2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Shear Processing of Wood Chips into Feedstock Particles

Lanning, David N

Forest Concepts, LLC 3320 W Valley Hwy N. D110, Auburn, WA 98001
dlanning@forestconcepts.com

Dooley, James H

Forest Concepts, LLC 3320 W Valley Hwy N. D110, Auburn, WA 98001
jdooley@forestconcepts.com

Lanning, Christopher J

Forest Concepts, LLC 3320 W Valley Hwy N. D110, Auburn, WA 98001
clanning@forestconcepts.com

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Abstract. *We have an objective to convert cellulosic biomass raw materials into small particles that are optimized for biochemical and/or thermochemical conversion to liquid transportation fuels. As a side effort, we are interested in producing feedstocks for composite bioproducts, solid biofuels, and other uses. Wood chips that have a typical length of 50mm are a common raw material. This experiment seeks to evaluate the change in particle sieve analysis, geometric mean dimension, and particle shape as wood chips are processed through one or more rotary shear configurations as well as to determine the incremental specific energy consumption. Wood chips processed by two passes through a 4.8mm cutter set changed the geometric mean dimension from 26.4mm to 5.6mm at a total cost of less 30MJ/odt. Additional combinations are discussed.*

Keywords. Wood chips, comminution, specific energy, rotary shear

Introduction

This project was supported in part by a US DOE SBIR Phase II research contract (SC0002291). The objective of our sponsored "low energy comminution to produce precision feedstocks" project was to apply an understanding of the modes of failure and structural biology to substantially reduce the comminution energy required to produce bioenergy feedstocks that have an optimal size and shape for conversion to liquid transportation fuels. The work plan included laboratory measurement of specific energy for comminution of woody raw materials into particles that were optimized for bioenergy conversion processes.

We have been approached by multiple independent entities to design processing equipment for conversion of whole-tree chips into feedstocks for their pyrolysis oil and pellet fuel projects. Among their first questions asked was how much energy would be consumed by our process versus hammer mills if the starting material was clean whole-tree chips, a common raw material.

This paper discusses an experiment with the objective of determining the energy consumption and particle size distribution for first and second-pass processing of fuel wood chips through our laboratory rotary shear using 4.8mm wide cutters. This report summarizes four months of work with a single sample of whole-tree conifer chips collected from Herman Brothers Logging near Port Angeles, WA.

Safety Emphasis

Processing materials through a rotary shear head is potentially dangerous. The infeed of the machine must be open enough for materials to flow freely into the head. Consequently there are openings where operators could potentially get fingers, hands, or loose clothing engaged in the cutter head causing serious injury or death. To mitigate as much hazard as practical we built infeed chutes and conveyors to distance the operator from the processing head. Additionally multiple emergency stop switches were placed within reach of the processing head. Standard personal safety gear including safety glasses and snug clothing were worn. Operators were trained on the machine including hazard avoidance.

Literature Review

The earliest comprehensive discussion of low-energy comminution for wood based on modes of failure appears to be the work of Keith C. Jones under contract to Forest Engineering Research Institute of Canada (Jones 1981, 1981). Jones assumed that the energy to shear across grain in black spruce wood was 100 times the published energy for parallel-to-grain shear. His values for black spruce were 0.1 J/cm^2 for parallel-to-grain shear and 1.0 J/cm^2 for shear perpendicular to grain. He further estimated that energy requirements to produce cubic particles of any size could be estimated for wood with an assumed specific gravity of 0.38 using the equation:

Surface energy requirement = 5.4/x MJ/ODt

Where: x = length of each side of the cube in cm.

Jones compared chipping to hammer mills which are much more tolerant of wood piece size, debris, rock, etc. He reported that the machine energy for hammer mills ranged from 80 MJ/ODt for 70mm average particle size to more than 450 MJ/ODt for 10mm average particle size.

Energy consumption for primary chipping of conifers has been studied in the U.S. and Europe many times over the past 50 years. Papworth (Papworth and Erickson 1966) conducted an extensive study of the effects of knife angle, sharpness, chip length, etc. on energy requirements for chipping maple, hemlock, and spruce logs. Papworth reported energy consumption in the range of 4-8 Hp/cu. Ft./minute for green spruce and hemlock. If we assume that the wood had a dry density of approximately 28 lb/ft^3 (450 kg/m^3), then we can convert Papworth's energy estimates to be equal to be approximately 14-30 MJ/odt to chip roundwood into paper grade wood chips.

