Effects of multi-stage milling method on the energy consumption of comminuting forest residuals

Yalan Liu, Jinwu Wang, John C. Barth, Kelly R. Welsch, Vincent McIntyre, Michael P. Wolcott

Abstract

This study has evaluated the comminution energy reduction efficiency of a multi-stage milling method and established a mathematical model for estimating the specific energy consumption as a function of moisture content and particle size change. A Bliss hammer mill was employed to grind the feedstock targeting at two final screen sizes of 0.84 and 0.69 mm. For the target screen size of 0.84 mm, the single-stage, two-stage, and three-stage milling process were employed. Whereas, the single-stage, two-stage, and four-stage milling process were employed for the 0.69-mm target screen size. Four moisture content levels were employed, i.e. 6%, 12%, 18%, and 28%. While the final particle sizes and distributions were similar independent of the intermediate stages, the results showed that the single-stage milling consumed 43% more energy than the three-stage grinding process. Also, multi-stage milling runs more stable in grinding high-moisture content materials. In addition, a mathematical model based on Bond’s comminution law was established to predict the specific energy consumption with the moisture content and the particle sizes before and after grinding.

1. Introduction

Fossil fuels, currently the primary source for liquid transportation fuels, bring about many environmental issues. Forest harvesting residuals are a potential resource for producing biofuels to provide an alternative to fossil fuels. For any route to convert woody biomass to ready-to-use fuels, size reduction is a necessary preprocessing process. However, the process of breaking down forest residuals is energy intensive because woody cell walls and structures are very tough (Dukes et al., 2013; Liu et al., 2016a; Repellin et al., 2010). Also, the woody biomass, especially softwood, is more recalcitrant to various agents than agricultural biomass materials (Chen et al., 2011; Shuai et al., 2010). Therefore, different pretreatment processes were adopted for woody biomass (Gao et al., 2013; Liu et al., 2017a, b; Liu et al., 2016b; Zhu et al., 2015, 2010), which required severe pretreatment conditions. In order to reduce the chemical pretreatment severity, a mechanical-chemical pretreatment was employed to achieve adequate total sugar conversion and a fine milling process was deployed in this combined process (Liu et al., 2017b; Miura et al., 2012; Peng et al., 2013; Zakaria et al., 2014). Since the feedstock preparation and the combined pretreatment both involve the milling process, manipulating the energy consumption in the milling process is of significance.

The energy consumption of a milling process mainly depends on material, moisture content, mill type, and particle size change between the feed and the milled product. Many studies showed that the specific energy consumption increased along with an increase of moisture content (Liu et al., 2016a; Mani et al., 2004; Tumuluru et al., 2014). Hammer mills are more energy-efficient in producing fine particles than knife mills (Liu et al., 2016a; Miao et al., 2011) and are appropriate for producing fine particles (Liu et al., 2016a). Also, the relationship between particle size change and energy consumption was described by a number of comminution laws (Charles, 1957). In these theories, the energy consumption during wood milling is expressed as the function of the particle size difference between the feed and the milled product. A constant of materials characteristics is used to identify the difference between various feedstocks under a specific grinding mechanism. It was found that the constant was not only related to the species of the feedstock but also influenced by the moisture content of the feedstock (Temmerman et al., 2013).

It has been noted that the energy consumption is influenced by both...
the initial size and final particle size (Adapa et al., 2011; Cadoche and Lopez, 1989; Naimi et al., 2013). When targeting at a very small screen size, there are strategies of going through several intermediate screens and then feed the grindings to the target screen size (Temmerman et al., 2013), which is a multi-stage milling. Also, one can directly feed raw materials to the final screen size, which is a single-stage milling. The differences in the overall energy consumption among these different milling methods have not been disclosed. It is also unclear whether the final product size is similar or not after subject to different milling routes. Also, the interaction between moisture content and particle size change is of interest to investigate. Many grinding energy values reported in the literature were generated with laboratory-scale mills. These mills are designed to attain a product size without optimization for energy efficiency. Moreover, test samples are often less than 1 kg, which may not generate a stable milling regime. For example, the specific energy consumption (SEC) of grinding a sawdust to a median size of 233 μm with a laboratory-scale rotor impact mill was 1.844 kWh/kg (Karinkanta et al., 2012), which is 46% of the total available wood energy. These laboratory-based values have created a perception that the mechanical grinding of wood to fine powders is too energy intense to be cost-effective. Few studies have been carried out to develop routes to realize a cost-effective industrial process of fine grinding woody biomass. Energy consumption and energy size relationship on an industrial scale have not been available. This information barrier has hindered the understanding of a scalable process on which economic estimates can be based to evaluate commercialization of fine wood grinding. Therefore, an industry scale Bliss hammer mill was employed to evaluate the energy consumption for different degrees of size reduction under various moisture content levels and grinding schemes.

