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Review and analysis of performance and productivity of size reduction equipment for fibrous materials

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Abstract. *Size reduction is an important pre-processing of biomass using as an energy source. The end technology and final use of ground biomass depends on the biomass specie, physical and chemical properties, organic and inorganic contaminants, and geometry of the ground particles. The purpose of this study is to review size reduction equipment on basis of selection criteria, operation, productivity, performance, energy requirement, input feedstock, particle size distribution of ground biomass, and their utilization. This review and analysis shows that there is a great potential of tub grinding as a means of preparing crop and forest residues for Bioenergy purposes. The review also reveals the correlation among the grinding rate, screen size, tub speed, particle size distribution and specific energy requirement. This study shows that an amount of US$3.01/ton is necessary to process agricultural residues with a tub grinder of capacity 70 ton/hr.*

Keywords. Size reduction, biomass energy, agricultural residue, hammermill, tub grinder

Introduction

Biomass supply logistics is one of the main challenges for cost-effective and wide use of biomass as an energy source. This includes biomass handling, transportation, size reduction, drying and storage of biomass for different conversion processes. Due to its heterogeneous nature, biomass materials possess high volume and low bulk densities. Densification is essential to reduce the transportation cost of biomass. Biomass size reduction is a pretreatment process that changes the particle size, shape and bulk density of the material. It increases the total surface area of the material and the number of contact points for inter-particle bonding in the compaction process (Drzymala, 1993). These make the size reduction as the first step of densification.

Size reduction of biomass particles is essential preprocessing for conversion of biomass into energy. Different particle sizes are needed for different energy conversion processes. In the production of fuel pellets and briquettes, the feedstock has to be ground to size less than 6 mm (Samson et al 2005, Mani et al 2003). Size reduction of lignocellulosic biomass is also necessary to eliminate mass and heat transfer limitations during the hydrolysis reactions (Schell et al 1994). Pulverized fuel burners suitable for biomass usually require particle sizes below 1000 µm (Kastberg 2002, Freeman et al. 2000, Anderl 1999), while the particle sizes used for coal in pulverized coal burner are usually below 100 µm (Freeman et al. 2000, White 1960, Siegle 1996). Biomass particles with sizes below 1000 µm (Kastberg 2002) can be considered as a pulverized feedstock due to its similar residence times like pulverized coal. In fast pyrolysis process, particles have to be very small to fulfill the requirements of rapid heating and to achieve high liquid yields. Feedstock must have moisture content less than 10% to minimize the water in the bio-oil (BTG, 2007). Feed specifications range from less than 200 µm for the rotating cone reactor (Bridgwater 2000) to less than 2 mm for fluid beds and less than 6 mm for transported or circulating fluid beds (DynaMotive 2006, Wisconsin Biorefining Development Initiative, 2007).

Various types of size reduction equipment are available in the market. Based on the classification of size reduction equipment done by Scubert et al. (2004) and Woldt et al. (2004), Miu et al (2006) added an extended layout of this classification and suggested hammermill, knife mill, and disc mill as the proper equipment for biomass comminution. Due to high size reduction ratio, good control of particle size range with relatively good cubic shape of particles, hammermills are widely used (Nikolov, 2004, Mani et al., 2004) and a number of literatures on grinding of different materials are available (Austin, 2004; Djordjevic et al., 2003; Paulrud et al., 2002; Austin, 2002; Hill and Pulkinen, 1988; Rypma, 1983). Knife mills work successfully for shredding forages under various crops and machine conditions (Ige and Finner, 1976). Disc mills produces very small particles if input feed is provided by knife mills or hammer mills (Womac, 2005).

The objectives of this study are:

- Analysis of the biomass particle size requirement for different energy production processes
- Analysis of the effect of biomass properties on the size reduction process
- Analysis of the performances of hammermill (especially tub grinder) using agricultural residues and wood as the input feedstock
- Cost analysis of size reduction process per ton of ground biomass production

Forms of Fibrous Material

Fibrous materials are available in different forms. Log is a piece of unprocessed timber, wood from trees used for construction or wood pulp for paper production. Branch is a part of a woody plant such as a tree, shrub, or vine. It is any woody structural member that is usually connected to but not part of the central trunk or boughs. A branch supports the terminal twigs, which in turn support the leaves. Branches may be oriented in any direction from horizontally to vertically, but usually have bark similar to the upper trunk (whereas twigs often have markedly different bark). Large or main branches are sometimes called limbs, while very small branches are called branchlets.

Due to expensive manual labor, there is a tendency to mechanize the agricultural production. Big bales are a result of such a development. It is suitable for tractor handling, too heavy to be handled manually. There are many different types of big balers. Some produce rectangular bales, but most make round bales.

