This is not a peer-reviewed article.

Paper Number: 036077
An ASAE Meeting Presentation

Review of Biomass Size Reduction Technology

Manlu Yu, Graduate Student

Biosystems Engineering & Environmental Science, University of Tennessee, Knoxville, TN 37996-4531, U.S.A

myu@utk.edu

Alvin R. Womac, Associate Professor

Biosystems Engineering & Environmental Science, University of Tennessee, Knoxville, TN 37996-4531, U.S.A

awomac@utk.edu

Lester O. Pordesimo, Associate Professor

Biosystems Engineering & Environmental Science, University of Tennessee, Knoxville, TN 37996-4531, U.S.A

pordesim@utk.edu

Written for presentation at the
2003 ASAE Annual International Meeting
Sponsored by ASAE
Riviera Hotel and Convention Center
Las Vegas, Nevada, USA
27- 30 July 2003

Abstract. *Biomass size reduction is an important step in biomass densification and this article reviews reduction studies. Hammermilling technology had the advantage of low maintenance over other methods including crushing, shearing and rollermilling. A review of equipment design parameters showed that hammermill tip speed, power requirements, grinding rate, screen size, and clearance affect performance to varying degrees. The effects of biomass tensile and shear properties, moisture content, and biomass density were noted in size reduction processes.*

Keywords. Particle size reduction, hammermill, shearing, rollermill, tip speed, power requirement, screen size, clearance, densification, density and moisture.

Introduction

The high volume, low density characteristics of agriculturally produced biomass are a significant impediment to using biomass feedstock for many processes, including bioenergy production (ORNL, 2003). The low density of biomass increases transportation costs and often makes it difficult to feed the material into processing equipment at existing facilities. Appropriate size reduction processes reduce the volume of the biomass, and are a first step in densification. Lack of engineering/ scientific knowledge of biomass fiber grinding hinders the use of some feedstocks for biomass use. This contrasts with our understanding of grinding brittle-materials that are mathematically described (Austin, 1971). Fibers behave differently when loaded in different directions unlike homogenous brittle materials; they are strong against loads oriented parallel to the fiber length. Although milling and grinding is one of the oldest methods for processing biomaterials, very little is known about optimizing the process based on the mechanical properties of the material to be ground. Mohsenin (1986) concluded that almost all of the energy in the grinding process is wasted as heat, and that from 0.06 to 1% of the input energy actually disintegrated the material.

Particle size reduction is an important procedure of biomass utilization for energy production and animal feedstock. Particle size and densification are important for harvesting, transporting, and drying an otherwise unwieldy crop (Lopo, 2002). Some have studied the macro-performance of grinders. Hammermills ground forage crops, grains and biomass materials (Hill and Pulkinen, 1988; Samson et al., 2000). Balk (1964) related hammermill specific energy to moisture content and feed rate of coastal Bermuda grass. Samson et al. (2000) reported a specific energy consumption of 44.9 kWh/t for a hammermill with a screen size of 5.6 mm with switchgrass. Moisture content, bulk density, true density and particle size and shape of biomass particles after grinding were important for downstream processing for 62 kinds of biomass (Ebling and Jenkins, 1985).

Hammermills have wide applicability in biomass size reduction because of their simple design, ruggedness, and versatility. According to Scholten and McEllhiney (1985), hammermills have achieved merit because of their ability to finely grind a greater variety of materials than any other machine. Some authors have studied factors that influence hammermill performance including tip speed, grinding rate, screen size, and clearance. The size of the resulting particles depends on the size of the wire mesh installed in the machine and on the feeding rate of material into the grinder. The capacity of a machine to grind particles depends on the power rating of the machine, and also the final size and moisture content of the resulting particles. Hammermill uses high-velocity rotating shafts to impart kinetic energy to the processed material. The leading edge of the "hammers" beat the biomass until it is small enough to pass though a wire mesh. The hammer can be fixed or freely swinging. The hammers can be inverted and rotated such that each hammer can be used in two or four different positions. This contributes to the low maintenance requirement for the hammermill machine.

