COMPARISON OF HAMMERMILL AND ROLLER MILL GRINDING OF GRAIN SORGHUM AND CORN

by

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INTRODUCTION

The steadily increasing cost of industrial electricity has forced feed manufacturers to look closer at ways to reduce their energy usage. A number of areas throughout the feed mill have been studied. One of these areas has been the grinding and processing of feed ingredients prior to incorporation into complete feeds. The hammermill is used almost exclusively for grinding feed ingredients; however, the roller mill has proven to be more efficient when coarse grinding or cracking grains. Feed manufacturers need to know whether or not the roller mill can produce fine ground grains more efficiently, as well. Unfortunately, very little research has been conducted using the roller mill for grinding feed ingredients, and that research has been done with the production of coarse ground grains.

The purpose of this research was to determine if the roller mill could be used to fine grind feed grains more efficiently than the hammermill. Experiments were conducted using both a hammermill and a roller mill for fine grinding grain sorghum and corn. Factors studied included: grinding efficiencies, particle size, product uniformity, surface area/gram, particles/gram, production rates, bulk densities, moisture losses, and grain temperature rises.

LITERATURE REVIEW

Reasons For Grinding

The justification for grinding feed ingredients has been, and continues to be, studied and debated. Many questions arise as to whether or not there is a need for grinding. If there is a need for grinding, additional questions arise. How fine should the ingredient be ground, or can the cost of grinding an ingredient to a specific size be justified? Pfost (1976), Behnke (1983), and Larson (1983) all gave reasons for grinding feed ingredients. The reasons given include: ease of handling, aid in further processing, customer preference, and animal performance.

The handling characteristics of some ingredients can be improved by grinding. Ingredients, such as dehydrated or sun-cured alfalfa are easier to handle after they have been ground (Pfost, 1976).

Grinding also aids in the further processing of animal feeds. Martin (1985) studied the effects of particle size on the mixing and pelleting of feeds. His results showed that, to mix thoroughly, the finer grinds required less mixing time than the coarser grinds. In his pelleting trials, the pellets made from the finer grinds had slightly better pellet durabilities than those of the coarser grinds. This would tend to indicate that pellet durability is a function of particle size. Behnke (1983) confirmed this and added that the extruding process is also affected by grinding.

Customer preference is a reason for grinding that may or may not be justified but is necessary to keep customers happy. Often, feed manufacturers or feed ingredient suppliers have been approached by customers who want feeds or ingredients that have been ground to a specific particle size.

Animal performance and feed acceptance are major reasons for grinding. Grinding can increase the palatability of some ingredients and decrease the waste of other less palatable ingredients (Larson, 1983). Grinding has also been shown to increase the digestibility of many grains when fed to animals. This topic will be discussed later.

Particle Size Determination

In order to study and compare grinding, it is important to clearly define the particle size being produced or used in a study. In the past, particle size has been defined by the appearance of the product or the grinding process. Terms like "fine", "medium", and "coarse" have often been used to describe particle size in scientific studies. These are very poor definitions of particle size, because "medium" to one person could very well be "fine" or "coarse" to the next.

The use of statements, such as, "ground through a 1/8 inch hammermill screen" or "through a five thousandths of an inch gap" are also poor descriptions of particle size. In both cases, the actual particle size produced has been shown to depend greatly on factors such as ingredient type, moisture content, screen type, hammer tip speed, roll corrugations, roll spiral, roll differential, and machine wear.

According to Pfost (1976), the first attempt to put a quantitative value on the particle size of ground feed ingredients was made by the American Society of Agricultural Engineers and the American Society of Animal Science. In 1940, the American Society of Agricultural Engineers adopted the Modulus of Fineness and Modulus of Uniformity (Recommendation R246.1). The procedure described by Pfost and Headley (1976), used a set of wire mesh sieves to determine the ratio of coarse, medium, and fine fractions of the sample which, is called the Modulus of Uniformity. The Modulus of Fineness is determined by multiplying the percentage of material left on each sieve by a fineness factor, adding, and dividing by 100.

Since the Modulus of Uniformity and Modulus of Fineness were difficult to compare statistically and lacked information like surface area and number of particles, there was a need for a better method. After determining that the size distribution of some feedstuffs nearly fit a log-normal distribution, Headley and Pfost (1966) applied log-normal distribution techniques to determine particle size. The method developed used either log probability paper or mathematical equations to determine the geometric mean diameter (d_{gw}) in microns and the geometric log-normal standard deviation (S_{gw}). By using d_{gw}, S_{gw}, specific density, and assuming the particles to be cubical or spherical, the total surface area per gram and particles per gram could be calculated. Since that time, the American Society of Agricultural Engineers has adopted this method (standard S319.1) of determining particle size. The method was described by Pfost and Headley (1976) and Behnke (1985).