During the mechanical treatment of fibrous material, powdered or a bigger size of fibrous materials are produced in bulk form. For example, sawdust or shavings are produced as byproduct in sawmill industries. These bulk forms are further utilized as raw materials for other products like pellets, hardboard etc.

Properties of Feedstock Affecting Size Reduction

Physical and mechanical properties of biomass species and varieties are very important when size reduction is performed. Literature on energy requirement of cutting operation of fibrous materials is inadequate (Brennan, et al. 1990). Cutting energy is related to the stem mechanical properties (e.g. maximum cutting force and stem shear strength), and physical properties e.g. stem diameter, dry matter density and moisture content (Mesquita and Hanna, 1995, El Hag et al. 1971, Prasad and Gupta 1975, Prince et al. 1969, and Chen et al. 2004). The physical measurements are extremely difficult in pinpointing exact failure stress and required energy due to differences in terms of material initial size, shape, surface, morphology etc.

Type of Material

The grinding output with the same energy consumption differs according to raw material. Output with cereal feed is higher than with roughage. With a screen hole diameter of 1.2 mm and a moisture content below 15 percent, the output in kg/kW is 45-60 for maize and sorghum; 17-22 for chaff; 12-16 for sweet potato vines; 8-12 for maize stover; 7-12 for sorghum stover; 6-10 for legume straw; and 3-4 for maize cobs (Guo, 2002).

Moisture Content

Tensile and shear properties of the biomass can influence the energy requirements for biomass size reduction. Size reduction studies shows that mean shear strength is approximately one-fifth of the tensile strength (Womac, 2005). Size reduction equipment is more efficient by applying shear stress rather than tensile stress, because shear mechanism may be considered the weakest mode of failure or natural fracture point.

According to Halyk and Hurlbut (1968) the ultimate tensile and shear stresses of alfalfa is inversely proportional to moisture content. Greenberg et al. (1989) reported that both ultimate stresses decreased with increasing moisture content for ryegrass. Annoussamy et al. (2000) observed that shear strength increased as moisture decreased for wheat straw. Ige and Finner

(1976) provided a similar result for corn stalk and alfalfa. They concluded that increased moisture content reduced shearing energy.

Others found an opposite trend. Igathinathane et al. (2007) shows that a math of moist switchgrass at 51% moisture content show more resistance to shear than a math of dry material at 20% moisture content. Kushwaha et al. (1983) reported a range of shear strength from 7.0 to 22 MPa for stem moisture content ranging from 5 to 30% w. b. in case of wheat straw. Minimum values of shear strength (7 to 10 MPa) occurred for stem moisture contents between 8% and 10% w. b. Mani et al. (2004) reported a positive correlation with specific energy consumption of wheat and barley straws, corn stover and switchgrass, the higher the moisture content; the higher was the specific energy consumption. Balk (1964) found similar pattern of results for alfalfa grinding.

O'Dogherty et al. (1995) also found reduced shear stresses (mean value of 5-30 MPa) for wheat straw at moisture contents 8 and 10% w. b., and hypothesized that dry brittle straw was weaker than moist tough straw. The results for tensile strength showed no consistent trends with varying moisture content. The modulus of rigidity decreased with increasing moisture content over a range of 499 to 389 MPa.

Plant Maturity

Plant maturity has significant effects on shear strength. Young's modulus also increases with maturity. O' Dogherty (1995) showed moisture content, Young's modulus, modulus of rigidity, and shear strength at different maturity stage of wheat straw. He carried out sampling on 6, 13, 23 July and on 6 August in 1990 to provide specimens at four stages of maturity. The shear strength was significantly greater for the first stage of maturity (7.26 MPa) than for the second to fourth stages (mean value 6.31 MPa).

Stalk Position

There is an increase in stem diameter and wall cross-sectional area from the first to the fourth stem internode from the plant ear. Shear strength at the lower side of the wheat straw are lower (O' Dogherty, 1995).

Equipment parameters affecting size reduction

Different size reduction equipment performs the comminution process differently due to the stress loading combination and magnitude in grinding space. Various parameters (equipment) affect the ground particle size of fibrous material. In the hammermill, impact loading occurs when the free swinging or fixed hammers, that rotate on a shaft strikes the material and is fired against the screen (Austin 2002). The material is broken into large piece and accelerated to a velocity similar to the tip speed of the hammer. The accelerated particle impact against the screen and are further comminuted. The particles retained on the screen are under the action of hammer again. Comminution is also done by rubbing the space between the hammer and the screen. For efficient operation of grinding in hammermill, following items is to be considered (Doerksen 1993):