Another commonly cited energy vs. particle size equation developed by Holtzapple, et. al (Holtzapple, Humphrey, and Taylor 1989). The Holtzapple, et. al., empirical equation for the relationship between grinding energy and resulting particle size is:

$E = -0.731 * \ln L + 0.742$

Where:

E = grinding energy (MJ /Kg oven dry wood)

L = length (mm) of wood cube that would just fit through a sieve opening

Like many others, Holtzapple used uniform wood chips that were 25.4mm square and 6.4 mm thick - typical of paper-grade pulp chips – as his raw material. The energy to produce wood chips from round logs or whole trees was neither measured nor assumed. His experimental data represented sieve sizes of 10, 20 and 140 mesh having openings of 2, 0.85, and 0.11 mm respectively. Because of the difficulty of producing the target particle sizes with any one "grinder" Holtzapple used three different machines to process the chips. A hammer mill was used to produce the No. 10 sieve material, a single stage attrition mill produced the 20 mesh material and a two-stage disk attrition mill produced the 140 mesh material. Holtzapple apparently assumed that all three machines used equivalent grinding methods.

In our earlier work we mathematically tested the limits of the Holtzapple equation. We found that the empirical equation shown above is only valid within his experimental range since the energy (E) value goes negative for sieve openings greater than 2.75 mm. Thus, the Holtzapple equation is not appropriate for estimating energy to produce particles for use in composite wood products, fuel pellets, biochemical conversion, or for most pyrolysis conversion methods.

Zhu more recently explored the comminution energy relationships with particle size for production of biofuels (Zhu et al. 2010). He used a knife mill to reprocess chips into a range of particle sizes. Energy consumption ranged from 100 Wh/kg (360 MJ/odt) to more than 600 Wh/kg (2,160 MJ/odt) depending on the desired particle size.

Cadoche (Cadoche and Lopez 1989) used an 8 kW (10 hp) knife mill to process straw, corn stover, and hardwood chips into feedstock for conversion to ethanol. He reported the energy consumption as a function of comminution ratio – the average change in particle size. To reduce the particle size by a factor of 2 took 8.0 kWh/tonne (30 MJ/odt) and produced particles with an average size of 12.7mm. Production of smaller particles with an average size of 1.6 mm constituted reduction by a factor of 14 and took 130 kWh/tonne (470 MJ/odt). All materials were processed at 4-7% moisture content, wet weight basis (wb).

Miao and others at the University of Illinois measured the specific energy for comminution of several biomass materials including willow wood into a range of particle sizes (Miao et al. 2010). The willow was processed by a Vermeer chipper to create raw material and then milled by knife or hammer mill to final screen size. Power was measured by a clamp on power meter. Power measurements were not corrected for motor efficiency or power factor at partial load. Energy requirement to regrind willow chips to 1 mm size consumed more than 2,100 kJ/kg (2,100 MJ/odt) and to regrind to 6 mm size consumed somewhat more than 200 MJ/odt.

Along with energy consumption, we are also concerned with the breadth of particle size distribution around a target. It is axiomatic that narrower size distributions are better. Additionally, production of very fine materials often results in losses due to dissolution during preprocessing, in health and safety issues from dusts, and in potential maintenance cost issues for facilities and equipment. Chris Wright at the Idaho National Laboratory investigated the utility of distributed grinding and densification to convert agricultural crop residues into a more easily transported form, and to conduct at least part of the size reduction at or near the source (Wright et al. 2006). Wright particularly explored the relationship between screen opening size and shape in tub grinders and the resulting particle size distribution for processed wheat straw. For the case of tub grinders, Wright found that dust production was a major issue, and resulted in large mass losses – up to 15% of the initial material was lost to fugitive dust. An objective of our approach is to minimize the production of fines and dust.

Experimental Procedure

Approach

Our primary objective was to design and build new generation wood comminution equipment. One way our new technologies can be utlitlized is in precision reprocessing of wood chips, an abundant and well understood feedstock. Our approach to gather data for comparisons to existing equipment was:

Raw chips were collected as fresh whole tree chips from a cooperator in western Washington. Characterizations included moisture content, green bulk density, anatomical content, particle shape, and particle size.