Particle Size Effects On Animal Nutrition

The effects of particle size on the performance of animals varies from one class of animal to another. In some animals, grinding has proven to be beneficial, while in others, it has been detrimental. A brief review of each class of animals will point out these differences.

Ruminants

A literature review by Armstrong (1972) indicated that coarse grinding or rolling of grains is sufficient for cattle. Some of the studies showed decreases in animal performance when fed finely ground grain. This appears to hold true for both beef and dairy cattle.

In the case of sheep, however, there is no need for grinding except in a few special cases according to Morrison (1956). These exceptions include: old sheep with poor teeth, lambs up to 5 to 8 weeks of age, or when fattening lambs with mixtures of grain and chopped hay.

Poultry

Vohra (1972) stated that grinding grain is essential for poultry because present management practices do not provide grit for the birds. He also indicated that the digestibility of grains is better when finely ground. However, fine grinding can cause dust problems and cause pasting of beaks.

In a broiler study conducted by Reece et al. (1985), mash and crumbled diets containing hammermilled or roller milled corn were used. The particle size for the rolled corn (1343 microns) was larger than that of the hammermilled corn (814 microns). Their results showed that, for the 21-day starter period, the hammermilled mash diet produced lower ($P <.05$) body weights and higher feed conversions than the rest of the diets. At 47 days, broilers fed diets containing roller milled corn were significantly heavier than those fed the mash diet of hammermilled corn. The crumbled diet containing hammermilled corn produced about the same results as the crumbled roller mill corn diets.

Swine

The effects of the particle size of corn and grain sorghum on the performance and nutrient digestibility of weaned pigs was studied by Ohh et al. (1983). Both corn and grain sorghum were rolled and hammermilled, through 3.2 mm and 6.4 mm screens, to produce fine and coarse diets. Results showed that daily gains were not different ($P >.05$) among the treatments except for the coarse rolled sorghum which had the lowest daily gain ($P <.05$).

Feed conversion of both grains was significantly better for the fine grinds. Increased dry matter and energy digestibilities were noted (P <.05) as the particle size decreased for both grains. Nitrogen digestibility showed a decrease as particle size was increased.

Owsley et al. (1981) studied the effect of grain sorghum particle size on the digestibilities of nutrients at the terminal ileum and over the total digestive tract of growing-finishing pigs. Grain sorghum was dry rolled (coarse) and ground, through a 6.4 mm hammermill screen (medium) or a 3.2 mm hammermill screen (fine). The ileal digestibility of dry matter, starch, gross energy, and nitrogen improved (P <.05) with each reduction in particle size. Total digestibility of these same components was highest (P <.05) for the fine grinds.

Three series of experiments using barley processed by different types of mills in growing pig diets were conducted by Simmonson (1978). The barley was ground using a peripherally fed hammermill, a centrally fed hammermill, a roller mill, and a plate mill (burr mill, attrition mill). In the first series, the peripherally fed hammermill and the roller mill were compared. Particle size varied from 420 to 1100 microns. The particle size was larger for the roller mill except when the husks were ground with a hammermill and added back. The results showed no significant differences in daily weight gain or feed conversion efficiency. In the second series, both hammermills were compared along with a roller mill grind with the husks again being ground through a hammermill and added back. Particle sizes for this series ranged from 640 to 1450 microns. Results indicated that a slightly higher daily gain and better feed conversion efficiency were obtained from the diets of the roller mill and centrally fed hammermill in the first experiment. However, in the second experiment, no differences were noted except when a larger screen size was used for the centrally fed hammermill. When the larger screen was used, daily gains and feed conversion efficiencies were significantly lower. The third series compared the peripherally fed hammermill and the plate mill using two different grinds. Particle sizes ranged from 510 to 1750 microns respectively. In the first experiment, the plate mill treatments resulted in lower daily gains and feed conversion efficiencies. In the second experiment, the particle size of the fine plate mill grind was the same as that of the hammermill. The results also showed a lower daily gain and feed conversion efficiency for the coarse plate mill grind.

Hammermill Grinding

The use of hammermills to grind feed ingredients is very popular in the feed industry. This popularity is due, mainly, to the wide variety of materials that can be ground with a hammermill. Several studies have been conducted to identify the factors that affect hammermill performance.