- i) Product
    - a. Friable and non-friable
    - b. Non-friable and fibrous
    - c. Feedstock particle size
- ii) Screen design
    - a. Opening size

b. Position of screen

iii) Hammer design

a. hammer pattern

b. hammer quantity

c. hammer tip speed

iv) Speed of rotation

v) Method of conveying ground material

vi) Moisture content of the feedstock

vii) Method of feeding

viii) Installation and maintenance

Screen Design

Mostly ground particle size depends on the size of the screen used at the grinder outlet side. Screen plays an essential role in the functioning of machines for grinding in the fine-size range. Grinding rate decreases with the decrease in screen size and also power requirement increases with small size screen to get the same output (Arthur 1992). Screen design depends on the size of screen openings, position of the screen and effective screen area. Screen generates an average particle size that is smaller than the operating diameter. Materials remain in the grinding chamber until the particles are small enough to fall through the screen. Larger screen openings reduce the time of material stay in the grinding chamber resulting higher capacity. The capacity almost doubles when the screen size changes from 2.4 to 6.4 mm (Von Bargen 1990). Screens are positioned in two ways, i) screen circle the grinding chamber almost 360º, and ii) screen is placed across the bottom 180º of the grinding chamber. First arrangement reduces the quantity of material rotating inside the screen and permits properly sized particles to drop out more quickly. This arrangement is suitable for processing more hard to grind material. Second arrangement makes changing the screen easier. Screen area limits the ultimate capacity of a hammermill regardless of the input power (Von Bargen 1990).

Screen hole pattern are either staggered or straight line pattern. The 60 degree staggered pattern is most popular hole arrangement due to its inherent strength and the wide range of open area it provides (Roskamp Champion, 1992). The straight line pattern is weaker and has a tendency to stretch the material to a greater degree. This screen is highly prone to tracking (wear between the holes).

Hammer Design

Hammer size, style, number and arrangement are very important to get a desired particle size. The design and placement of hammers is determined by operating parameters such as rotor speed, motor power, and open area in the screen. Optimal hammer design and placement provide maximum contact with the feed ingredient. The material to be ground and the design of hammermill determine the number and size of hammers (Von Bargen 1990). The number of hammers, rotor speed, the types of product being ground, the amount of materials for grinding, and available screen area are to be considered to establish an appropriate configuration.

The number of hammer with 1800 rpm, usually is 1 for every 2.5 to 3.5 horsepower, and for 3,600 rpm, one for every 1 to 2 horsepower (Roskamp Champion 1992, Feed Machinery 2006). This may change with wider hammers. The distance between hammer and screen should be 12 to 14 mm for size reduction of cereal grains and about 5mm for fibrous material (Roskamp Champion 1992, Feed Machinery 2006). More hammers are used for fine grinding and thin hammers grind most materials more efficiently.

Speed of Rotation

Hammer mills are of high speed (3600 rpm) or low speed (1800 rpm) types based on the rotor speed. Tip speed is the speed of the hammer at its tip or edge furthest away from the rotor. It is critical for proper size reduction. A common range of tip speeds seen in hammermill is in the range between 5,000 and 7,000 m/min (Feed Machinery, 2006). When the tip speeds exceed 7000 m/min, careful consideration must be given to the design of the hammermill, the materials used in its construction, and the fabrication of all the components.

The speed of the hammer tips is approximately equal for various manufacturers and for different rotor speeds. High speed mills with smaller diameter rotors are good for fine or hard to grind material. At high tip speeds material moves around the mill parallel to the screen surface making the openings only partially effective. At slower speeds material impinges on the screen at a greater angle causing greater amounts of coarser feed to pass through (Von Bargen, 1990).

Air in the Grinding System

Rotating hammers in the grinding mill acts as a fan and build up air pressure against the screen. As a result air, dust and material blow through the screen. Purposes of air flows are to prevent the screen from blinding, to prevent heat buildup, to increase capacity and to provide dust control. If the air flow is not sufficient, moisture accumulates causing ground material to clump and block the screen. This often occurs on smaller screen openings (<2.75 mm) because of fine grind handling.

Performances of Size Reduction Equipment

There are varieties of size-reduction equipment in the market. There is no unique standardization of these types of equipment due to i) varieties of feedstock to be ground, ii) product qualities demanded, iii) inadequacy of useful grinding theory, and iv) the requirements by different industries in the economic balance between investment cost and operating cost (Perry et al 1997). Classification can be done on the basis of applying fundamental stress on biomass to be processed in four different ways: impact, attrition, shear, and compression.

In hammermill, rotating drum with fixed or swinging blades or knives which use shear, impact, attrition, and compression on materials to reduce size. Materials are sheared by blades in the Knife mill. There are rotating blades and one stationary blade. In disc mill, material is cut by attrition and shear, particle size determined by the distance between the discs. A practical classification of size reduction equipment for fibrous material is shown in table 1. A matrix of equipment types for wood and wood residues are shown in table 2.