We processed fresh whole tree fuel chips with our first generation 4.8mm muncher while recording the specific energy - both torque arm and electrical energy based.

Materials from each run were sieved in our standard set of Gilson RoTap® sieves to plot the particle size distribution on both a wet weight and dry weight basis.

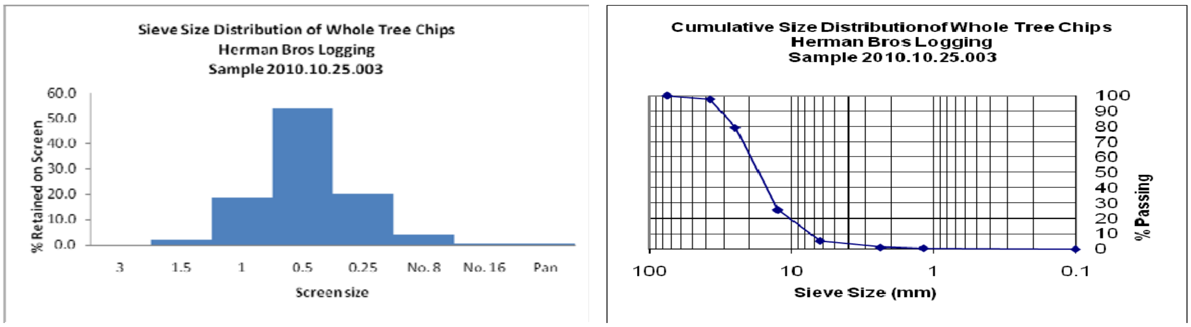
Comminution energy was calculated for each run and reported in a table with summary means and variances.

Materials

Several bins of whole tree fuel chips were collected on October 22, 2010 from a Hermann Brothers logging site near Port Angeles, WA. The observation numbers are 2010.10.22.xxx.

Figure 1. Handful of chips with bin of whole tree chips in the background.

The moisture content of the chips as-collected was 52.5 percent wet basis (wb). A sample was sieved through our standard Tyler sieves using a Ro-Tap shaker. Sieves in the stack were 1-1/2, 1, ½, ¼, No.8, No. 16, and pan. The distribution of chips retained on each screen are shown in the graphs below.



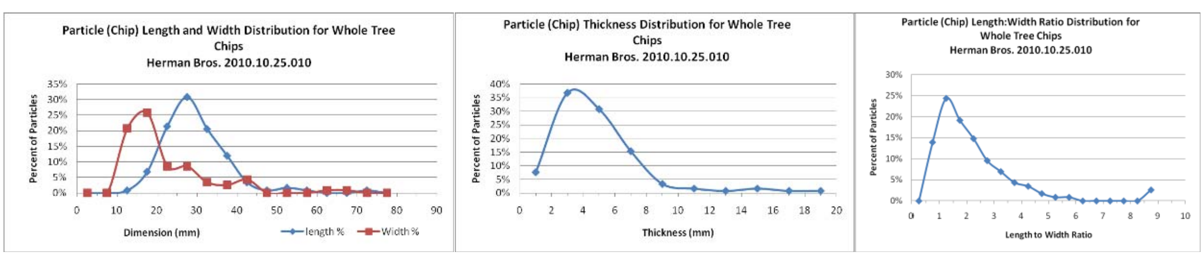
Figures 2a, 2b. Size distribution of whole tree forest residual chips from Herman Bros. Logging.

The larger chips tended to have a high width-to-length ratio while the chips smaller than 1-inch sieve tended to be narrower than long. This is obviously an artifact of the chipping operation where the chip length is controlled by feed rate into the chipping disk while the chip thickness and width are more a function of how the wood material fails due to mechanical stresses.

The bulk density of the raw chips was 309 kg/m^3 at the as-received moisture content of approximately 52.5 percent (wb).

From the sieve data, we can calculate that the geometric mean diameter is 22.3mm, and the S_{gm} is 1.86, per ASABE S319.3 (ASABE 2008).