The hammermill has been classified as a type of impact grinder. Rumpf (1959) discussed the stress theory of impact grinding and talked about the various collisions that occur between particles and mill components. As a result of these numerous collisions, particle size reduction occurs when the allowable stress of the particle is exceeded by the stress resulting from the kinetic energy of the collision. Rumpf also discussed how the energy required for particle reduction could be determined.

Three theories that relate the energy required for particle size reduction were discussed by Pfost (1976). Rittinger's theory stated that the energy required is dependent on the surface area of the particle. Kick said that the volume of the particle is the deciding factor of the required energy. Bond, however, stated that the dependence lies somewhere between these two. Headley and Pfost (1968) were able to relate energy to surface area using the log-probability method of particle size analysis. Corn and grain sorghum ground through 3/32, 1/8, 3/16, and 1/4 inch hammermill screens were used for the study. By plotting energy consumption against the change in surface area and performing a linear regression analysis, equations relating energy requirements to changes in surface area and changes in log-normal distribution parameters were determined.

Pfost (1976) listed and discussed a number of factors that affect hammermill performance. These factors include: motor horsepower, diameter and shape of screen openings, screen area, moisture content, type of grain, peripheral speed, location of feed intake, hammer tip and screen clearance, hammer width and design, number of hammers, feed rate, air flow through the mill, and the mechanical condition of the mill.

The peripheral speed of the hammermill has been shown to affect particle size, production rate, and grinding efficiency. Stevens (1962) found that, as the peripheral speed of the hammermill was decreased from 17,200 ft/min to 7,080 ft/min, the grinding efficiency increased when grinding grain sorghum, corn, and oats. He also found that the Modulus of Fineness increased as the peripheral speed decreased. Similar results were found by O'Callaghan et al. (1963) using barley. Friedrich (1959) showed that the capacity of the hammermill decreased with a decrease in peripheral speed when grinding barley.

The effect of screen area was studied by Baker (1960) while grinding corn, oats, and grain sorghum. Baker found that, when half of the screen area was blocked off, the grinding capacity and grinding efficiency were decreased from 19 to 23 percent. O'Callaghan et al. (1963) also noted a sharp increase in power consumption as the number of screen holes blocked off increased from 1/4, to 1/2, to 3/4 of the available holes. Baker (1960) also noted that a significant decrease in particle size occurred when half of the screen area was blocked off.

Both Baker (ibid) and Stevens (1962) studied the effects of screen size on hammermill performance. Results of both studies showed decreases in grinding efficiency and average particle size as the screen size was decreased. Baker (1960) also showed that the production rate of the mill decreased as screen size decreased.

According to Friedrich (1959), the optimum hammer tip and screen clearance is 8 mm. This comes after a great deal of research using various types of grains. His results for rye showed decreased energy requirements, increased capacity, and slightly larger average particle sizes as the clearance was increased from 2 mm to 26 mm. O'Callaghan et al (1963) obtained similar results in their study with barley.

Baker (1960) used 1/16 inch and 1/8 inch thick hammers to study the effects of hammer thickness. His results indicated that 1/16 inch thick hammers produced much higher production rates and grinding efficiencies. The 1/16 inch thick hammers also produced a larger average particle size with fewer fines. The effects of hammer thickness were also studied by Stevens (1962) who used 1/16, 1/8, and 1/4 inch thick hammers for his study. His results showed the same trends as Baker's (1960) with the 1/16 inch thick hammers being the most efficient followed by the 1/8 and 1/4 inch thick hammers, respectively.

The type of grain and the moisture content are also deciding factors in hammermill performance. Baker (ibid) found that grinding oats was two times harder than grinding corn and three times harder than grinding grain sorghum based on grinding efficiencies. Stevens (1962) also stated that oats are the hardest to grind followed by corn and grain sorghum. Both Friedrich (1959) and Baker (1960) showed lower mill capacities and grinding efficiencies as the moisture content of the grain was increased.

Stevens (1962) found that there was little effect on grinding efficiency and particle size as airflow through the hammermill was increased from zero to 424 cfm, or to 582 cfm. Baker (1960) compared fan discharging and gravity discharging of the ground product in his study. His results showed increases in production rates and grinding efficiency when a fan discharge was used. The particle size analysis of his samples showed that some particle size reduction had occurred in the fan when using the fan discharge.