The objective of this study was to investigate the effects of the multi-stage milling method on the specific energy consumption of comminuting feedstock with various moisture contents and correlate the energy consumption with particle sizes. Specifically, the wood chips were subject to a series of multi-stage grinding and the wood particles were characterized; the Von Rittinger’s, Kirk’s, and Bond’s laws were used to describe the relationship between energy consumption and particle size change. The best fitted mathematic model was selected to predict the energy consumption under various moisture content and targeting particle sizes.

2. Materials and methods

2.1. Materials

The Douglas-fir forest harvest residuals were produced from a roadside slash pile in southwest Oregon, USA. The slash pile was comminuted using an on-site horizontal grinder into a product passing through a 102 × 102 mm² screen, which was delivered to a facility and was then screened with a Black-Clawson gyratory screen (Model 580, Serial 4095-76, Black Clawson, Everett, WA) with a 45 mm round-hole punched plate top deck to remove “overs”, and a 6 mesh (3.35 mm) woven-wire bottom deck to remove “fines”. The accepted material was air-dried for storage and labeled as FS. The sieving analysis of the whole stock showed the geometric mean diameter of the raw materials was 10.62 mm.

The moisture content of the forest residuals was determined according to ASAE Standard S358.2 (2006) for five replicate samples and expressed as a fraction of total mass. The FS moisture content was 13.1%. Three other moisture content levels were prepared by placing the FS inside an environmental chamber for two weeks with an equilibrium moisture content setup at the 6, 18 and 28% of moisture content, respectively. The final moisture content was confirmed to be 6.7%, 16.1%, and 27.8%, which covers a range of moisture content in typical wood grinding.

2.2. Methods

2.2.1. Experimental design

The routes of the multi-stage milling are listed in Table 1. The two target screen sizes of these six routes were 0.84 mm and 0.69 mm. The target screen size of 0.84 mm included a single-stage milling, two-stage milling, and three-stage milling process. Whereas, the 0.69-mm target screen size had a single-stage milling, two-stage milling, and four-stage milling process. These two sizes are standard screen sizes and the smallest and second smallest size in which the hammer mill can be operational stably without causing overcharging and orifice blocking. The selected moisture content levels for assessment are 6%, 12%, 18%, and 28%. Under each moisture content, all the different milling routes were carried out. Each milling sample weighed 23 kg. Mass, moisture content, and particle size distribution of the material after each grinding were determined; the total electrical energy used in each milling was recorded.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Hammer mill screen size and multi-stage milling route selection.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target screen size</td>
<td>0.84 mm</td>
</tr>
<tr>
<td>Starting size</td>
<td>1</td>
</tr>
<tr>
<td>Feedstock (Geometric mean diameter: 10.62 mm)</td>
<td>6.35</td>
</tr>
<tr>
<td>Intermediate screen size (mm)</td>
<td>3.18</td>
</tr>
<tr>
<td>Target screen size (mm)</td>
<td>0.84</td>
</tr>
</tbody>
</table>
2.2.2. Energy consumption of grinding process

A Fluke 1735 Power Logger (Fluke Corporation, Everett, WA) was used to measure the electrical energy consumption of the milling process of a hammer mill (Bliss Eliminator Fine Grind Hammer mill, EMF-24115-TFA, 45 kW, Bliss Industries Inc. Ponca City, OK, USA). The total energy consumption, a sum of idle energy and net energy, was derived from the recorded active power and milling time. The idle energy can be calculated through the baseline power of the hammer mill under a run without a charge and milling time. The net energy was calculated by subtracting the idle energy from the total energy (Liu et al., 2016a).

\[
\text{Net SEC} = \frac{\text{Total Energy} - \text{Idle Energy}}{\text{Sample mass}/(1 + MC)}
\]  
(1)
The baseline idle power and rated power were found to be 12 kW and 42 kW for the Bliss hammer mill. Whereas, the net energy can be obtained by subtracting idle energy from total energy from each actual run.