We measured a subsample of 120 chips to physically measure length, width and thickness following our published protocol (Dooley, 2011). Additional data was collected on the number of particles that were bark or had bark attached. We did not measure particles less than about 6 mm length. More than 95 percent of the particles were judged to be chip shaped with a few shard, stick, and flake shaped particles in the mix. Less than two percent of the particles were bark or barky.



Figures 3a, 3b, 3c. Distribution of particle length, width, thickness, and L:W Ratio for whole tree forest residual chips from Herman Bros. Logging.

The above charts show the high overlap of length and width measurements for wood chips, making it impractical to orient the chips with respect to grain using traditional aspect-ratio methods (e.g., vibrating trough). More than 40% of the particles had a Length-to-Width Ratio (L:W) of less than 1.5, further supporting the difficulty of sorting or orienting the chips by length. Chip thickness had an expected 2 – 8 mm range for whole tree 25-30 mm chips.

For the purposes of this comminution energy experiment, large subsamples were taken from the bins of raw material and grossly oversize (more than 150 mm wide) and over-thick (more than 10 mm thick) particles were removed to protect our laboratory rotary shear machine. The remaining chips were then used as experiment feedstock.

Methods and Equipment

Characterization followed Forest Concepts protocols:

- Collection of Chipped or Shredded Biomass Samples for Quality Assurance and Characterization - Created 2008.08.21 – Revised 2010.07.20
- Protocol for Assessing Particle Shape of Comminuted Biomass
- Protocol for Moisture Content and Oven Dry Weight Determination
- Protocol for Stacked Wire Screen Size of Biomass Fuel & Feedstock Samples
- Bulk density

The Forest Concepts laboratory rotary shear machine (muncher) was used for processing of the chip samples. A conveyor was added above the infeed chute so materials could be fed more evenly than simply pouring onto the chute. Energy data was recorded using both torque arm based measurement as well as electrical draw measurements captured through a LabView® program and analyzed in Excel (Lanning, 2011). The muncher was set up with 4.8 mm (3/16-in.) wide cutters and operated at a shearing speed of one meter per second (200 feet per minute). Each 1 kg (approximately 0.5 kg dry basis) sample was processed in 17 to 40 seconds. There was no attempt to orient the chips with respect to grain direction; thus, it was expected that both the energy and resulting particle geometry would represent a mix of chips sheared at all angles with respect to grain. Particles sheared parallel to grain should consume low energy, but result in long particles, while particles sheared pure cross-grain should consume higher energy and result in short particles.

Figures 4. Forest Concepts' laboratory rotary shear machine (muncher). Shown here processing veneer strips.

Specific energy for comminution was measured as follows:

- Six subsamples of approximately 1kg each were collected from the raw material. Stones and very large biomass pieces are not included so as to protect the laboratory muncher.

We assume that such pieces would be removed from the raw material by our beneficiation process in an operational situation.

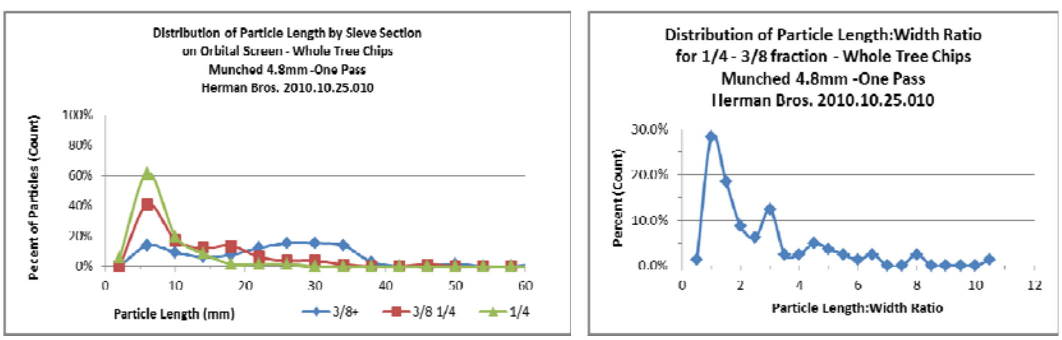
- Each subsample would constitute one first-pass run on the laboratory muncher. Energy data was collected using LabView program and Excel analysis.
- Prior to each run, the mass of the sample was measured.
- Output of the muncher was separately collected for each sample run.
- Three random output containers were selected for reprocessing via a second pass through the muncher where energy was again recorded and analyzed.
- All six output samples were processed through the sieve analysis.
- After sieving and weights were recorded on a green weight basis, the six output samples were recombined, weighed and individually dried to determine oven dry mass.

