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Milling of Lignocellulosic Biomass

Results of Pilot-Scale Testing

DANIEL J. SCHELL*,[1] AND CHUCK HARWOOD[2]

[1]*Alternative Fuels Division, National Renewable Energy Laboratory, Golden, CO 80401; and* [2]*John Brown Engineering and Construction, Chicago, IL*

ABSTRACT

Ethanol is being considered as an attractive alternative transportation fuel for the future. One method of producing ethanol from lignocellulose involves reducing the size of biomass to smaller particles, and using acid or enzyme treatments to hydrolyze the biomass to sugars. The size-reduction step is necessary to eliminate mass- and heat-transfer limitations during the hydrolysis reactions. However, milling to small size consumes large amounts of energy, and reducing the energy usage is critical to the overall process economics. In this study, the energy requirements and size distribution for milling wood were measured for various pilot-scale size-reduction equipment. Hammer milling used less energy than disk milling, but produced particles with a larger-size distribution. Additionally, energy requirements were measured for shredding paper and switchgrass.

Index Entries: Hammer mill; disk mill; shredder; lignocellulose; energy usage.

INTRODUCTION

Lignocellulosic biomass includes such materials as agricultural and forestry waste, municipal solid waste, waste paper, and wood and herbaceous energy crops. These materials represent one of the most abundant renewable resources on earth. Both the cellulosic and hemicellulosic fractions of biomass can be converted to simple sugars that can subsequently

*Author to whom all correspondence and reprint requests should be addressed.

be fermented to ethanol. The conversion of even a small portion of this resource into ethanol could substantially reduce gasoline consumption and dependence on petroleum.

Acid- and enzyme-based processes are the two most common methods of converting cellulosics to simple sugars. Various processes based on dilute and concentrated acids are used to hydrolyze the cellulose and hemicellulose to their respective sugars (*1–3*). Enzymatic processes are based on the use of a pretreatment step to hydrolyze the hemicellulose or dissolve the lignin, thereby increasing the digestibility of the cellulose. Then, cellulase enzyme is used to hydrolyze the cellulose, and both sugars are subsequently fermented to ethanol (*4*). Before the hydrolysis step, biomass is first reduced in size to decrease heat- and mass-transfer limitations. Studies have shown that particle size must be reduced to 1–2 mm to eliminate these limitations (*5,6*). However, this size-reduction step consumes large amounts of energy (33% of the total electrical demand [*7*]). Thus, reducing the energy usage would improve the process economics.

In this study, the energy required for milling several lignocellulosic biomass feedstocks and the resulting size distributions were measured for several types of size-reduction equipment that could be used in a biomass-to-ethanol process. Tests were conducted with a hybrid poplar wood chip on three pilot-scale disk refiners at the Andritz Sprout-Bauer pilot-plant test facility in Springfield, OH. Wood chips were also milled using an air-swept hammer mill at the ABB Raymond Combustion Engineering Inc. test facility in Naperville, IL. Two other feedstocks, switchgrass and paper, were shredded using a shredder manufactured by the MAC Corporation at its test facility in Grand Prairie, TX.

BACKGROUND

There is little information available in the literature on the energy requirements for size reduction of biomass. Datta (*8*) indicates that 20–40 kWh/ton are required for course reduction of hardwood chips to 0.6–2.0 mm and that 100 to 200 kWh/ton (metric) are required for size reduction to 0.15–0.30 mm. However, the moisture content of the feedstock, the type of mill, and the particle size distribution are not given. Cadoche and López (*9*) tested a knife and hammer mill on hardwood chips, straw, and corn stover at a 4–7% moisture content. Energy consumption to reduce hardwood chips to a particle size of 1.6 mm (defined as the screen size that will allow all the particle to pass through) was 130 kWh/ton for both the hammer and knife mill. At a 3.2-mm particle size, the knife mill required 50 kWh/ton and the hammer mill used 115 kWh/ton. The hammer mill required considerably more energy at the larger particle sizes. Both straw and corn stover are easier to mill, and required 6–36% of the energy required for wood. However, without a particle size distribution, it is difficult to compare these energy usages to other data.