The hammermll is especially useful for grinding medium and fine material and because less power is needed for fine grinding. The resulting fineness of the material depends of the screen size and rate of movement through the grinder. The capacity of a particular grinder depends upon the grain, fineness, power available, speed, and moisture content of the product. Normally about 1 kW is required to grind 1 kg/min for medium grinding (Hall and Davis, 1979).

Tensile and shear properties of the biomass can influence the energy requirements for biomass size reduction. Some authors have studied cutting and shearing forces for biomass materials. The location of the applied force has also been studied. A notable study by Iwaasa et al. (1995) examined the cutting force for alfalfa at the node locations and at internode locations. Another study by O'Dogherty et al. (1995) scrutinized the tensile and shear strengths of cutting stems between nodes. In addition, Annoussamy et al. (2000) studied shearing and bending stresses in wheat straw.

Another aspect of biomass size reduction is material property. The mechanical properties of biological materials are not always possible to determine as precisely as metals. Also, the difficulty of exact physical measurements like diameter, length, and thickness, may lead to errors in calculating stress, strain and modulus of elasticity (Prince et al., 1968).

The objective of this article was to identify, organize, and interpret biomass, and related, particle size reduction studies, with special attention given to hammermills.

Methods

Articles were identified using the UT Library and Interlibrary services, including the online ASAE and international (CAB) databases. A variety of key words and concepts related to biomass size reduction were searched, with additional emphasis placed on hammermills. Studies of comparing size reduction techniques were searched. Emphasis was given to distinguishing between normal and shear stress applications. Results were listed in chronological order, and then an integrated format was organized by design factors.

Results

Chronological Listing

Gustafson and Kjelgaard (1963) determined the effects of alfalfa hay pellet geometry, forage moisture content and treatment, and material weight on pellet stability, durability, and forming pressure. They studied hay compaction over a wide range of moisture content (28 - 44%) and found that the dry density of the product decreased as moisture content increased. For example, an 134 cm^3 pellet with 44% moisture expanded less than those made at 28 or 36% moisture. Also, the lowest moisture contents required increased forming pressures. At 44% moisture, pellets made from short chopped (1.3 to 3.8 cm fiber length) and lacerated (no set fiber length) forages required lower forming pressures than those pellets made from the long chopped (6.4 to 8.9 cm fiber length) forage. Pellets made from the short chopped or lacerated material were less durable than the pellets made from the long chopped forage. There were no significant differences in the maximum pressures required to form pellets from long chopped forage over the moisture range of 28 to 44%.

Prince et al. (1968) provided engineering properties of corn stalks, including tensile, compressive, and shear strengths, and bending characteristics. Also, they indicated that the ultimate compressive force of alfalfa was directly proportional to stalk diameter, and was obtained at a moisture content of 30% wet basis (w.b.). Compressive stress parallel to the stalk of 3.8-cm diameter corn showed a non-linear stress-strain relationship at a loading rate of 2.5 cm/min.

Austin (1971) mathematically described grinding processes generally used for homogenous brittle materials. Topics included particle size distribution, differential equations describing particle breakage, and thee notion that grinding is a rate process dependent on some small period of time Δt. Continuous flow and batch grinding were considered.

Mohsenin and Zaske (1976) determined the minimum pressure and hold time required to compact unconsolidated wood particles and forage cuttings, including high moisture grasses. Compactions of these biomaterials required pressure as high as 48,265 kPa for a piston velocity of 33 cm/s. Three different forage materials (alfalfa hay, fresh alfalfa and grass) were tested. The maximum hay particle size was 80 mm after the hammermillling action of the shredder. The initial moisture content for grass was 51%. The test showed that lower moisture content yielded higher final density for both unshredded hay and shredded hay. The moisture content 8% w.b. and 25% w.b. for both unshredded hay and shredded hay had around 641-801 kg/m^3 and 320 kg/m^3 final density. Moisture content in the material also affected the residual stress. With increasing moisture content, less energy was required to get a certain initial density. Also, the influence of the moisture content on the energy requirement is related to the final density.

