes should display a higher bulk density at similar conditions (Chevanan et al., 2010; Ghorbani et al., 2012; Miao et al., 2011). However, the knife-milled grindings resulted in consistently higher bulk densities than those from the hammer mill at the same screen size. This discrepancy was also noted by Miao et al. (2011) for hammer and knife milled energy crop (miscanthus and switchgrass) particles.

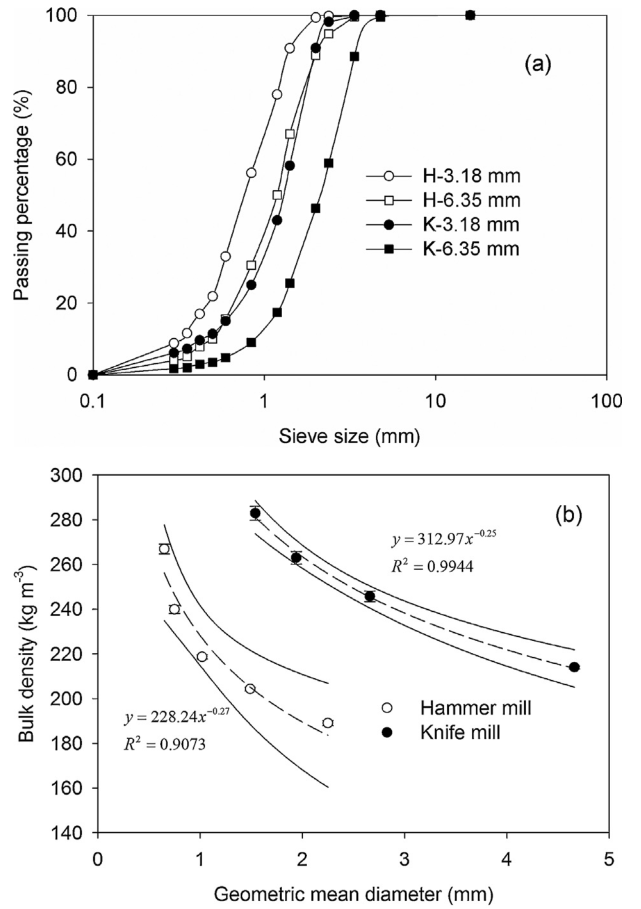

Fig. 1. (a) Cumulative distribution of hammer-milled (H) and knife-milled (K) grindings at 6.35 and 3.18 mm screen; (b) Bulk density transformation of resulting particles along with geometric mean diameter.

3.3. Aspect ratio

In addition to geometric mean diameter, particle shape also contributes to differences in bulk density. The aspect ratio was determined for the 6.35 mm screen grindings for both hammer and knife milled material was completed following the sieve analysis. The weighted average was used to distinguish the difference between two mill types at the same screen size:

$$\textit{Weighted average Aspect ratio} = \frac{\sum_{i=1}^{n} \text{Aspect ratio}_i * Mass_i}{\sum_{i=1}^{n} Mass_i} \quad (3)$$

The grindings from hammer mill possessed a higher average aspect ratio of 5.56 than 4.55 of the knife mill, which likely contributed to the decreased bulk density observed in this study (Gozdecki et al., 2011). Others have found that larger aspect ratio particles bridge, resulting in increased voids and decreased bulk density during packing (Mahdavi et al., 2010). The hammer mill uses impact and shearing actions during milling, while the knife mill mainly produces cutting and impact forces. The cutting action tended to shorten fiber length, resulting in a smaller aspect ratio.

3.4. Specific energy consumption

Many variables (feeding rate, screen size, milling type, and moisture content of feedstock,) have been found to affect SEC (Miao et al., 2011; Womac et al., 2007). Feeding rate influences SEC through affecting motor efficiency. Decreasing of screen size increased SEC dramatically and different grinding mechanisms may resulted in

Table 1
Geometric mean diameter and bulk density of grindings of hammer mill and knife mill.