Roller Mill Grinding

The primary use of roller mills in the feed industry has been for steam rolling or flaking and coarse cracking of grains. Due to steadily increasing energy costs, an increased interest in the use of roller mills for fine grinding has occurred. This increased interest has been sparked by claims of high energy efficiency when using roller mills. However, very little research has been published on the use of roller mills for grinding.

Aubel and Pfost (1961) gave the efficiencies they obtained when grinding grain sorghum through a 1/8 inch hammermill screen and dry rolling. The hammermill had an efficiency of 2.6 cwt/kwh (Modulus of Fineness 1.99, Modulus of Uniformity 0:4:6) while the roller mill efficiency was 19.4 cwt/kwh (M.F. 3.72, M.U. 0:9:1). These results showed that the roller mill was considerably more efficient than the hammermill; however, the particle size reduction was less for the roller mill.

According to Reece and Lott (1985), corn for broiler rations is normally ground through a 3/16 inch hammermill screen. In their research, they determined that the grinding rate in lb/hp-hr was greater for the three different roll settings than the hammermill with a 3/16 inch screen. The grinding rates for the roller mill varied from 643 to 1,059 lb/hp-hr while the mean particle size varied from 1,427 to 1,759 microns. The 3/16 inch hammermill screen produced a grinding rate of 579 lb/hp-hr and a mean particle size of 858 microns. Other screen sizes used where 1/8, 1/4, and 3/8 inch. Grinding rates for these screens where 423,739,and 1,049 lb/hp-hr with mean particle sizes of 679,987, and 1,287 microns, respectively. Once again, the efficiency of the roller mill was better, but the particle size was larger.

Efficiencies for grinding corn and grain sorghum were measured by Martin (1985). Corn and grain sorghum were ground through 3.2 mm and 6.4 mm hammermill screens or rolled twice with different gap settings. The mean particle sizes were 612 and 920 microns for the hammermilled corn and 1,045 and 1,494 microns for the rolled corn. The grinding efficiencies for each were as follows: 8.22, 5.05, 4.26, and 2.47 kwh/mt, respectively. This, again, showed that the roller mill was more efficient, but the particle size was higher. The same trend can be seen in Martin's grain sorghum data with mean particle sizes of 552, 676, 1,146, and 1,444 microns and efficiencies of 5.76,4.79, 2.92, and 1.18 kwh/mt.

A cost comparison of roller mills and hammermills for grinding corn was conducted by Naylor and Smith (1981). Their comparison showed that, for coarse cracking of corn based on electrical costs of .045 cents per kwh, the hammermills cost from $436 to $1,090 a month above the cost of a roller mill processing 25 ton/hr. At 35 ton/hr the additional cost varied from $523 to $1,396 per month. When fine grinding corn at 13 ton/hr, the additional cost ranged from $349 to $1,658 per month, while at 18 ton/hr the varied from $218 to $872 per month.

McEllhiney (1986) compared the costs of purchasing, installation, maintaining, and operating hammermill, roller mill, and steam flaking systems. These costs were then added up and stated on a per ton basis. His results showed that the roller mill system is the least costly at $1.79 per ton followed by the hammermill system at $2.34 per ton and the steam flaking system at $5.19 per ton.

Comparison of other factors for considering a roller mill for grinding, such as equipment and installation costs, dust control, noise levels, particle size, moisture loss, and maintenance have been made by both Naylor and Smith (1981) and McEllhiney (1983). When comparing each of these factors, the roller mill appears to be superior to the hammermill in all cases.

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EXPERIMENTAL PROCEDURE

Research was conducted to determine the differences in hammermill and roller mill grinding with regards to: energy consumption, particle size, production rate, bulk density, moisture loss, and temperature rise. The effects of initial moisture content and screen size or roll gap setting were also studied. Single lots of grain sorghum and corn were used in the study to remove any effect of changing lots of grain. To obtain grain of a different moisture content than that received, the grain was either tempered or dried to the desired moisture content.

Experiments involving the hammermill were performed using a Jacobson full circle hammermill (see Appendix A for specifications), while experiments involving the roller mill were conducted using a Roskamp three pair high roller mill (see Appendix A for specifications). Roll gaps were chosen in an effort to obtain the same particle size as the corresponding hammermill grind (see Appendix A). Three replications of each grind were completed for the study. In two instances additional replications were completed because of unusually different production rates. These two instances were fine hammermilled high moisture grain sorghum and medium roller milled high moisture corn. The length of each grinding run was timed using a stop watch. An electronic 454 kg batch scale was used to weigh the grain after grinding. Electrical energy consumption for the hammermill was measured with a recording amp probe. Electrical usage for the roller mill was measured by reading the digital amperage meters connected to the roller mill motors. Grinding efficiencies were calculated using the amperage required under load and under no load (see appendix B).