Ige and Finner (1976) developed a mathematical model based on the energy requirements for shearing whole alfalfa and corn stalks less ears. Their objective of the optimization was to minimize the shearing energy. They concluded that the higher the moisture content, the lower the shearing energy. The corn stalks could be sheared efficiently by setting the knives at clearance distances greater than zero while alfalfa required a clearance distance as near zero for efficient shearing. Parameters included knife dullness, clearance distance, moisture content, cutting force, normal force, shearing energy, and rotational speed.

Nelson et al. (1982) emphasized the densification of cubing versus typical pellet milling. The pellet mill required 35-70 kwh/ton on a given raw material (ex. straw), whereas the cuber will require only 10-20 kwh/ton. Pellet mills are limited in the size of biomass particles that can be ground. The particles processed by pellet mills are generally restricted to 80% of the die-opening diameter or less. A cuber by contrast can more easily process particles. 75% of these particles are smaller than 3.2 cm.

Heimann (1983) used indicted that roller mills were 16% more energy effective than hammermills in reducing grain to a small particle size (approximately 400 microns). Roller mills were up to 86% more energy efficient than hammermills for processed grain particle sizes approaching 2000 microns. Less heat build up in the roller mill appeared as an advantage. It should be pointed out that the grain was perhaps more brittle than many biomass feedstocks.

Scholten and McEllhiney (1985) determined that using pre-breakers and sieves had little affect on the final particle size of U.S. No. 2 yellow corn being ground by a hammermill. Final geometric mean particle diameters were about 700 μm. The 22.4 kW hammermill, equipped with a 3.2 mm screen, used approximately 7.5 kWh/Mton of energy.

Related to required particle sizes, Shen (1987) developed a new method to produce a water resistant pellet from mill residue with a conventional pelletizing process plus a simple pretreatment of high-pressure steam for a short period of time. He suggested the following standard: coarse particles are those that cannot pass through a 5 mm mesh. Medium particles can pass through a 5 mm mesh, but cannot penetrate a 1.7 mm mesh. Fine particles can penetrate a 1.7 mm mesh. In animal feed, medium and fine size is desirable because of its moisture-absorbing properties.

Greenberg et al. (1989) studied the tensile behavior of grass. Stiffness, toughness, and strength increased as strain rate increased, though ductility was inversely proportional to strain rate. Also, the brittle behavior increased with increased strain rate. Increased brittle tensile behavior was generally associated with reduced toughness values.

Usrey et al. (1992) studied internal shear (tensile test) and shear strengths, and the pressure-density relationships of rice straw during compression. The result showed that the cross-sectional shearing strength of rice straw stems ranged from 28 to 87 N.

Vigneault et al. (1992) investigated hammer thickness effects on the hammermill grinding rate and energy consumption for grains and forage pellets. They examined 3.18 and 6.35 mm thick hammers for grinding corn, alfalfa pellets, and wheat grain. Results indicated that thin hammers saved 13.6% in energy consumption and increased the grinding rate by 11.1% for a similar quality of grain grind. The results also showed the specific energies ranged from 5.5 to 9.5 kWh/ton for hammer thickness ranging from 1.59 to 8.00 mm, respectively. Also, specific energies ranged from 4.6 to 12.9 kWh/t for hammer tip speeds ranging from 54 to 86 m/s, respectively, for a 6.35 mm thick hammer.

Guritno and Haque (1994) observed that energy per unit mass of milled product and energy per unit surface area of milled product also decreased when the fast roll speed increased. These increased as the roller gap setting was reduced and as the differential speed decreased. When the rolls were set on the dull-to-dull configuration, the energy per unit mass increased, but the energy per unit surface area decreased.

Iwaasa et al. (1995) studied the stem shearing force for three alfalfa cultivars grown under dry land and irrigated conditions. Shearing forces were higher for alfalfa stems grown under irrigation than under drying condition. Shearing force and stem diameter had a significant positive correlation. Also, shearing force at the bottom of the alfalfa stem was greater than at the stem middle and top.