Mill type	Hammer mill					Knife mill			
Screen size (mm)	11.11	6.35	3.18	1.59	0.79	9.53	6.35	4.76	3.18
Moisture content (%)	12.7	12.2	12.4	11.3	8.1	12.3	11.6	10.9	9.0
X_{gm}[a] (mm)	2.25	1.49	1.02	0.84	0.65	4.66	2.66	1.94	1.54
S_{gm}[b] (mm)	1.88	1.81	1.78	1.75	1.83	1.77	1.83	1.76	1.86
Bulk density (kg m^{-3})	189	204	218	240	267	214	246	263	283
Optimal feeding rate (kg min^{-1})	8.7	7.1	3.9	3.3	2.3	5.7	3.0	2.3	1.1
Total SEC (kJ kg^{-1})	113	194	310	524	734	138	303	370	1050
Net SEC (kJ kg^{-1})	59	95	141	223	328	70	153	205	345

[a] Geometric mean diameter.
[b] Standard deviation.

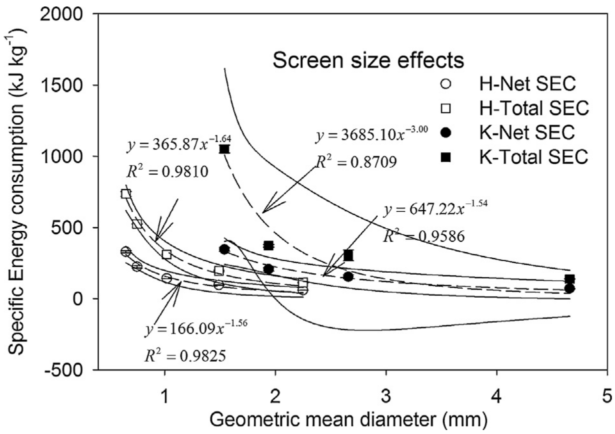

Fig. 2. Specific Energy Consumption of hammer mill and knife mill with an increase in geometric mean diameter.

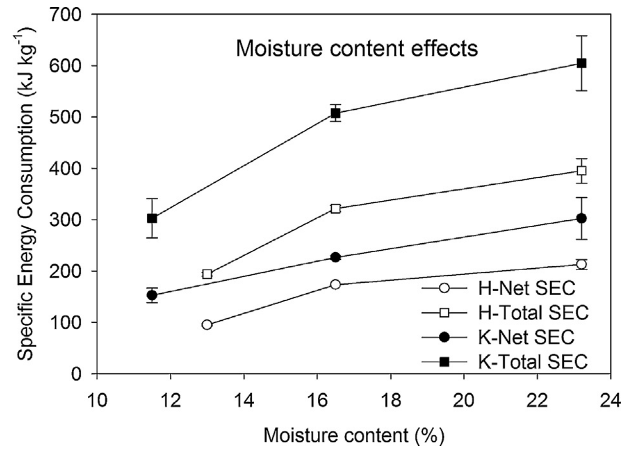

Fig. 3. Moisture content effects on Specific Energy Consumption of hammer mill and knife mill fitting with 6.35 mm screen.

various difference in SEC. Additionally, increasing of moisture content may increase SEC due to moisture bonding in wood cell wall structure.

3.4.1. *Feeding rate effect*

The feeding rate influenced specific energy consumption due to varying motor efficiencies with different loadings. Four feeding rates were selected for each screen according to preliminary test results. Table 2 demonstrates the SEC of the hammer and knife mills fitting with a 6.35 mm screens. The net SEC increased as feeding rate increased, while the total specific energy achieves a minimum at a feeding rate that had the motor approximately reached its rated full-load capacity. This trend was prominent for the hammer mill than the knife mill. In addition, total SEC began to decrease when operated maximum power of knife mill reached around 70% of its rated power, and then increased along with an increase of operated power.

3.4.2. *Screen size and milling type effect*

A power law fitting between SEC and the geometric mean diameter is showed in Fig. 2. The power-law function between SEC and the geometric mean diameter of resulting particles suggests that the target particle size must be carefully determined to achieve a compromise between energy cost and size reduction. In addition, a hammer mill consumes less specific energy to comminute wood particles than the knife mill to result in a given size. For example, the hammer mill consumes 194 kJ kg^{-1} compared to 303 kJ kg^{-1} of knife mill to produce particles with a geometric mean diameter of 1.49 mm and 2.66 mm, respectively. This observation for the softwood materials examined here, is consistent with the findings of Miao et al. (2011) for energy crops. Furthermore, the percent of idle specific energy in total energy of the knife mill is higher than that of hammer mill. Therefore, it is safe to conclude that the hammer mill is more energy-efficient than the knife mill.