Size reduction equipment can be further categorized as primary and secondary types. Typically, primary reduction equipment is selected to maximize the amount of processed materials in the desired size range, while minimizing fines and overs. This is really difficult as the wide varieties of raw materials processed. For wood and wood waste industry, the target size range for primary reduction is generally < 3", with some restrictions to the amount of fines depending on the end user (CWC 1997). A secondary type provides a ground product of greater uniformity in sizing.

There are various scenarios in size reduction processes of agricultural residues. The possible pathways for producing fine particles using single equipment or a combination of equipment are shown in figure 1.

Bales/loose → Tub grinding
Bales/loose → Tub grinding + Hammermill
Bales/loose → Shredder + Hammermill
Bales → Unrolling + Chopper + Hammermill
Bales → Linear Knife Grid + Hammermill
Bales → Knife Mill + Hammermill
Bales → Knife Mill / (+) Hammermill + Disc Mill

Figure 1 Possible pathway of size reduction processes of agricultural residues

A number of factors affect the selection of equipment for size reduction. Throughput, product size range, power input, frequency of repair and maintenance, and finally cost per ton product etc are among the major factors. Table 3 shows a guideline of selecting different models of equipment of Morbark brand (Weedmark 2006). This includes approximate prices, throughput, engine rpm, amount of fuel (power input) needed to get the specific output.

Tub Grinder

Mechanical properties play an important role on the energy requirement for particle size reduction of agricultural residues. Arthur et al (1992) investigated the energy requirement for size reduction of cereal residues (wheat straw, cornstover and rice straw) and woody residues with two different tub grinders, W.H.O and Medallion 905. The performances with agricultural residues are shown in table 4. The W.H.O grinder had a diesel engine with a 298 kW power a 3.05m diameter tub with the speeds of 1.5, 3.1, 5.7 & 9.5 rpm and 48 free swinging hammer with 1.42m long each. Medallion 905 was equipped with a 138 kW diesel engine. This grinder had a 2.23m diameter (base), and 2.87m diameter (top) tub with variable speed (1 to 14 rpm) and the hammer length of 1.02 m with 40 free swinging hammers. Interchangeable hammermill screens with hole diameters of 12.7, 19.1, 50.8 and 76.2 mm were used. There was substantial increase in grinding rate when the hole size is increased from 12.7 to 19.1 mm and a moderate increase between 19.1 and 50.1 mm. The increase was less with big round bales of rice straw than with loose straw from rectangular bales.

Table 4 also shows the relation of grinding rate to tub speed for three screen hole sizes with wheat straw from rectangular bale. In general, the grinding rate increases with tub rotational speed. However, the rate of increase of grinding rate becomes less as the tub speed increases. Specific energy requirements are greatest for the smaller screens. Rice straw requires nearly twice as much energy per unit mass as do wheat straw, and cornstover requires slightly more energy than wheat straw. The specific energy requirement tends to decrease as the grinding rate increases.

Results of Ro-Tap screening analysis are shown in the last column of table 4. The larger screen hole sizes give larger average particle sizes and a smaller percentage of fines. For a given hole size, particle sizes are greater for cornstover than for the other two materials. With wheat straw there is no appreciable difference in particle size distributions from the two grinders. Particle sizes for rice straw using a 50.8 mm screen are greater with Medallion grinder than with the W.H.O unit because of moisture content.

The performances of WHO grinder with wood residues as the input feedstock are stated in figure 2. The moisture contents were 29 to 32% for green forest slash, 11 to 12% for dry forest slash. The grinding rate increases more rapidly in relation to screen hole diameter between 50.8 and 76.2 mm than between 19.1 and 50.8 mm. The grinding rate for the green forest slash is less than the rate for the dry forest slash.

Specific energy requirements are shown in figure 3. It decreases with the increase of hole size. Dry forest slash requires less specific energy than green forest slash. The difference becomes less as the screen hole size is increased. Figure 4 shows the results of the Ro-Tap screening analysis with 19.1 hole size screen at a tub speed of 9.5 rev/min. As with the cereal crop residues, the larger screen hole sizes give larger average particle sizes and a smaller percentage of fines.

PAMI (Prairie Agricultural Machinery Institute, Saskatchewan) and AFMRC (Alberta Farm Machinery Research Centre, Alberta, Canada) evaluated five different models of portable tub grinders. The models used were Haybuster Model H-1000 and Model C-9, New Holland Model 379, Farmhand Model F890-A, and Bearcat Model 4200. These tub grinders are portable power take-off driven hammer mill with rotary feed tub, designed to grind loose, stacked or baled straw and hay. They are designed to be batch fed with a suitably equipped front end loader. Variable speed tub regulates the feed to the hammer mill. Fineness of grind is determined by the size of screen used below the hammer mill. Ground material falls through the screen onto conveyors which deliver it.