2.2.3. Particle size characterization
After milling, the resulting particles were sieved with a Ro-Tap Shaker (The W. S. Tyler Company, Cleveland, Ohio, USA) for 20 min to analyze the size distribution, geometric mean diameter ($X_{50}$), and standard deviation ($S_{50}$) following ASAE Standard S319.4 (2008).

2.2.4. Energy-size relationship
Three comminution laws were used to describe the relationship between energy consumption and particle size change. Von Rittinger’s law, Kick’s law, and Bond’s law were used to analyze the relationship as shown in Eqs. (3)–(5) (Charles, 1957; Temmerman et al., 2013).

$$E_{1-2} = C_{VR} \left( \frac{1}{X_2} - \frac{1}{X_1} \right)$$ (3)  

$$E_{1-2} = C_{k} \ln \frac{X_1}{X_2}$$ (4)  

$$E_{1-2} = C_{B} \left( \frac{1}{\sqrt{X_2}} - \frac{1}{\sqrt{X_1}} \right)$$ (5)  

where $E_{1-2}$ is the required energy per unit mass for reducing a particle size from $X_1$ to $X_2$. $x$ is a particle size characteristic, which refers to the geometric mean diameter here. The numbers 1 and 2 represent the particle size before and after grinding. $C$ is a constant characteristic of the forest residual materials.

3. Results and discussion

3.1. Particle size distribution and geometric mean diameter

Fig. 1(a) shows the size distribution of the raw materials and the resulting particles from each step of the three-stage milling of the 0.84-mm screen. Fig. 1(b) shows the size distribution of the final particles from three different milling routes of the 0.84-mm screen for the samples with a moisture content of 6%. The final particle size cumulative distribution curves from three different milling routes overlap mostly as shown in Fig. 1b. The geometric mean diameter and standard deviation of the final resulting particles from different milling routes are summarized in Table 2. The comparison of the geometric mean diameter found that there is no substantial difference among these different milling routes. It indicates that the screen size solely determines product size distribution.

Table 3

| Parameters obtained from linear fitting with Von Rittinger’s, Kick’s and Bond’s law. |
|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|
| Moisture content (%) | SEC Type | Von Rittinger’s law | Kick’s law | Bond’s law |
| (%) | | $C_{VR}$ | $R^2$ | $C_k$ | $R^2$ | $C_B$ | $R^2$ |
| 6 | Net | 0.0218 | 0.89 | 0.0218 | 0.68 | 0.0512 | 0.85 |
| Total | 0.0303 | 0.89 | 0.0303 | 0.68 | 0.0711 | 0.85 |
| 12 | Net | 0.0347 | 0.93 | 0.0287 | 0.50 | 0.0743 | 0.86 |
| Total | 0.0489 | 0.93 | 0.0402 | 0.50 | 0.1039 | 0.86 |
| 18 | Net | 0.0398 | 0.82 | 0.0359 | 0.65 | 0.091 | 0.91 |
| Total | 0.0556 | 0.82 | 0.0502 | 0.65 | 0.1271 | 0.91 |
| 28 | Net | 0.0548 | 0.58 | 0.0571 | 0.75 | 0.1387 | 0.92 |
| Total | 0.0761 | 0.57 | 0.0795 | 0.76 | 0.1928 | 0.92 |

equation.

$$Total\ SEC' = \frac{Net\ Energy}{Rated\ Power - Baseline\ Power} \times Rated\ Power$$ (2)
3.2. Multi-stage milling effect on SEC

Fig. 2 summarizes the net SEC and total SEC under various milling routes and moisture contents. Fig. 2(a) shows the SEC under a moisture content of 6%, while Fig. 2(b) and (c) show the corresponding data with a moisture content of 18% and 28%, respectively. As shown in Fig. 2(a), the single-stage milling process of the 0.84-mm screen consumed 21% more than the three-stage milling process in both total SEC and net SEC, while 43% more when compared to the single-stage milling of the 0.69-mm screen to the four-stage milling. Fig. 2(b) and (c) show the advantage of multiple-stage milling with a target size of 0.84 mm decreased along with an increase of moisture content from 6% to 28%.