Flow diagrams of the hammermill and roller mill systems and points where temperatures were measured are shown in Figures 1 and 2. Grain temperature was measured before grinding, after grinding, and after elevation. These points are labeled T in figures 1 and 2. Two after grinding temperature measurements were made to see if large differences in temperature rise occurred when different measurement procedures were used. One temperature measurement after grinding was made from a sample that was collected in a styrofoam cup. This sample is labeled "sample temperature" in the tables. The second after grinding temperature measurement was made by inserting a thermometer in the grain stream. This measurement is labeled "in-stream temperature" in the tables. Grain temperature rise was then calculated by subtracting the temperature before grinding from the temperature after grinding, the temperature before grinding from the in stream temperature, and the temperature after grinding from the temperature after elevation. The total temperature rise was calculated by adding the temperature rises excluding the in-stream temperature rise. Negative values indicate temperature losses instead of rises.

Grain samples were taken before grinding, after grinding, and after elevation for determination of moisture content (A.A.C.C. 1975). Sample locations are marked as MC in Figures 1 and 2. Moisture loss was determined by subtracting the moisture content

FIGURE 1. FLOW DIAGRAM OF THE HAMMERMILL SYSTEM

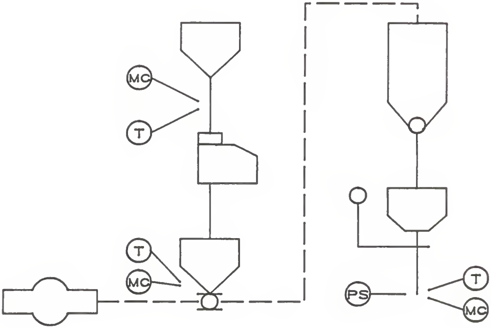
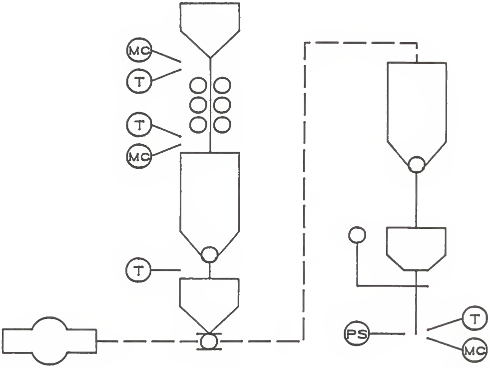


FIGURE 2. FLOW DIAGRAM OF ROLLER MILL SYSTEM



after grinding from the moisture content before grinding and the moisture content after elevation from the moisture content after grinding. The total moisture loss was calculated by adding the moisture losses. Positive values indicate increases in moisture rather than losses. The moisture content samples before and after grinding were also used to determine the bulk density of the grain (see appendix C). One additional sample marked PS in Figure 1 and 2 was taken for particle size analysis (appendix D).

Statistical analysis of the data was done using SAS[1] analysis of variance procedure GLM (General Linear Models) with least squares means (LSMEANS). Analysis of the data for interactions between grind and moisture content showed little interaction. As a result, the data were reanalyzed according to moisture content. In either case, no attempt was made to compare the grain sorghum and corn data.

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[1] SAS Institute Inc. SAS circle. P.O. Box 8000. Cary, N.C. 27511-8000.

RESULTS AND DISCUSSION

Grinding Efficiency

Grinding efficiency results for grain sorghum (Tables 1 and 2) showed that gross efficiency (total energy required for grinding) was worse for the roller mill than the hammermill when fine grinding. No significant difference was found in the medium ground grain sorghum. When compared to the hammermill, the net efficiency (gross energy - no load energy) was significantly better for the roller mill at both the medium and fine grinds indicating that the roller mill required less energy to reduce particle size and was more efficient than the hammermill. The surface area efficiency showed that the roller mill produced more surface area per unit of effective energy used than the hammermill. As the initial moisture content of the grain increased, an increase in the energy for grinding was required. Similar results using hammermills where reported by Baker (1960) when grinding grain sorghum and corn and by Friedrick (1959) when grinding barley. Energy required for grinding also increased as the screen size or roll gap was reduced. Baker (1960) and Stevens (1962) also found that energy consumption increased as the screen size decreased.