The performances of the five tub grinders are illustrated in table 5 and particle size distribution of the ground products are shown in table 6. Table 7 shows the production capacity of a Duratech model tub grinder using different feedstock.

The method of feeding in most of the tub grinder impose a heavy shock loads on the power train and results in wide power fluctuations. A tractor with a higher power take-off output is needed to prevent tractor stalling due to the power fluctuations. Smaller tractors could be used at reduced grinding rates by adjusting the tub governor.

The maximum grinding rate for a tub grinder depends on the type of agricultural residues being ground, whether the residue is baled or loose, its moisture content, temperature, the screen size used, and the available tractor power. Screen size is the most important operating factor directly affecting grinding rate, power consumption and specific capacity. Reducing screen size by a factor of two generally doubles power consumption and halves grinding rate and specific capacity. Tub grinders are inefficient, requiring high power inputs to produce modest throughput.

Wood Chipper

Asikainen et al (1998) evaluated three different models of wood chippers for grinding wood. The grinder models were Evolution 910R drum chipper, the MOHA chipper truck, and the Morbark 1200 tub grinder. Their productivity and particle size distribution are shown in table 8 and figure 5 respectively. The produced chips from the three grinders were acceptable for use in heat-generation plants. The proportion of large particles is small in all cases. On the other hand, the proportion of small particles is relatively high. The Morbark and the Evolution achieve the highest productivity level because they work at roadside landings, whereas the MOHA chipper truck works in the woods. In case of chain-flail debarking/delimbing, the productivity of Morbark 1200 grinder is significantly higher, 100 to 150 m^3 loose/hr ((Pulkkinen 1996).

Table 9 shows the four different models of drum chippers, their productivity and power for biomass chipping operation (Desrochers 1995). Two models of chippers are off-road chippers and the other two models are trailer mounted chippers. The productivity of trailer mounted chippers is higher than off-road chippers. But as for trailer mounted chipper's reach is limited, the slash has to be piled up before chipping. After chipping the site is cleaner when trailer mounted chippers were working than when off-road chippers are working.

Equipment Costs

Equipment costs are the sum of the ownership and operating costs. Ownership costs are often called as fixed or overhead costs and it is independent of the amount of using equipment. On the other hand, operating costs increase in proportion to the amount the machine is used. Ownership, operating, and total equipment costs can be calculated on an annual or hourly or per hectare basis. A custom cost is the amount needed for hiring an operator and equipment to perform a given processing work. So an analysis is to be done whether it would be better to purchase a machine or to hire the equipment to do the work. A certain minimum amount of work must be available to justify the purchase of a machine. The more the work available, the larger ownership costs can be economically justified.

Ownership costs include purchase price, interest, taxes, insurance and housing of the machine. Operating costs includes machine maintenance, fuel costs and labor costs. The following owning and operating cost analysis is based on test runs conducted by a tub grinder manufacturer. The tub grinder has a production rate of up to 400 yards per hour (120 ton/hr) depending on material processed. Due to variations in conditions, materials being processed, and methods of loading, actual costs may vary. This cost is a factual cost of a tub grinder; the accumulated data for operating costs is based on actual grinding. This analysis is based on 5 years life cycle with 1750 hours per year of actual grinding operation. There will be a considerable value of the unit after the stated period. However, to ensure maximum figures for budget purposes, calculation has been done to have fully depreciated the equipment over the 5 years period.

Details of various costs are in table 10 on itemized basis. Purchase price is based on a US$535,750, amortized over 8750 hours of machine life. Interest rate is assumed as 8.00% per year on a declining balance of $535,750. Insurance cost is based on a replacement value of $535,750 at an average rate of $2.40 per $100 per year =$12858, divided by 1750 hours.

Machine maintenance is elaborated in table 11 considering parts to be replaced or repaired. It includes labor and materials for daily maintenance involving lubrication, inspection, and wear parts. Equipment maintenance includes labor, hammer replacement, screen maintenance and replacement, hammer rod inspection and replacement and 100 hour routine maintenance schedule on engine and grinder. Hammer life, screen life, and rod life are dependent upon operator experience, product being processed, screen size, climatic conditions, and methods of loading material in tub grinder.

Fuel consumption for the Caterpillar 3412 860 hp is estimated at 28 gallons per hour, multiplied by the estimated cost of $2.50 per gallon. Labor cost including benefits depends on the area.