3.4.3. *Knife dulling effect*

The cumulative consumed time of knife for each set of experiments had been recorded. It had been employed as a variate to evaluate its influence on SEC. Multivariate analysis of variance showed that time of knife uses in these experiments did not significantly affect SEC ($\alpha = 0.05$). The variability of SEC with knife use at the same screen size was further examined to be less than 5%. The knife blades had been used for about 16 h in total for this set of experiments. Therefore, the blade condition have not changed significantly.

3.4.4. *Moisture content effect*

For to hammer mill, the net and total SEC increased by 83% and 66%, respectively, when the moisture content increased from 13 to 16.5%. But when further increasing the moisture content from 16.5 to 23.2%, both SEC values increased by only an additional 23% (Fig. 3). For the knife mill, the net and total SEC increased by 48% and 68%, respectively as moisture content increased from 11.5 to 16.5%. When moisture content was further increased from 17 to 23%, the increases of net and total SEC were only an additional 34% and 19%. Below the fiber saturation point (22–23% for most wood species), free water, i.e. liquid water filling the cell lumens, is eliminated and only bound water adsorbed on the cell wall polymers exists. Consequently, it is the bound water that might contribute to the large energy increases found between 13–17%, whereas free water contributes less energy consumption. This finding is consistent with the dependence of mechanical properties of wood on moisture content (Glass and Zelinka, 2010).

Table 2
Specific Energy Consumption of hammer mill and knife mill fitting at 6.35 mm screen with an increase in feeding rate.

Hammer mill				Knife mill			
Feeding rate ($kg\ min^{-1}$)	Maximum power (kW)	Net SEC ($kJ\ kg^{-1}$)	Total SEC ($kJ\ kg^{-1}$)	Feeding rate ($kg\ min^{-1}$)	Maximum power (kW)	Net SEC ($kJ\ kg^{-1}$)	Total SEC ($kJ\ kg^{-1}$)
4.7	10.5	87	219	1.3	1.6	156	313
6.0	12.4	93	208	3.0	2.4	153	303
7.1	14.5	95	195	6.9	3.3	162	311
8.8	18.6	104	205	11.6	3.5	154	324