O'Dogherty et al. (1995) studied the physical properties of tensile and shear strength of cutting stems between wheat straw nodes. Tensile strength was in the range 21.2 to 31.2 MPa and shear strength in the range 4.91 to 7.26 MPa for the four stages, and Young's modulus was between 4.76 and 6.58 GPa. Measurements were done on physical properties, strength and elastic model; they found that plant maturity had some significant effects on shear strength.

Yang et al. (1996) determined particle size distribution and particle shape of hammermill-ground alfalfa. This study concluded that the particle density was in the range of 1390 to 1599 kg/m^3 at a moisture content of 5.3% w.b. The mean particle length, width, area, and perimeter ranged from 0.074-0.979 mm, 0.034-0.425 mm, and 0.002-0.295 mm^2, and 0.188-2.421 mm, respectively, as retained by various sieves with openings that ranged from 20 to 850 μm.

Hauhouot et al. (1997) showed that a Jay Bee Disintegrator hammermill (Tyler, Texas) equipped with 16 hammers, a 4.58 mm screen, and an operating speed of 3600 rpm was more effective at grinding a mixture of 1.24 mm (minor diameter) cheat seed, chaff, and straw than a roller mill set with a roller gap greater than 0.1 mm. They noted that the roller mill subjected kernels to shear and compressive forces, and that the hammermill simply subjected the seeds to impact forces - without distinguishing between shear and normal stresses.

Fang et al. (1998) showed a high correlation between the characteristics of a single wheat kernel and the power and energy requirements for milling wheat through an instrumented two-roll mill. They used specific energy as a measure of energy efficiency of first-break grinding. Variables examined included class of wheat, moisture content, feed rate, fast roll speed, roll speed differential, and roll gap. Roll gap had an inverse effect on new specific surface area and energy per unit mass and a direct effect on specific energy.

Annoussamy et al. (2000) examined shearing and bending stress properties of wheat straw left on a soil surface. They attributed a higher Young's modulus and maximum bending stress of the internode to its higher proportion of hemicelluloses. The decomposition properties of wheat were studied focusing on the relationship between the ability to shear and bend the wheat straw and the wheat straws moisture and decomposition.

Fang et al. (2000) studied the energy requirements of the roller mill for wheat milling size reduction using neural networks for prediction. They concluded that kernel hardness had the most significant positive effect on power and energy requirements for wheat milling among wheat physical properties. Roll gap had the most significant negative effect on power and energy requirements for wheat milling among roller mill operating parameters. Kernel weight, and size had significant negative effects on specific energy, a heavier and larger kernels utilized energy more efficiently than smaller kernels, but had positive effect on energy per unit mass. Moisture had negative effect on power and energy requirements. Wheat class had also effect on specific energy.

Molenda et al. (2001) considered the mechanical properties of granular feed ingredients. They also investigated the properties of wheat, ground corn, and soybean meal in terms of densification. By using a shear apparatus, the moisture content, unpacked bulk density and multipycnometer density were: 10.4%, 733 kg/m^3 and 1.41 g/cm^3 for wheat; 11.4%, 583 kg/m^3 and 1.35 g/cm^3 for soybean meal; and 11.7%, 595 kg/m^3 and 1.41 g/cm^3 for ground corn, respectively.

Pasikatan et al. (2001a) studied the affect of roller mill gap and single-kernel properties on energy requirements for wheat grinding. They found that roll gap had an effect on specific energy, new specific surface area, energy per unit mass, and also did single kernel hardness. Also, they showed that roll differential, roll diameter, roll speed, and roll corrugation affected grinding energy. Energy consumption increased with the capacity of grinders. Net specific energy consumption increased as roll gap was reduced, but decreased as fast roll speed increased. Wheat class had a significant effect on the energy per unit mass, new specific surface area created and specific energy.