Conclusion

Types of grinder selection depend on a number of factors. There are limitations of particle size requirement of biomass product for different energy conversion process. So product size is the main criterion for selecting size reduction equipment if the target is the conversion of energy. Performance data of most grinders with agricultural residues are inadequate especially with respect to particle sizes. A number of literatures are available on the requirement of grinding energy in the lab scale. Extensive study is necessary to study the performances and cost required to get a target particle size through different pathways. This study showed the performances and particle size distribution of the product by tub grinder. A wide range of particle size is obtained from tub grinder. The study also showed that a cost of US$3.01/ton product is needed for a commercial tub grinder of capacity 70 ton/hr.

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Table 1 Types of size reduction equipment

A. Portable

B. Stationary

C. Chipper
  1. Disc type chipper
    a) Horizontal feed type
    b) Gravity or drop spouts feed
  2. Drum type chipper
    a) Horizontal feed system
    b) Gravity feed system

D. Wood chunker
  1. Spiral head
  2. Involuted
  3. Double involuted

E. Hammer Hog
  1. Swing hammer
  2. Fixed hammer
  3. Punch and die
  4. Mass rotor
  5. Knife hogs

F. Hammermill
  1. Swing hammer
  2. Fixed hammer
  3. Tub grinder
  4. Rotary knife hammer mill

G. Shredder

H. Knife mills

J. Disc mills

Table 2 Matrix of equipment types (CWC, 1997)

Equipment	Reduction device	Speed	Feedstock	Sensitivity to contaminants	Geometry of particles
Disk chipper	Replacement knives	High	Whole log Clean residue	High	Clean edge/two sided
Drum chipper	Replacement knives	High	Whole log Clean residue	High	Clean edge/two sided
Swing hammer hogs	Swinging hammers	Moderate	Wood waste Stumps	Low	Coarse/multi-surface
Fixed hammer hogs	Fixed hammers	Moderate	Wood waste Stumps	Low	Coarse/multi-surface

Punch and die	Fixed impact surfaces	Moderate	Wood waste Stumps	Moderate	Coarse/multi-surface
Mass rotor	Rotating impact surface	Moderate	Wood waste stumps	Low	Coarse/multi-surface
Knife Hogs	Semi-sharp hammers	Moderate		Moderate	Semi-coarse
Pan and disc grinder	Cutting disk with blade hammers	Low		Moderate	Semi-coarse

Table 3 Grinder for agricultural residues (Weedmark, 2006)

Raw materials	Grinder model	Price US$ (approx)	Engine speed rpm	Power input or diesel consumption per hour	Throughout, tons/h
Cornstover Straw Switch grass	1300 Tub Grinder	$535,750	2250	860hp around 28 gal/hr	60~80
Bagasse, Wood waste	6600 Woodhog	$535,750	2250	860hp around 28 gal/hr	80~100
Wood log	6600 Woodhog	$535,750	2250	860hp around 28 gal/hr	75~80

Table 4 Tub grinding results for agricultural residues

Screen hole size, mm	Tub speed rpm	Moisture content % wb	Grinding rate, Mg/h	Specific energy consumption kJ/kg	Particle size distribution*
Wheat straw from rectangular bales, WHO grinder					
12.7	3.1	11	8.2	208	11/40/25/24
12.7	5.7	10	11.3	186	3/38/27/32
12.7	9.5	11	12.5	193	11/45/20/24
19.1	3.1	10	11.0	149	14/40/22/24
19.1	5.7	12	15.1	144	18/43/21/18
19.1	9.5	10	17.2	137	16/40/22/22
50.8	3.1	10	16.0	91	30/35/20/15
50.8	5.7	10	19.1	109	39/33/14/14
50.8	9.5	**			
Wheat straw from rectangular bales, Medallion grinder					
12.7	2.5	10	4.9	268	6/51/23/20
50.8	2.5	11	7.2	128	37/36/17/10
50.8	6.3	11	11.7	105	34/36/18/12
Corn stover from rectangular bales, WHO grinder					
12.7	2.5	10	10.8	244	38/30/19/13
19.1	3.1	11	11.7	212	53/20/15/12
19.1	5.7	11	15.7	154	52/25/14/19
50.8	3.1	11	17.5	144	65/17/10/08

50.8	5.7	11	17.5	137	71/13/07/09
Rice straw from rectangular bales, WHO grinder					
12.7	1.5	7	5.3	484	22/31/24/23
19.1	1.5	8	8.4	326	36/30/20/14
50.8	1.5	8	12.7	209	34/31/21/14
Rice straw from big round bales, WHO grinder					
12.7	1.5	8	9.2	186	21/23/22/34
19.1	1.5	8	8.1	270	14/15/24/37
50.8	1.5	8	9.2	186	21/23/22/34
76.2	1.5	8	10.0	168	45/21/13/21
Rice straw from rectangular bales, Medallion grinder					
50.8	1.0	13	5.4	207	45/22/17/16

***** Number shown represent, from left to right, percentage of materials obtained in Ro-Tap tests with U.S standard sieves; (1) >2.36 mm (2) 2.36 to 1.17 mm (3) 1.17 to 0.59 mm; (4) <0.59 mm.