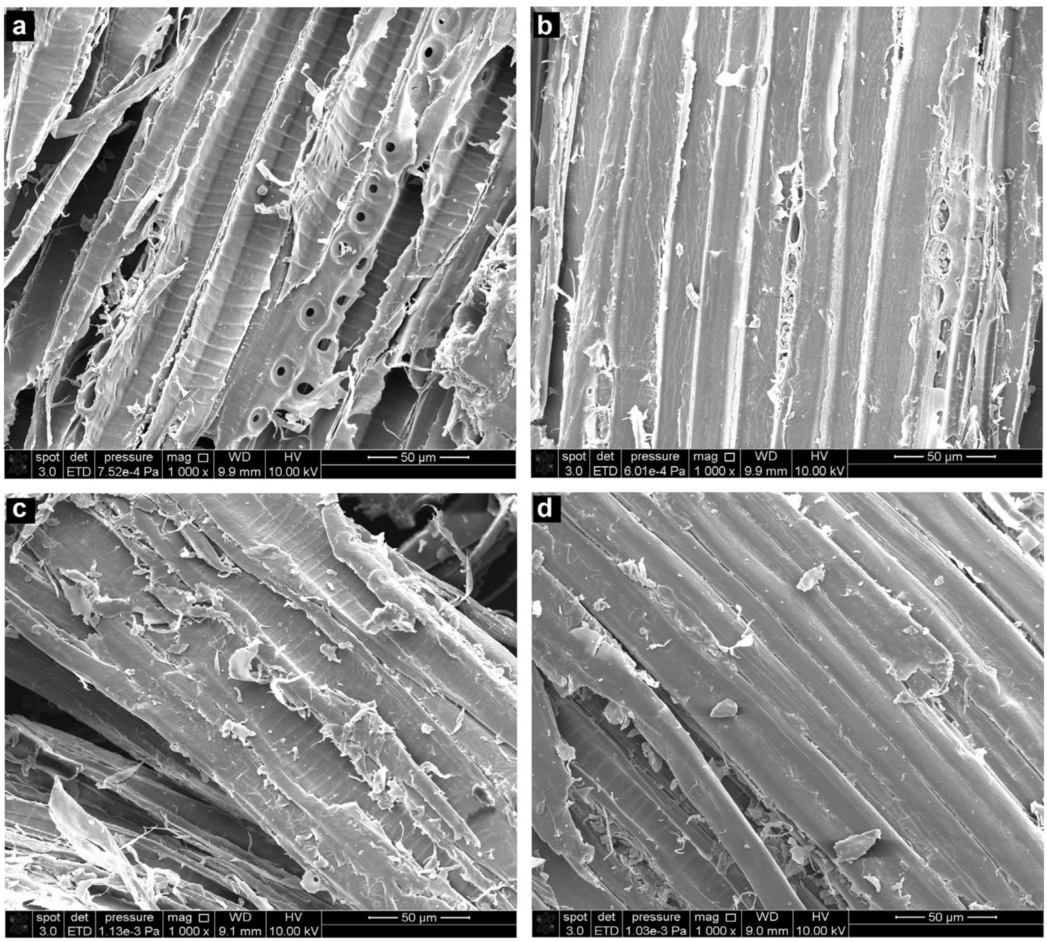

Fig. 4. SEM images of (a), (b): hammer mill grinds; (c), (d): knife mill grinds.

3.5. Morphology of grindings

Fig. 4 presents SEM images of grindings from hammer and knife mills. The fracture surfaces shown in Fig. 4(a) and (c) represent earlywood, as evidenced by the obvious presence of the spiral thickenings. In contrast, those cells shown in Fig. 4(b) and (d) were more likely latewood. The earlywood section of resulted grindings both have fracture modes across the lumen as shown in Fig. 4(a) and (c). However, in the latewood region, the fracture mode along the middle lamella became dominant in knife-milled grindings, while fracture through lumen is dominant in both the earlywood and latewood of the hammer-milled grindings.

3.6. Discussion

The physical characteristics of grindings were correlated with SEC based on specific operating conditions. In order to comprehensively understand the relationship, we compared our results with those of other published studies investigating size reduction of woody material (Fig. 5). Whereas all of the data generally fits a power law relationship between SEC and geometric mean diameters, the variability of SEC between the published results appear high. These differences are due to different raw material conditions such as moisture content and initial feedstock size.

To normalize the effect of initial size on SEC, comminution ratio (CR), first introduced by Cadoche and Lopez (1989), was defined as the ratio between the initial and final particle size. We computed CR as the ratio of initial and final geometric mean diameter of wood particles. A good linear regression between SEC and CR-1 was built (Fig. 5(b)), implying the importance of initial particle size on SEC.

Table 3 summarizes the properties of raw material, net SEC and mill type in the literatures. Esteban's initial chip size and moisture content of feedstock are quite similar to our initial chip size of 10.36 mm and moisture content of 11–13% (Esteban and Carrasco, 2006). Their findings on SEC are also close to ours. Repellin's data suggests that the ZM1 ultra centrifugal mill consumes more energy

Table 3
Specific Energy Consumption of comminuting lignocellulosic materials.