Pasikatan et al (2001b) investigated the single kernel properties of wheat and the milling data based on roller mill's roll gap and the size properties of first-breaking ground wheat. The experimental first-break roller mill used in this study was 52.3 rad/s fast roll speed; 20.9 rad/s slow speed (2.5:1 roll speed differential); 1.34 kg/m-s feed rate. Former studies showed any variation below 50% of the theoretical feed rate would not affect ground wheat properties. They concluded that roll gap had an inverse effect on break release and a direct effect on geometric mean diameter. Single kernel hardness had a direct effect on geometric mean diameter and an inverse effect on break release. Single kernel mass had direct effects on geometric mean diameter and inverse effects on break release. Wheat class had a significant effect on break release and geometric mean diameter.

Zhang and Buckmaster (2001) constructed a novel shredding/crushing machine (a forest harvester) and evaluated power requirements as a function of particle size as affected by roll speeds, speed difference, and minimum roll clearance. Increased clearance required increased specific energy. Minimum roll clearances of 10 mm (front rolls) and 1 mm (rear roll), along with unit roll forces of 15 N/mm (front) and 45 N/mm (rear) produced more processed material with thinner stalks and shorter pieces than the minimum roll clearance of pair 10 mm (front) and 2 mm (rear) or unit roll forces of 30 N/mm (front) and 30 N/mm (rear). Energy requirement was similar for roll speed differences of either 17% or 50%. There are very small differences in specific energy requirements among different speed treatment.

Lopo (2002) comparing three kinds of equipment (hammermill, roll mill, and vertical hammermill) that could produce a generally acceptable grind in the range of 600 to 800 μm. Hammer tip speed was a critical factor for good grinding. Typical tip speeds ranged from 81 to 117 m/s. He also concluded that the grind size depended on the roll gap. In order to improve size reduction, one of the rolls should rotate faster than the other, with the typical speed differentials ranging from 1.2:1 to 2.0:1 (fast to slow). Typical roll speeds range from 6.6 m/s for a 23-cm roll and 16 m/s for a 30-cm roll. The hammermill used energy less efficiently than a roller or vertical hammer mill. Comparing the vertical hammers and horizontal hammers, vertical hammer had lower energy consumption, less moisture loss, reduced grinding shrink, narrower particle size, and fewer fines.

Mani et al. (2002) ground energy crops including wheat and barley straw, corn stover, and switchgrass with a hammermill using three different screen sizes (3.175 mm, 1.588 mm, and 0.794 mm). The densities of the biomass ranged from 40 to 250 kg/m^3. Switchgrass required the most grinding energy and corn stover used the least energy. Physical characteristics of the resulting particles were studied including the distribution of particle sizes, moisture content, geometric mean diameter, and resulting densities. The experiment found that the large hammermill screen size resulted in reduced energy requirements for all types of tested biomass.

Marcotte et al. (2002) described a mobile extractor for wet fractionation of alfalfa. Two chop lengths (8.9 and 17.7 mm); three levels of feed rate (ranging from 81 to 451 kg/h) and two types of hammers (flat edge, V-edge) were evaluated during the experiment. Vertical hammermills had a higher degree of cell rupture with hammers was obtained with an increased number of hammers, a higher rotating speed of hammers, and decreased feed rate. Also the degree of cell rupture was higher with a short chop, V-edge hammers. V-edge hammers yielded a lower dry matter extraction ratio than the flat edge hammers.

Yore et al. (2002) determined mean peak shear forces and shearing energies ranging from 5.5 to18.6 N stem^{-1} and from 0.20 to 0.36 J stem^{-1}, respectively, for a rice straw node being sheared by a standard double knife sicklebar interfaced to a universal testing machine. The cutting speed was 0.21m/s. Shear force and energy increased at stem nodes compared to internodes.