The most complete data on biomass milling are provided by Himmel et al. (*10*). Aspen wood chips, wheat straw, and corn stover and cobs at moisture contents from 4 to 7% were milled using a hammer, knife, and attritor mill. The attritor mill (Herbert Associates, Ltd.) is similar to the hammer mill used in this work. The energy usage and particle size distribution as a function of rejection screen size are presented. For aspen wood, the attritor had the highest energy consumption (200–400 kWh/ton), followed by the hammer mill (90–130 kWh/ton), and finally the knife mill, which had energy usage ranging from 8 to 120 kWh/ton, depending on particle size. Again, lower energy input was required to achieve the same size reduction with straw and corn stover and cobs.

EQUIPMENT AND METHODS

Shredder

A shredder is a method of achieving course size reduction of difficult-to-handle feedstocks, such as waste paper and grasses. For example, grasses reduced to approx 3 cm in length can more easily be fed to other milling equipment to further size reduction to particle sizes (1–2 mm) most appropriate for the ethanol conversion process. The purpose of the test was to determine the power requirements to reduce baled waste paper and switchgrass to particles approx 3 cm long.

The equipment used in these trials were a Saturn Model 62-40HT (149 kW, 200 hp) rotary shear shredder with 3.8 cm (1.5 in.) thick cutter blades and a Saturn Model 44-28HT (75 kW, 100 hp) rotary shear shredder with 2.5 cm (1.0 in.) thick cutter blades. Both units are manufactured by the MAC Corporation and were tested at its facility in Grand Prairie, TX. Because of the setup at the test facility, the material was first fed by conveyor to the model 62-40HT shredder and then conveyed for a second pass through the model 44-28HT shredder. This material was collected in a hopper and then fed for a third pass through the model 44-28HT shredder.

Hammer Mill

The purpose of this test was to determine the power required to hammer mill moist wood chips and the resulting size distribution of the milled material. The wood chips were a hybrid poplar chip harvested in Canada by the company Domtar. The moisture content of the chips as measured at the vendor test site was approx 60%. Several hammer mill vendors were contacted concerning this test. In all cases involving a mill that grinds material through a screen, the vendors declined to test the material, citing previous problems with milling moist wood chips. These problems were low production rates, excessive heat buildup, screen blinding, and equipment damage.

The mill selected for this test is described as an air-swept swing hammer impact mill manufactured by ABB Raymond Combustion Engineering Inc. A Raymond Series 3 Imp Mill was tested at ABB's facility in Naperville, IL. The mill consists of hammers mounted on a rotating disk that is enclosed within a liner. Material is drawn into the mill by a suction fan, and ground by impact between the hammers and the liner. The air flow sweeps ground material from the mill, which is then separated from the air stream by a cyclone. Particle size can be controlled by the number of hammers, the rotational speed of the hammers, and the air flow rate, which controls particle residence time in the mill. The hammer mill vendor classified the size of the milled material using a dry sieving technique (screens on a shaker). The current was measured to determine energy usage for both the hammer and disk mill tests, and specific energy usage was determined by subtracting idle load from the total load and dividing by mass flow rate. The specific energy usage allows the different machines to be compared on the same basis.

Disk Mills

Disk mills have been commonly used for many years in the paper and pulp industry for milling wood chips. Size reduction is achieved by grinding material between two counterrotating plates or a rotating and a stationary plate. The resulting particle size is determined by the refiner type, type of plate, plate spacing, and machine speed. The purpose of this test was to determine performance of various refiners for producing milled wood chips appropriate for the biomass-to-ethanol process. Three mills were tested: a 91-cm (36 in.) Double Disc Pressurized Refiner (Model 418), a 91-cm Double Disc Atmospheric Refiner (Model 401), and a 91-cm Double Disc Attrition Mill (Model 445). All three mills are manufactured by Andritz Sprout-Bauer and were tested at Andritz's pilot-plant facility in Springfield, OH.

Energy usage and size distributions of the resulting milled material were determined for all three mills. Plate spacing was adjusted until suitable size reduction was obtained. Then the plate spacing was kept constant. The pressurized refiner has a steamer ahead of the disk mill. Both the residence time of chips in the steamer and steam temperature can be varied. Steam pressure was maintained at 241 kPa (20 psig), and the retention times tested were 3 and 6 min. Also tested were mill speeds of 1200 and 1800 rpm. For the atmospheric refiner, there is no steaming of the chips; instead, water is injected between the plates. This mill was tested at a speed of 1200 rpm. The attrition mill was tested at a speed of 1800 rpm, and in this case, there was no treatment to the chips or mill. The disk mill vendor classified the size of the milled material using a wet fiber classifer.