Results:

A total of six whole-tree chip samples were processed, with three reprocessed by a second pass through the laboratory muncher.

Figures 5a, 5b, and 5c. Whole tree chips as received, results of one pass through 4.8mm wide rotary shear, results of two passes through 4.8mm wide rotary shear.

It is readily apparent from the above photographs that processing through the rotary shear substantially reduces the particle size.



Figures 6a and 6b. 6a) Particle length for whole tree chips processed with 4.8mm rotary shear cutters and then sieved through orbital screen into three fractions. 6b) Particle length to width ratio for the 3/8 to ¼ screen fraction of the munched whole tree chips.

The above charts show that particles retained on the coarser screens tended to have a broader and higher distribution of particle length as would be expected. The particles passing through a ¼ inch screen predominantly were less than 10mm length. The length-to-width ratio of the target (pass 3/8, no-pass ¼) fraction shows that more than half the particles had a L:W ratio of less than 2.0 suggesting that orientation for further cross cutting will be difficult with conventional particle orientation systems.

Visually, the unprocessed chips have a high width to length ratio while the comminuted chips appear to have a high length to width ratio. Since the chips were not oriented with respect to the grain, they are cut at random orientation with some chips cut cross grain into short particles and others cut parallel to grain producing long particles. Although the visual effect is that particle length to width ratio increases in the munched particles, the graph of particle shape analysis shows that the effect is minor at best.

Particle Size Results:

The output from each of the six experimental runs was collected and sieved through a standard screen set using our Tyler Ro-Tap® shaker for ten minutes. The mass collected on each screen was weighed and entered into an Excel® spreadsheet template that calculates particle size distribution and geometric mean diameter (X_{GM}). It is important to note that the sieve results are a function of particle width and thickness properties and do not represent particle length.

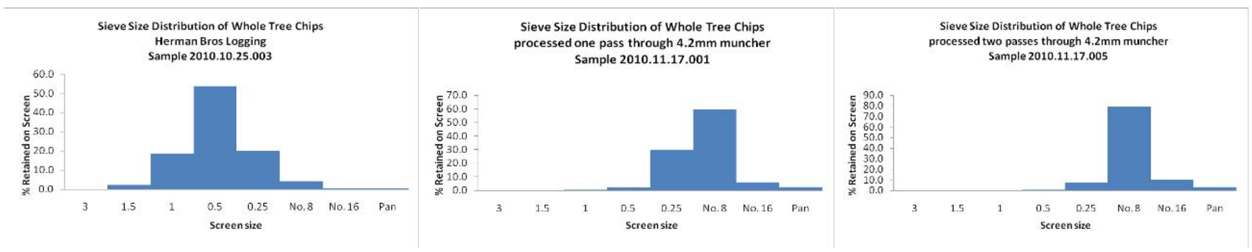


Figure 7. Histogram of particle sieve size distribution for raw chips, single pass and two pass through the rotary shear muncher. (Percent retained is on a mass basis)

Figure 8. Change of geometric mean diameter for whole tree chips processed through a rotary shear using 4.8mm wide cutters.

Comminution of whole-tree chips through the 4.8mm wide rotary shear machine reduced the geometric mean diameter from 22.3 mm to 6.6 mm on the first pass and then to 5.1 mm on the second pass. The typical histograms (randomly selected from the three replicates of each treatment) in the above figure show how the particle size distribution shifted to smaller sizes and the particle size range narrowed substantially for the two-pass material. Two passes through the 4.8mm muncher resulted in more than 70 percent of the resulting particle mass to pass the screen with a 6.3 mm opening and be retained on the screen with a 2.4 mm opening.

Specific Comminution Energy Results:

Specific energy for comminution was calculated from Labview® captured data using an Excel® spreadsheet for each run. Each run processed approximately one kilogram of wood chips at field moisture content. Moisture content of each subsample was determined by oven drying the sheared particles. Power consumption was determined using a torque-arm and tension load cell to determine no-load and processing power. The Labview® system operated at 960 observations (lines of data) per second.