Results for grinding corn are shown in Tables 3 and 4. The efficiency for fine grinding high moisture corn with the hammermill was significantly higher than the other processing methods used for high moisture corn. This indicates that the hammermill was less efficient when fine grinding high moisture corn. Net efficiencies

TABLE 1. GRINDING EFFICIENCY FOR LOW MOISTURE GRAIN SORGHUM[1,2]

	Gross Efficiency	Net Efficiency	Surface Area Efficiency
Grind	Kwh/Mt	Kwh/Mt	m^2/Wh
Roller Mill Fine	10.62^{c}	1.18^{b}	10.19^{b}
Roller Mill Medium	3.66^{a}	$.38^{a}$	20.19^{c}
Hammermill Fine	7.67^{b}	5.07^{d}	2.15^{a}
Hammermill Medium	4.60^{a}	2.60^{c}	3.74^{a}

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[1] Columns means with the same letter are not significantly different $(P < .05)$.

[2] Values are means of 3 replications.

TABLE 2. GRINDING EFFICIENCY FOR HIGH MOISTURE GRAIN SORGHUM[1,2]

	Gross Efficiency	Net Efficiency	Surface Area Efficiency
Grind	Kwh/Mt	Kwh/Mt	m^2/Wh
Roller Mill Fine	18.02^{c}	2.32^{ab}	5.94^{b}
Roller Mill Medium	4.12^{a}	$.80^{a}$	10.31^{c}
Hammermill Fine	11.77^{b}	7.72^{c}	1.50^{a}
Hammermill Medium	6.01^{a}	3.73^{b}	2.54^{a}

[1] Columns means with the same letter are not significantly different ($P < .05$).

[2] Values are means of 3 replications (except hammermill fine which is the mean of 6).

TABLE 3. GRINDING EFFICIENCY FOR LOW MOISTURE CORN[1,2]

	Gross Efficiency	Net Efficiency	Surface Area Efficiency
Grind	Kwh/Mt	Kwh/Mt	m^2/Wh
Roller Mill Fine	12.87^c	3.71^b	3.09^{de}
Roller Mill Medium	7.50^b	3.17^{ab}	2.61^{cd}
Roller Mill Coarse	6.23^{ab}	2.58^a	3.52^e
Hammermill Fine	12.62^c	8.26^d	1.01^a
Hammermill Medium	7.45^b	4.76^c	1.64^{ab}
Hammermill Coarse	5.16^a	2.99^{ab}	2.20^{bc}

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications.

TABLE 4. GRINDING EFFICIENCY FOR HIGH MOISTURE CORN[1,2]

	Gross Efficiency	Net Efficiency	Surface Area Efficiency
Grind	Kwh/Mt	Kwh/Mt	m^2/Wh
Roller Mill Fine	13.86^{d}	4.35^{b}	2.30^{cd}
Roller Mill Medium	9.75^{bc}	3.23^{a}	2.44^{cd}
Roller Mill Coarse	7.87^{ab}	2.78^{a}	2.62^{d}
Hammermill Fine	23.59^{e}	15.91^{d}	.60^{a}
Hammermill Medium	10.09^{c}	6.58^{c}	1.28^{ab}
Hammermill Coarse	6.43^{a}	3.79^{ab}	1.84^{bc}

[1] Columns means with the same letter are not significantly different ($P < .05$).

[2] Values are means of 3 replications (except roller mill medium which is the mean of 4).

were again better for the roller mill on all grinds of corn. The roller mill had significantly better surface area efficiencies than the hammermill. As seen with grain sorghum, increases in energy required for grinding were noted with increasing moisture content and reduction in screen size or roll gap.

Particle Size Analysis

The average particle size of grain sorghum (Tables 5 and 6) was the same for the fine ground grain and higher for the roller mill medium grinds. These results showed how close the attempt to produce the same particle size with the roller mill as the hammermill came out. In the case of the medium grind, the rolls should have been closed slightly. The uniformity of the grind, indicated by the geometric standard deviation, was the same for both mills using low moisture grain; however, with high moisture grain the roller mill produced a less uniform product than the hammermill. The surface area/gram was nearly the same for both mills except where differences appear for the low moisture medium grind and the high moisture fine grind where opposite results were seen. No significant differences were noticed in particles per gram for low moisture grain sorghum; however, for high moisture grain sorghum, the roller mill produced more particles/gram than the hammermill. The change in moisture content appeared to have little effect on the grain sorghum data. Smaller screen size and roll gap produced smaller average particle sizes, better uniformity, and more surface area. Stevens (1962), Martin (1985) and Reece et al. (1985) also