Table 1
Energy Usage for Shredding Paper and Switchgrass

Feedstock	Energy usage, kWh/ODT[1]
Paper	
First pass	15.2
Second pass	7.6
Third pass	6.3
Switchgrass	
First pass	8.2
Second pass	4.1
Third pass	4.1

[1] Oven-dried ton.

RESULTS

The following section presents the results of testing at each of the three vendor facilities. Data were collected on feedstock moisture content, particle size distribution, machine speed, and energy usage.

Shredding

For paper, the first pass through the shredder reduces the bundled paper to approx 4-cm (1.6-in.) bundled cubes. The second pass reduced the size to approx 2.5 cm (1.0 in.) and broke the bundles apart. The third pass continued to break the bundles apart, but resulted in little size reduction. For switchgrass, the first pass acted more as a bale breaker and produced material 10–20 cm long. The second pass reduced the grass length to approx 2.5–6 cm. No significant reduction in size was achieved on the third pass. For both paper and switchgrass, the initial moisture content was 10%.

The energy usage for each pass through the shredder for both paper and switchgrass is shown in Table 1. The results show that it is much more difficult to shred paper than grass, requiring double the energy. In all cases, a significant reduction in energy use occurs after the first pass.

Hammer Milling

A summary of hammer mills runs is shown in Table 2. The table lists the speed of the mill, and the type and arrangement of hammers. A maximum of three hammers consisting of either bars (B) or knives (K) can be mounted in a row along the edge of the rotating disk. In the table, the

Table 2
Summary of Hammer Mill Runs on Wood

Run number	1	2	3	4
Speed (rpm)	2500	2500	2500	3600
Hammer arrangement and type	2-2-0 B[1]	2-2-0 B	6-6-0 K[2]	6-6-0 K
Feedstock solid concentration (%)				
Inlet	31	40	40	40
Outlet	35	41	46	45
Energy usage (kWh/ODT[3])				
Fan	67	67	67	67
Mill	13	13	22	35
Total	80	80	89	102

[1] Bars.
[2] Knifes.
[3] Oven-dried ton.

dashes separate the rows, and the number gives the number of hammers mounted along the periphery of the disk. Thus, for run number 1, there are two bars in the row, and two rows used were 180° opposite each other on the disk.

The table also gives the feedstock solid concentration before and after the mill, and the specific energy usage for the fan and the mill. The fan energy has been included in the calculation of the specific energy usage because it is an integral and essential component of this milling technique. The value given in the table is an estimate from the manufacturer of the required fan power. The actual measured value was approximately three times higher because the vendor was using an oversized fan on its pilot demonstration unit.

Figure 1 gives the cumulative size distribution for the four hammer mill runs. The figure shows the cumulative weight fraction of particles smaller than the indicated size. All the runs had essentially the same size distribution except for run 2, which produced significantly larger particles. As can be seen from Table 2, there was no difference in run conditions between run 1 and 2, except that run 1 was performed on freshly chipped green wood, whereas run 2 was performed on older wood that had been dried and rewetted. The drying process may have made the chips more resistant to size reduction; thus, larger chips were obtained at the same energy input. Runs 3 and 4, which were also performed on rewetted chips, showed that the lower speed produced the same sized chips at a lower energy consumption. Because of the varying conditions between these runs (e.g., different feedstock and hammer type and arrangement), it is not possible to draw any other meaningful comparisons between these runs.