Feedstock species	Moisture content (%)	Initial size (mm)	Final size (mm)	Mill type	Net SEC (kJ kg^{-1})	Resources
Poplar	9.9–14.9	9.52	0.42	Hammer mill (11 kW)	297[c]	Esteban and Carrasco (2006)
Pine	9.9–14.9	12.1	0.41	Same as above	429[c]	Esteban and Carrasco (2006)
Hardwood	3.8–6.5	22.4/22.9	1.6/2.54	Hammer mill (11.2 kW)	468/432	Cadoche and Lopez (1989)
Hardwood	3.8–6.5	22.4/22.9	1.6/2.54	Knife mill (7.5 kW)	468/264	Cadoche and Lopez (1989)
Lodgepole pine	0	L[a]: 6–38 T[a]: 3–8	0.76[b]	Disk mill	2217	Zhu et al. (2010)
Poplar and Aspen	12	25.4 × 6.4	2	Two-stage hammer mill	180	Holtzapple et al. (1989)
Spruce	Green	2–4	0.237	ZM1 ultra centrifugal mill	2700[c]	Repellin et al. (2010)
Beech	Green	2–4	0.284	Same as above	3060[c]	Repellin et al. (2010)
Aspen	33.3	20 × 20 × 3	0.93[d]	Ring roller mill (14.9 kW)	504	Trass et al. (1987)
Poplar	37.5	NA	1.5[d]	Hammer mill	320	Schell and Harwood (1994)
Poplar	37.5	NA	0.38[b]	Knife mill	2484	Schell and Harwood (1994)
Willow	13	60 – 580 × 60 – 760 × 50 – 250	2.12	Knife mill	203	Miao et al. (2011)

[a] L: length, T: thickness.
[b] This data is Screen size, final size of particle is not available.
[c] This data is total specific energy consumption.
[d] This data is d50 mass median diameter.

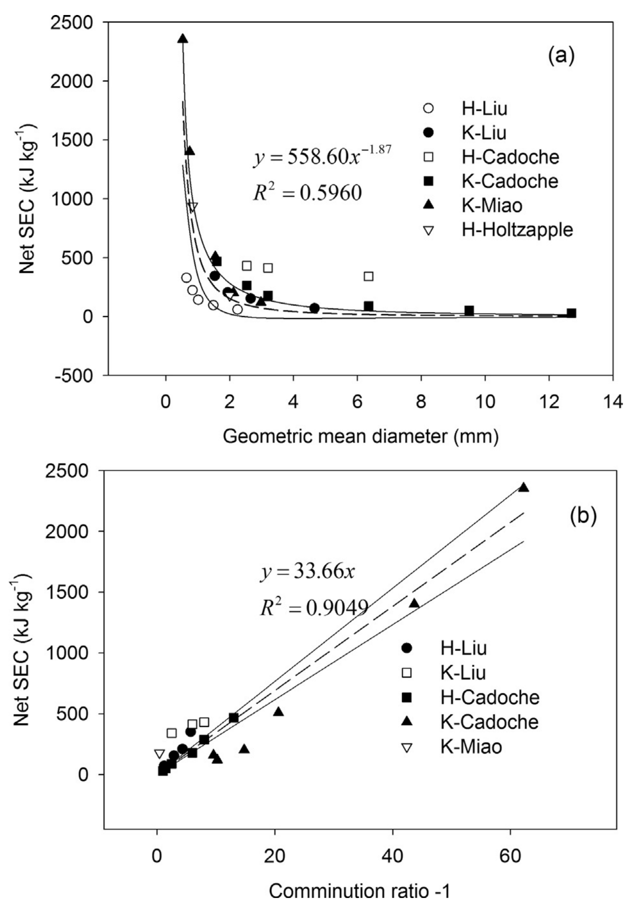

Fig. 5. Relation between Net Specific Energy Consumption and (a) geometric mean diameter, (b) comminution ratio -1 for hammer (H) and knife (K) milling processes.

than the hammer mill. However, the feedstock used in their study was green chips, which had a high moisture content. Also, the disk mill tends to consume more energy than the hammer mill and knife mill (Schell and Harwood, 1994; Zhu et al., 2010). When comparing data in literatures, these summarized properties may better explain the differences in SEC.

4. Conclusions

A linear regression can be used to describe the relationship between SEC and comminution ratio, which can be widely used for estimating SEC of various particle size of feedstocks. Importantly, the minimum total SEC was achieved at a feeding rates that produced the approximate rated power of the motor. Also, hammer milling produced finer wood particles with a higher aspect ratio and lower bulk density but consumed less energy than knife milling. The process SEC increased dramatically with an increase of moisture content from 11–17%. Fractures across the cell lumen dominated hammer-milled grindings, while fractures along middle lamellae dominated the knife-milled grindings.

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