TABLE 5. PARTICLE SIZE ANALYSIS FOR LOW MOISTURE GRAIN SORGHUM[1,2]

	Ave. Part. Size	Geo. Std. Deviation	Surface Area	Number of Particles
Grind	μ		cm^2/g	per gram
Roller Mill Fine	427^{a}	1.69^{a}	120^{c}	38,500
Roller Mill Medium	741^{c}	1.97^{b}	76^{a}	15,400
Hammermill Fine	470^{a}	1.67^{a}	108^{bc}	23,900
Hammermill Medium	549^{b}	1.82^{ab}	97^{b}	22,400

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications.

TABLE 6. PARTICLE SIZE ANALYSIS FOR HIGH MOISTURE GRAIN SORGHUM[1,2]

	Ave. Part Size	Geo. Std. Deviation	Surface Area	Number of Particles
Grind	μ		cm^2/g	per gram
Roller Mill Fine	419^{a}	2.03^{bc}	138^{c}	$106{,}700^{b}$
Roller Mill Medium	736^{c}	2.17^{c}	82^{a}	$29{,}300^{a}$
Hammermill Fine	458^{a}	1.62^{a}	111^{b}	$30{,}400^{a}$
Hammermill Medium	589^{b}	1.86^{b}	92^{ab}	$24{,}300^{a}$

[1] Columns means with the same letter are not significantly different ($P < .05$).

[2] Values are means of 3 replications (except hammermill fine which is the mean of 6).

found that smaller screen sizes or roll gaps produced smaller particle sizes.

Particle size analysis for corn (Tables 7 and 8) showed differences in average particle size between hammermill and roller mill grinds indicating that slightly different roll gaps should have been used. However, for high moisture corn, the fine and coarse grinds were not significantly different. This would indicate that similar grinds could be produced with a slight roll adjustment as grain conditions change. The ground corn from the roller mill ,in general, was less uniform than that from the hammermill in most cases. The surface area/gram was the same or slightly higher for the roller mill. No significant differences were noted in the particles/gram for either low or high moisture corn regardless of the grinding process. An increase in initial moisture content appeared to have more of an effect on corn than sorghum, as the average particle size for the roller mill is slightly higher. As with the grain sorghum, smaller screen sizes or roll gaps produced smaller average particle sizes, better uniformity, and more surface area in most cases with corn.

Production Rate and Density

Production rate and dry matter production rate of the grain sorghum (Tables 9 and 10) were significantly lower for the roller mill, indicating longer grinding times when using this particular roller mill. No statistical analysis could be done on the bulk density before grinding values due to the small number of samples.

TABLE 7. PARTICLE SIZE ANALYSIS FOR LOW MOISTURE CORN[1,2]

Grind	Ave. Part. Size μ	Geo. Std. Deviation	Surface Area cm^2/g	Number of Particles per gram
Roller Mill Fine	506^{a}	1.94^{bc}	112^{d}	43,700
Roller Mill Medium	751^{d}	2.19^{dc}	83^{bc}	29,200
Roller Mill Coarse	762^{d}	2.47^{d}	91^{c}	119,300
Hammermill Fine	586^{b}	1.39^{a}	82^{bc}	6,200
Hammermill Medium	664^{c}	1.67^{ab}	78^{b}	8,500
Hammermill Coarse	896^{e}	2.06^{c}	66^{a}	10,900

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications.

TABLE 8. PARTICLE SIZE ANALYSIS FOR HIGH MOISTURE CORN[1,2]

	Ave. Part. Size	Geo. Std. Deviation	Surface Area	Number of Particles
Grind	μ		cm^2/g	per gram
Roller Mill Fine	578^{a}	1.93^{bc}	98^{c}	28,000
Roller Mill Medium	797^{bc}	2.05^{bc}	76^{a}	17,100
Roller Mill Coarse	880^{c}	2.23^{c}	72^{a}	21,900
Hammermill Fine	529^{a}	1.56^{a}	95^{bc}	12,700
Hammermill Medium	662^{ab}	1.82^{ab}	83^{ab}	15,100
Hammermill Coarse	899^{c}	2.20^{c}	70^{a}	25,400

[1] Columns means with the same letter are not significantly different ($P < .05$).

[2] Values are means of 3 replications (except roller mill medium which is the mean of 4).