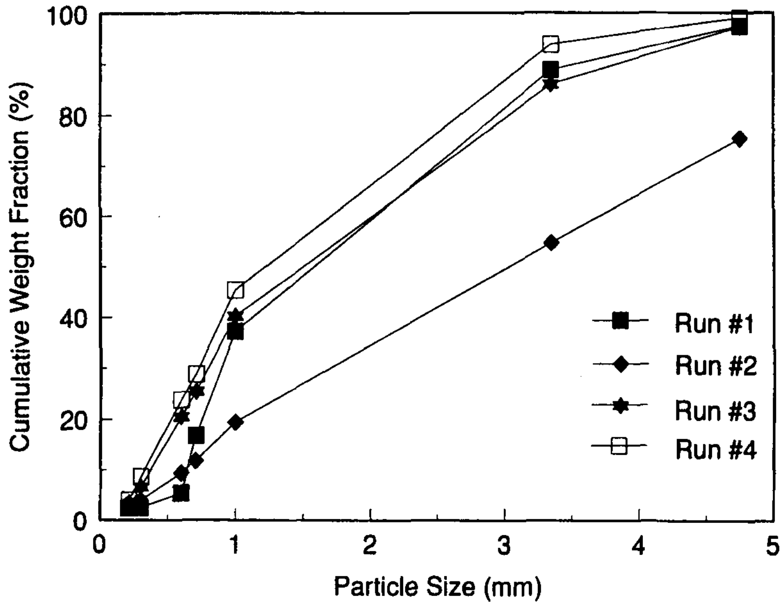

Fig. 1. Cumulative size distribution of wood from the impact hammer mill (*see* Table 2 for description of runs).

Table 3
Summary of Disk Refiner Runs on Wood

Run Number	1	2	3	4	5	6	7	8
Machine	418	418	401	445	418	418	445	445
Speed (rpm)	1200	1200	1200	1800	1800	1800	1800	1800
Plate gap (mm)	2.03	1.96	0.38	2.41	1.78	1.78	2.41	2.41
Pressure (kPa)	241	241	101	101	241	241	101	101
Temperature (°C)	126	126			126	126		
Retention time (min)	6	3			3	3		
Feedstock solid concentration (%)								
Inlet	40	40	40	40	40	40	40	29
Outlet	38	37	31	44	35	33	44	34
Energy usage (kWh/ODT[1])	551	429	609	122	309	244	158	159

[1] Oven-dried ton.

Disk Milling

A summary of the test runs conducted on the disk mills is given in Table 3. This table lists each machine used and the operating conditions for each run. Only temperature and retention times are given for the pressurized refiner (418). Note that four runs were conducted on the pressurized refiner (runs 1, 2, 5, and 6), one on the atmospheric refiner (run 3), and three on the attrition mill (runs 4, 7, and 8). The table also shows the

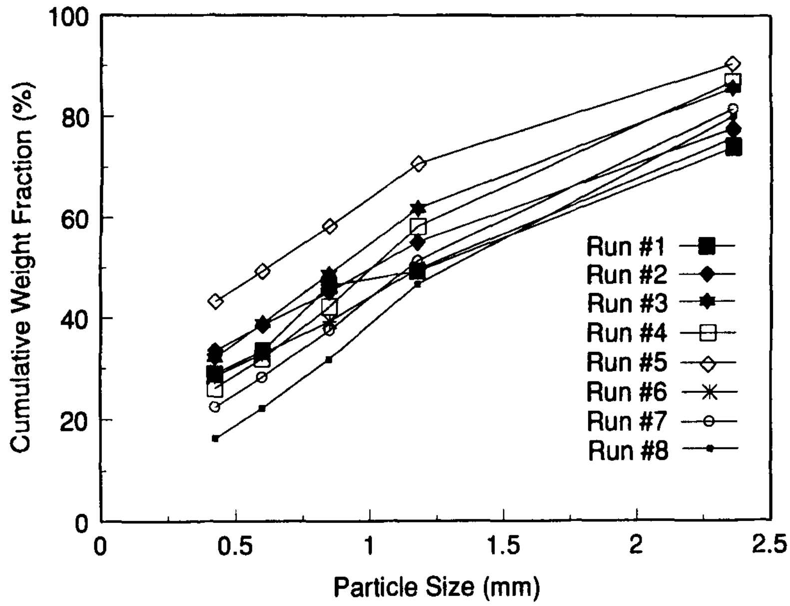

Fig. 2. Cumulative particle size distribution of wood from the disk refiner runs (*see* Table 3 for description of runs).

feedstock inlet and outlet solid concentration, and the energy usage for each run. The feedstock coming out of the pressurized and atmospheric refiners is wetter because of steam or water addition, whereas the attrition mill dries the feedstock to some extent.

Figure 2 shows the corresponding cumulative size distribution of the particles for each of the runs. Plate spacing was adjusted for each run in an attempt to obtain the same size distribution from each run, so that energy usage could be compared on the same basis. The size distributions for most of the runs are roughly equal, except for run 5, which has a significantly smaller size distribution. Although runs 5 and 6 are identical runs, smaller particles were produced in run 5, which is reflected in the higher energy usage for that run.