Table 5 Throughput and specific energy requirement for tub grinder (PAMI and AFMRC)

Biomass	Screen size	Throughput / Specific energy	H-1000	C-9	NHM 379	F890A	BCM 4200
Alfalfa	51	t/h	13-16	4.5-4.8	6.5-8.0	4.2-5.4	3.4-11.0
		t/kWh	0.27	0.37	0.32	0.36	0.16
	25	t/h	6.5-8.0	2.2-2.4	3.2-4.0	2.1-2.7	1.7-5.5
		t/kWh	0.14	0.19	-	0.18	0.08
Straw	51	t/h	10.0-18.6	5.7-7.9	6.5-7.6	2.8-3.7	7.5-7.8
		t/kWh	0.20	0.15	0.08	0.08	0.08
	25	t/h	5.0-9.3	2.8-3.9	3.2-4.0	1.4-1.9	3.7-3.9
		t/kWh	0.10	0.08	-	0.04	0.04

BCM – Bearcat model, NHM – New Holland model

Table 6 Particle size distribution of tub grinding agricultural residues

Biomass	Equipment	<3mm	3-10mm	10-18mm	18-25mm	25-38mm	>38mm
Barley straw-loose	C-9	6.0	23.9	20.3	13.6	28.0	8.2
	H-1000	9.8	35.4	21.5	11.1	17.5	4.7
	NHM 379	10.9	34.5	17.8	14.5	17.6	4.7
	F890-A	8.5	32.0	21.8	12.4	19.9	5.4
	BCM4200	10.5	34.0	20.4	14.4	17.3	3.4
Barley straw-baled	C-9	18.9	41.1	18.0	11.0	9.4	1.6
	H-1000	8.8	39.1	18.4	16.3	14.5	2.9
	NHM 379	17.5	40.2	17.2	12.0	11.1	2.0
	F890-A	11.4	34.7	17.9	13.4	17.9	4.7
	BCM4200	22.5	40.2	15.9	10.4	9.5	1.5
Alfalfa-	C-9	20.1	34.1	12.5	11.2	17.5	4.6

loose	H-1000	28.0	34.8	12.2	9.2	12.9	2.9
	NHM 379	16.8	39.5	13.8	11.6	14.8	3.5
	F890-A	23.1	37.1	11.4	12	13.5	2.9
	BCM4200	17.2	39.5	13.1	13.3	14.1	2.8
Alfalfa baled	C-9	12.9	42.3	13.1	14.9	14.5	2.3
	H-1000	-	-	-	-	-	-
	NHM 379	14.8	48.2	12.7	12.3	10.5	1.5
	F890-A	20.1	40.9	12.1	14.1	11.3	1.5
	BCM4200	17.2	46.2	12.6	13.7	9.0	1.3

Table 7 Production rates of Duratech tub grinder (Duratech, 2006)

Feedstock	Screen size	*Production rate, tons/hr
Grass and leaves	3" round hole	60
	4" round hole	80
	5" x 7" hole	120
Bark	2" round hole	65
	3" round hole	80
	4" round hole	110
	5" x 7" hole	130
Pallets	2" round hole	18
	3" round hole	22
	4" round hole	30
	5" x 7" hole	42
Brush and mixed lumber	2" round hole	27
	3" round hole	32
	4" round hole	45
	5" x 7" hole	65
Logs under 20" diameter	2" round hole	30
	3" round hole	37
	4" round hole	42
	5" x 7" hole	60

*Production rate shown is an estimate as it varies with screen size, weather conditions, wear of hammer tips, and the loader operator.

Table 8 The productivity of wood chippers (Asikainen et. al.1998)

Model	Equipment type	Operation Site	Engine Output (kW)	Productivity m3 loose/hr	Productivity, 103 kg (dry mass)/hr
Evolution 910R	Drum chipper	Roadside landing Truck mounted	267	160	11.5
MOHA	Drum chipper	Logging site Truck mounted	229	175	4.7
Morbark 1200	Hammermill	Roadside landing	481	330	9-10.5

Table 9 Productivity of off-road and trailer mounted chippers

Model name		Productivity (gmt/PMH)*	Power (kW)
Bruks 1000CT and 1001CT	Off-road	7.6	160-230
Bruks 1000CT and 1001CT	Off-road	9.5	160-230
Nickolson WFP 3A	Trailer-mounted	49.2	450
Erjo 120HM 903	Trailer-mounted	22.2	412