Synthesis of Design Information

Biomass Response to Stress Application

Various designs of size reduction equipment apply different stresses. For instance, a roller mill applies compressive stresses; whereas, a hammermill may apply a combination of normal and shear stresses. Some studies examined the effect of stress application on biomass. Iwaasa et al. (1995) found a significant positive correlation between shearing force and thickness of alfalfa stem. Not as intuitive as thicker stems requiring increased cutting force, shearing location along the stem affected the shearing force (Yore et al., 2002). Shearing force measured near the base of the alfalfa stem was significantly higher than the shearing force measured in the middle and top of the alfalfa plant.

It was discovered that the shear and tensile strengths of alfalfa were inversely proportional to moisture content and directly proportional to dry-matter density (Greenberg et al. 1989). For the tensile behavior, as strain rate of grass was increased, the stiffness, toughness and strength increased, while ductility decreased.

Prince et al. (1968) provided information concerning the tensile and shearing strength properties of corn stalk for designing a biomass size reduction apparatus. The test showed actual shear-stress displacement curve shapes, which were regarded as being typical of other biological material. O'Dogherty et al. (1995) studied the physical properties of tensile and shear strength of cutting stems (wheat straw) between nodes. Tensile strength was in the range 21.2 to 31.2 MPa and shear strength in the range 4.91 to 7.26 MPa for the four stages of plant maturity. They found that plant maturity had some significant effects on shear strength. Yore et al. (2002) found mean peak shear forces and shearing energies that ranged from 5.5 to18.6 N stem^{-1} and from 0.20 to 0.36 J stem^{-1} respectively. This study focused on rice straw nodes being sheared by a standard double knife sicklebar. Shear force and energy increased at stem nodes as compared to internodes.

Hammermill Engineering Variables

Hammermills were expected to reduce particle size through hammer impact and were classified as straight hammermill, prebreaker-hammermill and prebreaker-sieve-hammermill. Many variables affect hammermill performance and grinding efficiency. Some of the variables are: hammer tip speed and hammer thickness, input power, and screen size and hammer clearance. These variables are discussed in the following paragraphs:

Hammer tip speed and hammer thickness

Hammer tip speeds can vary because of equipment design and size-reduction needs. However, tip speeds generally range from 76 m/s (Hall and Davis, 1979) to 117 m/s (Lopo, 2002). Tip speeds are usually achieved at shaft speeds ranging from 2500 to 4000 rpm (Hall and Davis, 1979). However, an interaction between hammer tip speed and hammer thickness affected energy efficiency of the hammermill (Vigneault et al., 1992). Results indicated that thin hammers saved 13.6% in energy consumption and increased the grinding rate by 11.1% for a similar quality of grain grind. Specific energies ranged from 5.5 to 9.5 kWh/ton for hammer thickness ranging from 1.59 to 8.00 mm, respectively. Also, specific energies ranged from 4.6 to 12.9 kWh/t for hammer tip speeds ranging from 54 to 86 m/s, respectively, for a 6.35 mm thick hammer (Vigneault et al., 1992).

Input power

The power requirements for grinding biomass are related to biomass selection, initial and final particle sizes (geometric mean diameter), moisture content, and feed rate of the material. Switchgrass required more specific energy for hammermill grinding than straws and corn stover (Mani et al., 2002). Because of its low fiber content and the presence of sponge vascular tissues in the stem, it was expected that corn stover would consume less energy. Little information related particle size to power requirements. Most studies indirectly studied particle size by focusing on the effects of screen size. Power requirements generally increased as the feedstock moisture content increased, within typical ranges of moisture content. Hall and Davis (1979) stated, "For ear corn and shelled corn the energy increase occurs as the moisture increases from 9 to 26%. From 1½ to 2 times as much feed can be ground at 10% as at 25% moisture." Finally, approximately 1 kW was needed to process 1 kg/min of medium size material (Marcotte et al., 2002).