The atmospheric refiner had the highest energy requirement at 609 kWh/oven-dried ton (ODT), followed by the pressurized refiner, and finally the attrition mill. A comparison of the pressurized refiner runs shows that at 1200 rpm (runs 1 and 2), a shorter retention time lowered the energy usage from 551 to 429 kWh/ODMT. Increasing the refiner speed to 1800 rpm (runs 5 and 6) lowered the energy usage even further to an average of 276 kWh/ODMT.

All attrition mill runs were conducted at 1800 rpm. Runs 4 and 7 were identical and gave an average energy usage of 140 kWh/ODT. To determine if initial moisture content affected the results, run 8 was performed with chips that had been soaked in water. Given the range of the data, it appears that lowering the initial moisture content had no effect on energy usage for the attrition mill.

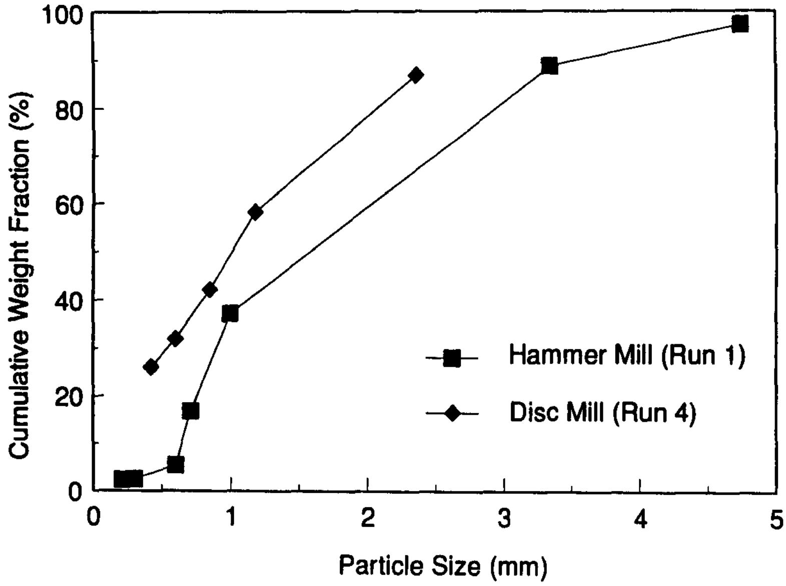

Fig. 3. Comparison of particle size distribution from hammer and disk mill runs.

DISCUSSION

The purpose of this study was to determine the most appropriate milling technique for a biomass-to-ethanol process. However, the nature of the particles produced by both mills is very different. The disk mill produces a particle that is more elongated and needle-like; the hammer mill produces a particle that is shorter and broader. This has implications for mass- and heat-transfer processes, which occur more rapidly along the grain. However, quantifying these factors was beyond the scope of this study. Figure 3 compares the particle size distribution of a hammer mill run (run 1, 80 kWh/ODMT) to a disk mill run (run 4, 122 kWh/ODMT). Both runs were conducted on the same freshly chipped green wood. Although the disk mill produced smaller particles, it also had the higher specific energy input.

Using the data of Himmel et al. (*10*), it is possible to find a size-distribution curve for the knife mill (data not shown) that approximately matches the results from our hammer mill run shown in Fig. 3. The reported energy consumption was 15 kWh/ODT. However, this was for dry wood. This suggests that dry wood may be much easier to mill than wet wood, but in any case, typical hammer and knife mills are not appropriate for wet materials.

CONCLUSIONS

Because of the different particle size distribution and characteristics produced by each mill, it is difficult to recommend a mill for the biomass-to-ethanol process. From the above data, we can conclude that (1) the hammer mill used less energy than the disk mill, but produced particles with a larger size distribution and different particle characteristics, and (2) it is easier to mill dry wood than wet wood. Since the disk mill used more energy and produced smaller particles, it is not possible to identify which mill may be more advantageous in terms of energy consumption. Other factors, such as heat- and mass-transfer considerations during hydrolysis, which are affected by particle dimensions, may be equally important in determining the most appropriate mill for a large-scale process.

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