Fig. 4. The linear fittings between net SEC and particle size change under various moisture contents.

3.3. Moisture content effect on SEC

Fig. 3 summarizes the moisture content effects on the net SEC under multi-stage milling routes. Fig. 3(a) shows that the increasing moisture content resulted in an increasing net SEC; the net SEC at the moisture content of 28% was 2–3 times more than the one at the moisture content of 6%. This finding was also in agreement with other studies (Liu et al., 2016a; Mani et al., 2004). Fig. 3(b) and (c) show the moisture effects on the energy consumption in each step of the three-stage milling for producing 0.84-mm grindings and the four-stage milling for 0.69-mm grindings. It can be observed that the moisture content substantially influences on the first two stages of these two milling routes. As these stages are consecutive, the resulted grindings become the feed materials for the next step. Also, the moisture content decreased due to the drying effects of the milling process. Therefore, the

Fig. 5. The relationship between (a) Von Rittinger’s Constant and moisture content, (b) Bond’s Constant and moisture content.

However, the four-stage milling still consumed less energy than the two-stage milling with a target size of 0.69 mm. It can be concluded that at moisture content level of 28%, the advantage of the multiple-stage milling method decreased when producing 0.84 mm particle size grindings. In addition, the single-stage milling at the moisture content level of 18% and 28% were not able to be carried out due to the overheating of the mill motor resulting from current spikes. Therefore, the multi-stage milling method is essential when grinding materials with a high moisture content and targeting an extra fine particle size.
moisture content appears to have less effect on milling energy consumption.

3.4. Analysis with the comminution laws

The three comminution laws were employed to describe the relationship among the energy consumption, particle size, and the moisture content of the feedstock. The experimental data were fitted with the Von Rittinger’s, Kick’s and Bond’s laws as expressed by Eq. (3), (4), and (5), respectively (Temmerman et al., 2013). The parameters were extracted by the least squares method. Table 3 summarizes the results from the linear fitting for all the four moisture content levels with these comminution laws. Fig. 4 shows the linear fitting between the net SEC and standardized size differences. The linear fitting obtained by Von Rittinger’s law and Bond’s law are better than the fitting from Kick’s law as indicated by R squares. At the high moisture content levels, Bond’s law performs better than Von Rittinger’s law in the linear fitting. Generally, the linear fitting with Bond’s law obtained the best results with the R-square values ranging from 0.85 to 0.92. Furthermore, the increasing moisture content in feedstock resulted in an increasing comminution constant, which is characteristic of grindability of the feedstock. Fig. 5 demonstrates the changes of the Von Rittinger’s and Bond’s constants along with an increase of the moisture content in the feedstock. A linear fitting was employed to obtain the relationship between moisture content and the constants. Substituting the Bond’s constant as a function of moisture content into Eq. (5), the following equations are obtained:

\[
\text{Total SEC} = (0.0055 \times MC + 0.0364) \times \left( \frac{1}{\sqrt{\Delta S}} - \frac{1}{\sqrt{\Delta S_0}} \right)
\]

\[
\text{Net SEC} = (0.0039 \times MC + 0.0259) \times \left( \frac{1}{\sqrt{\Delta S}} - \frac{1}{\sqrt{\Delta S_0}} \right)
\]

With these equations, one can roughly estimate the net and total energy consumption in the range of investigated moisture content and particle size change. These predictors of Eqs (6) and (7) will facilitate the techno-economic analysis of hammer mill grinding.

4. Conclusion

The multiple-stage milling process substantially decreased the specific energy consumption of hammer milling process for producing fine particles at low moisture content. It also provides advantages in grinding the materials with high moisture content compared to single-stage milling. Bond’s law was found to better correlate the specific energy consumption with particle size change. Also, the constant in the Bond’s law has a good linear relationship with moisture content. Therefore, the developed Bond’s law equations are recommended to be used to estimate the total specific energy consumption under various moisture content and particle size change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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