Screen Size and Hammer Clearance

The larger hammer mill screen size required lower specific energy consumption for all biomass samples. The specific energy consumption for grinding wheat straw using hammer mill screen sizes of 0.794, 1.588 and 3.175 mm were 51.55, 39.59 and 10.77 kWh/t respectively at 8.30% (wb) moisture content (Mani et al., 2002). Screen size dictated final particle sizes. Yang et al. (1996) indicated alfalfa mean particle length, width, area, and perimeter ranged from 0.074-0.979 mm, 0.034-0.425 mm, and 0.002-0.295 mm^2, 0.188-2.421 mm, respectively, for the sieve opening from 20 to 850 μm. The median particle size of alfalfa grind was 238 μm with standard deviation of 166 μm. A hammermill with 16 hammers, a 4.58 mm screen, and an operating speed of 3600 rpm was more effective at grinding a mixture of 1.24 mm (minor diameter) cheat seed, chaff, and straw than a roller mill set with a roller gap greater than 0.1mm (Hauhouot et al., 1997).

Summary

- Published studies evaluated several aspects of biomass strength and particle size reduction.
- Many studies evaluated the overall performance of size reduction equipment, with general observations or hypotheses formulated to explain performance results.
- Trends were observed between hammermill engineering variables, such as hammer tip speed, hammer thickness, input power, screen size, and hammer clearance.
- No comprehensive engineering model described the size reduction process as it related to feedstock material properties and equipment design.

References

Annoussamy, M., G. Richard, S. Recous, and J. Guerif. 2000. Change in mechanical properties of wheat straw due to decomposition and moisture. *Applied Engineering in Agriculture* 16(6): 657-664.

Austin, L.G. 1971. A review: introduction to the mathematical description of grinding as a rate process. *Powder Technology*. 5(1): 1-17.

Balk, W.A. 1964. Energy requirements for dehydrating and pelleting coastal bermudagrass. *Transactions of the ASAE* 4:349-351;355.

Ebling, J.M., and B.M. Jenkins. 1985. Physical and chemical properties of biomass fuels. *Transactions of the ASAE* 28(3):898-902.

Fang, Q., E. Haque, C.K. Spillman, P.V. Reddy, and J.L. Steele. 1998. Energy requirements for size reduction of wheat using a roller mill. *Transactions of the ASAE* 41(6):1713-1720.

Fang, Q., M.A. Hanna, E. Haque, and C.K. Spillman. 2000. Neural network modeling of energy requirements for size reduction of wheat. *Transactions of the ASAE* 43(4):947-952.

Greenberg, A.R., A. Mehling, M. Lee, and J.H. Bock. 1989. Tensile behaviour of grass. *Journal of Materials Science* 24:2549-2554.

Guritno, P., and E. Haque. 1994. Relationship between energy and size reduction of grains using a three-roller mill. *Transactions of the ASAE* 37(4):1243-1248.

Gustafson, A.S., and W.J. Kjelgaard. 1963. Hay pellet geometry and stability. *Agricultural Engineering 44:422-425.*

Hall, C.W., and Davis D.C. 1979. *Processing Equipment for Agricultural Products.* The AVI Publishing Company, Inc. Westport, Connecticut

Hauhouot, M., J.B. Solie, G.H. Brusewitz, and T.F. Peeper. 1997. Roller and hammer milling cheat (*brooms secalinus*) to reduce germination as an alternative to herbicides. Paper No. 971002, ASAE, St. Joseph, MI.