*gmt/PMH - Green metric tonnes per productive machine hour

Table 10 Total cost of a tub grinder of capacity 70 ton/hr

Cost items	Amount US$/hr
Owning cost	
Purchase price	61.23
Interest	13.26
Insurance	7.35
Subtotal, owning cost	81.84
Operating cost	
Machine maintenance	28.62
Fuel cost	70.00
Labour cost	30.00
Subtotal, operating cost	128.62
Total, owning cost + operating cost	210.46
Estimated cost, US$/ton	3.01

Table 11 Maintenance parts and costs details (Morbark, 2006)

Machine parts	US$/hr
Inserts, nuts & bolts	
20 inserts@$18.00 each, every 80 hours	4.50
40 bolts@$2.40 each, every 160 hours	0.60
40 nuts @$2.40 each, every 160 hours	0.60
Grates	
2 grates@$1,000 (average) each, every 500 hours	4.00
Hammers	
20 hammers@$170 each, every 1,000 hours	3.40
Rakers	
18 rakers@$155 each, every 500 hours	5.58
Rods	
8 rods@$160 each, every 2000 hours	0.64

Maintenance labour Labour involved in changing wear parts and general maintenance @ $30/hr, every 8 hours	3.75
Grease 1 tube/s@$4.82 per tube, every 8 hours	0.60
Maintenance 1 primary fuel filter @ $80 each, every 200 hours 1 oil filter @ $20 each, every 200 hours 2 primary air filter/s @ $110 each, every 200 hours 2 secondary air filter/s @ $70 each, every 200 hours 2 hydraulic filter/s @ $65 each, every 200 hours	 0.40 0.10 1.10 0.70 0.65
Miscellaneous parts Includes an estimated per hour cost for all non-standard maintenance such as seal kits, bearing etc.	2.00
Total maintenance costs	28.62

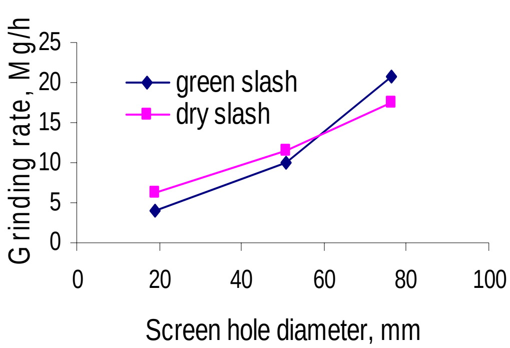

Figure 2 Grinding rate of wood slash with respect to screen hole diameter

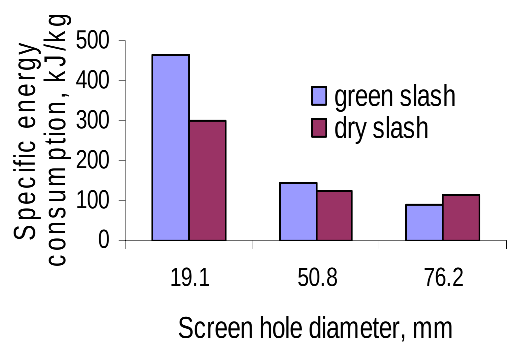

Figure 3 Relation between specific energy consumption and screen hole diameter

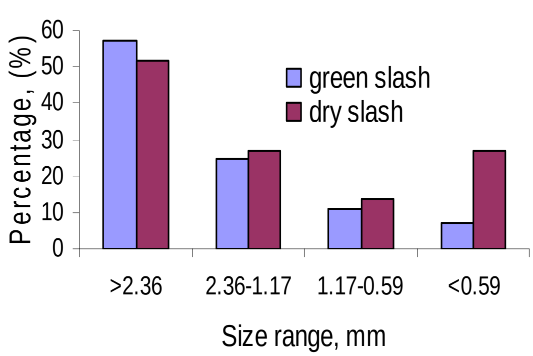

Figure 4 Particle size distributions of wood slashes (Asikainen et. al. 1998)

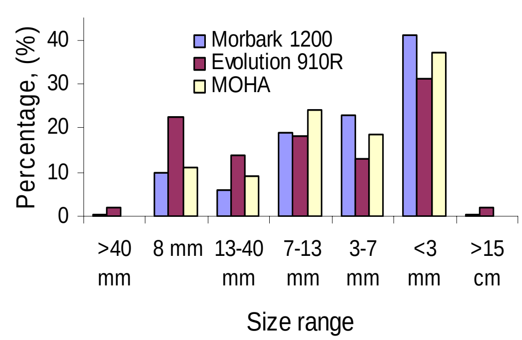

Figure 5 Particle size distribution of chips