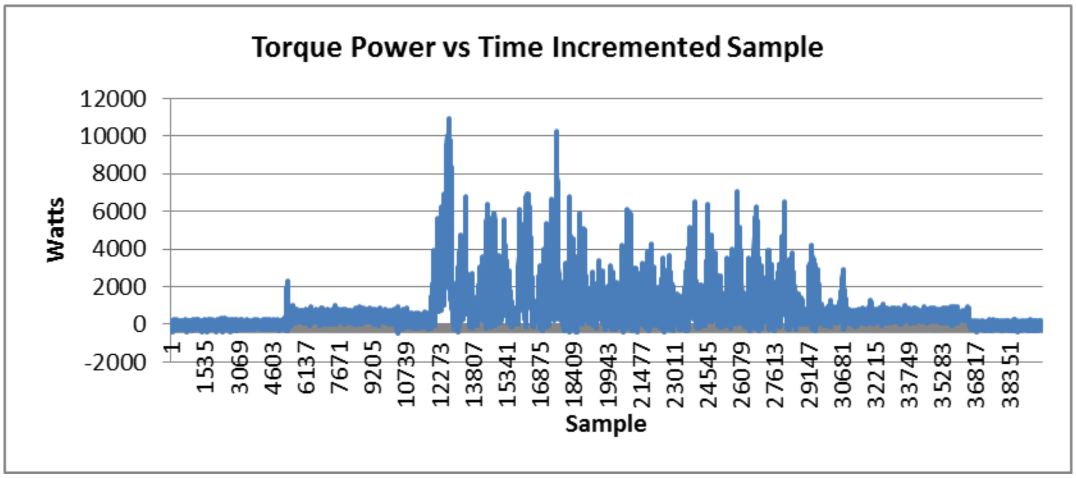


Figure 9. Typical torque measurement data set showing no-load from line 5000 to 11,500 and processing load from line 12,000 through 30,500. Each line represents 1/960 of a second.

Torque measurements were averaged across the no-load and processing load ranges. The "spikyness" of the processing load is due to the highly variable thickness and size of wood chips as they flowed into and through the shearing head.

As noted earlier, three of the samples were reprocessed a second pass through the rotary shear munching head. Results are summarized in table form below.

Table 1 Summary of conditions and energy data from wood chip comminution experiment.

				No load Power	*Specific Power*	*Specific Energy*
Sample File Number	MC (%wb)	Kg	Sec	Tpwr (W)	Tpower (W)	MJ/ODT
File: 20101117.001.Pass1	47.5	1.051	19.77	407	1088	20.5
File: 20101117.002.Pass1	49.8	1.003	17.77	564	852	16.8
File: 20101117.002.Pass2	49.8	1.003	17.09	474	512	8.7
File: 20101117.003.Pass1	43.8	1.124	40.35	367	590	21.2
File: 20101117.003.Pass2	43.8	1.124	25.79	421	391	9.0
File: 20101117.004.Pass1	51.7	0.966	28.91	479	552	16.5
File: 20101117.005.Pass1	48.3	1.035	17.97	409	1127	19.6
File: 20101117.005.Pass2	48.3	1.035	30.96	463	243	7.3
File: 20101117.006.Pass1	46.4	1.073	21.46	469	927	18.5

The average specific comminution energy for the six samples on first pass is 18.8 MJ/odt (s=1.9, SE=10%), and the average second-pass energy was 8.3 MJ/odt (s=0.9, SE=11%) for the three samples reprocessed a second time.