Heimann, M.A.1983. Energy consumption and machine efficiency in particle reduction: A roller mill and hammermill comparision*. In: First international symposium on particle size reduction in the feed industry.* Kansas State University, Manhattan, KS, United States.
Hill B, and Pulkinen DA. 1988. A study of the factors affecting pellet durability and pelleting efficiency in the production of dehydrated alfalfa pellets. A Special Report. Saskatchewan Dehydrators Association, Tisdale, SK, Canada.
Ige, M.T., and M.F. Finner.1976. Optimization of the performance of the cylinder type forage harvester cutterhead. *Transactions of the ASAE* 19(3):455-460.
Iwaasa, A.D., K.A. Beauchemin, J. G. Buchanan-Smith and S.N.Acharya.1995. Assessment of stem shearing force for three alfalfa cultivars grown under dryland and irrigated conditions. *Canadian Journal of Animal Science* 75(1):177-179.
Lopo, P. 2002. The right grinding solution for you: roll, horizontal or vertical. *Feed Management* 53(3):23-26.
Mani, S., L.G. Tabil, and S. Sokhansanj. 2002. Grinding performance and physical properties of selected biomass. Paper No. 026175, ASAE, St. Joseph MI.
Marcotte, D., P. Savoie, D. Hamel, and L. P. Vezina. 2002. A mobile extractor for alfalfa fractionation. Paper No. 021070, ASAE, St. Joseph, MI.
Mohsenin, N. 1986. *Physical Properties of Plant and Animal Materials*, Gordon and Breach publishers Inc., Amsterdam, The Netherlands.
Mohsenin, N., and J. Zaske. 1976. Stress relaxation and energy requirements in compaction of unconsolidated materials. *Journal of Agricultural Engineering Research.* 21:193-205.
Molenda. M., M.D. Montross, J. Horabik, and I.J. Ross. 2001. Mechanical properties of granular feed ingredients. Paper No. 01-4019, ASAE, St. Joseph, MI.
Nelson G.B., G.C. Nelson, and H. White. 1982. Densification: cuber versus typical pellet mill. Annual Conference Report-41:98-99, Hawaiian Sugar Technologists, Honolulu, Hawaii.
O'Dogherty, M.J., J.A. Huber, J. Dyson, and C. J. Marshall. 1995. A study of the physical and mechanical properties of wheat straw. *Journal of Agricultural Engineering Research* 62(2):133-142.
(ORNL) Oak Ridge National Laboratory. 2003. Energy crops and the environment. Available at: http://bioenergy.ornl.gov/papers/misc/cropenv.html. Accessed 21 May 2003.
Pasikatan, M.C., G.A. Milliken, J.L. Steele, E. Haque, and C. K. Spillman. 2001a. Modeling the energy requirements of first-break grinding. *Transactions of the ASAE 44(6): 1737-1744*.
Pasikatan, M.C., G.A. Milliken, J.L. Steele, C.K. Spillman, and E. Haque. 2001b. Modeling the size properties of first-break ground wheat. *Transactions of the ASAE 44(6): 1727-1735.*
Prince, R.P., D.D. Wolf, and J.W. Bartok, Jr. 1968. Mechanical properties of corn stalks. Research Report 29, The University of Connecticut, Storrs, Connecticut.
Samson P, Duxbury P, Drisdelle M, and Lapointe C. 2000. Assessment of pelletized biofuels. Available at: http://reap.ca/Reports/pelletaug2000.html. Accessed 20 June 2001.

Scholten R.L., and R.R. McEllhiney. 1985. The effects of prebreaking in hammermill particle size reduction. Paper No. 85-3542, ASAE, St. Joseph, MI.

Shen K.C. 1987. Development of a waterproof densified solid fuel. Proceedings of the Sixth Canadian Bioenergy R & D Seminar, Elsevier Applied Science Publishers, London.

Usrey, L.J., J.T. Walker, and O.J. Loewer. 1992. Physical characteristics of rice straw for harvesting simulation. *Transactions of the ASAE* 35(3):923-930.

Vigneault, C., T.M. Rothwell, and G. Bourgeois. 1992. Hammermill grinding rate and energy requirements for thin and conventional hammer. *Canadian Agricultural Engineering* 34(2):203-205

Yang, W., S. Sokhansanj, W.J. Crerar, and S. Rohani. 1996. Size and shape related characteristics of alfalfa grind. *Canadian Agricultural Engineering* 38(3):201- 205.

Yore, M.W., B.M. Jenkins, and M.D. Summers. 2002. Cutting properties of rice straw. Paper No. 026154, ASAE, St. Joseph, MI.

Zhang, M., and D.R. Buckmaster. 2001. The design and evaluation of a novel forage harvester. Paper No. 01-1088, ASAE, St. Joseph, MI.