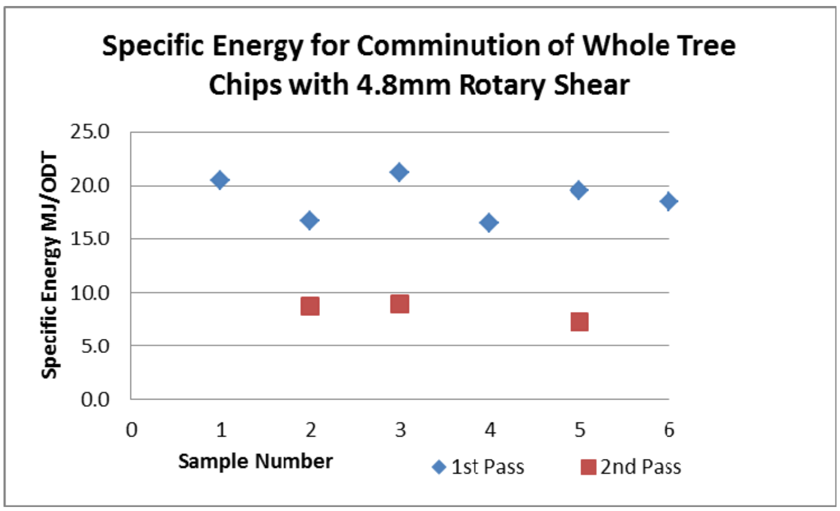


Figure 10. Specific energy for comminution of whole-tree chips with 4.8mm wide rotary shear (muncher) cutters for six subsamples where all were processed one pass and three were processed a second pass through the same cutter set.

The data suggest that it takes about half the energy to reprocess wood particles a second pass through the same cutter set. The particle size data presented earlier also suggests that particle size is further reduced with a second pass – most likely due to the random nature of how individual particles orient as they pass through the cutter head. Some particles are further sheared parallel to grain and some long particles are further sheared across grain.

Discussion:

Whole tree chips are the dominant form of woody biomass from forest thinning, logging residuals, and mill residuals in North America. Clean chips from roundwood that was debarked before chipping have sufficiently low ash content to meet the ash content standards for residential grade wood pellets. Clean chips also are a preferred raw material for biochemical and thermochemical conversion to liquid transportation fuels.

However, traditional chips must be further comminuted into small particles for pelletizing or conversion to liquid fuels. The nominal size desired by many users is between one and four millimeters, which may be represented by passing a No. 4 or No. 8 sieve depending on the use. Particle sieve size results shown in Figure 7 suggest that whole tree chips can be reduced to the target size range by one or two passes through a 4.8mm cutter set in our rotary shear machine.

Although we processed the material twice through the same cutter set in this experiment, operational processing equipment would most likely involve a sequence of smaller width cutters in successive shearing heads. Such an arrangement is expected to reduce the resulting particle size variance without substantially changing the comminution energy requirement.

Conclusions and Implications for Low Energy Comminution of Biomass:

The results of this set of experiments achieved the objective within our DOE SBIR Phase II agreement (SC0002291) to determine the applicability of our rotary shear technology to comminution of whole-tree chips.

The series of experiments demonstrate that we can reprocess whole-tree chips through our research scale rotary shear (muncher) to produce particles in the size range desired for pellet fuel and liquid transportation fuel feedstocks. The 4.8mm wide cutter set proved strong enough to cut highly variable wood chips.

Specific energy for comminution was approximately 20 MJ/odt (6.1 kWh/short ton) for the first pass through our muncher and less than 10 MJ/odt for a subsequent second pass. The specific energy for first pass comminution is less than we have measured for cross-grain comminution of conifer veneer into similar particle sizes. This is probably a consequence of the random orientation of wood chips as they are cut in this experiment. Those chips that are sheared parallel to grain will consume very little energy while those sheared cross-grain will consume higher energy.

Specific energy consumption for reprocessing whole tree chips through a rotary shear appears to consume less than half the energy that would be required by a knife mill, grinder, hammer mill or other attrition mill device. Actual differences must be determined in a side-by-side experiment with the same raw material chips and same output particle size objectives.

In an operational setting, multipass shearing may be directly coupled where output from one muncher would feed directly into the next; or each muncher may be followed by a screening operation to remove on-target particles before passing the oversize particles to a subsequent muncher head.

As was expected, bulk feeding of whole tree chips into the muncher did not materially alter the shape distribution of the resulting particles due to the random cutting orientation. When compared to our highly uniform Crumbles® precision feedstock it is apparent that only small percentage of the reprocessed chips would meet the Crumbles® uniformity specifications. Considerable investment in conversion research is needed to fully understand the effects of particle shape on conversion yield, time, and efficiency, particularly to compare Crumbles™ feedstocks, munched woodchip feedstocks, and traditionally hammermilled etc. feedstocks.

Shearing wood chips through fixed-width rotary cutters substantially shifted the particle size (as measured by sieve analysis) downward and narrowed the distribution of particle sizes in the resulting population.

Acknowledgements

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