TABLE 9. PRODUCTION RATE AND DENSITY FOR LOW MOISTURE GRAIN SORGHUM[1,2]

Grind	Production Rate kg/hr	Dry Matter Production Rate kg/hr	Bulk Density Before Grinding kg/m^3	Bulk Density After Grinding kg/m^3
Roller Mill Fine	326^a	290^a	692	510^a
Roller Mill Medium	963^b	852^b	692	534^{ab}
Hammermill Fine	2955^c	2670^c	701	562^b
Hammermill Medium	3871^d	3540^d	701	601^c

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications (except bulk density before which is the mean of 5).

TABLE 10. PRODUCTION RATE AND DENSITY FOR HIGH MOISTURE GRAIN SORGHUM[1,2]

	Production Rate	Dry Matter Production Rate	Bulk Density Before Grinding	Bulk Density After Grinding
Grind	kg/hr	kg/hr	kg/m^3	kg/m^3
Roller Mill Fine	193^{a}	164^{a}	690	481^{a}
Roller Mill Medium	909^{b}	767^{b}	690	510^{a}
Hammermill Fine	2000^{c}	1695^{c}	688	528^{ab}
Hammermill Medium	3351^{d}	2826^{d}	688	572^{b}

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications (except hammermill fine which is the mean of 6 and bulk density before which is the mean of 5).

Densities before grinding should have been the same, since single lots of grain were used. The density was somewhat lower for the high moisture grain. The bulk density of the grain sorghum after grinding was lower for the roller mill than the hammermill except for the fine ground high moisture grain. Lower bulk densities for the roller mill after grinding were also found by Martin (1985). Decreased production rates were noted with an increase in moisture content. Similar results were reported by Friedrich (1959). As expected, finer screen size and smaller roll gap produce lower production rates and dry matter production rates. Friedrich (Ibid) also found that as the screen size decreased so did the production rate.

Results for the corn (Tables 11 and 12) showed the same trends as the grain sorghum. The roller mill had significantly lower production rates and dry matter production rates for all grinds. Density after grinding was significantly lower for the roller mill on all grinds. High moisture corn appeared to have lower densities than the low moisture corn. Finer screen sizes produced lower production rates and dry matter production rates for the hammermill. Production rates and dry matter production rates for the roller mill were not significantly different.

Moisture Loss

Little or no moisture lost occurred when grinding grain sorghum (Tables 13 and 14). In fact, in most cases, moisture was gained (positive loss) by the product as it was ground. It would

TABLE 11. PRODUCTION RATE AND DENSITY FOR LOW MOISTURE CORN[1,2]

	Production Rate	Dry Matter Production Rate	Bulk Density Before Grinding	Bulk Density After Grinding
Grind	kg/hr	kg/hr	kg/m^3	kg/m^3
Roller Mill Fine	462^a	404^a	756	476^a
Roller Mill Medium	575^a	503^a	756	495^b
Roller Mill Coarse	678^a	593^a	756	505^b
Hammermill Fine	1779^b	1556^b	756	551^c
Hammermill Medium	2842^c	2483^c	756	556^c
Hammermill Coarse	3542^d	3101^d	756	605^d

[1] Columns means with the same letter are not significantly different $(P < .05)$.

[2] Values are means of 3 replications (except bulk density before which is the mean of 4).

TABLE 12. PRODUCTION RATE AND DENSITY FOR HIGH MOISTURE CORN[1,2]

	Production Rate	Dry Matter Production Rate	Bulk Density Before Grinding	Bulk Density After Grinding
Grind	kg/hr	kg/hr	kg/m^3	kg/m^3
Roller Mill Fine	461^a	390^a	684	440^a
Roller Mill Medium	439^a	372^a	684	471^b
Roller Mill Coarse	510^a	432^a	684	466^b
Hammermill Fine	1003^b	855^b	680	526^d
Hammermill Medium	2187^c	1845^c	680	499^c
Hammermill Coarse	2898^d	2452^d	680	536^d

[1] Columns means with the same letter are not significantly different ($P < .05$).

[2] Values are means of 3 replications (except roller mill medium which is the mean of 4 and bulk density before which is the mean of 4).

TABLE 13. GRAIN MOISTURE LOSS FOR LOW MOISTURE GRAIN SORGHUM[1,2,3]

Grind	After Grinding	After Elevation	Total
	---------------	%WB	---------------
Roller Mill Fine	$-.8^{b}$	-.1	$-.9^{c}$
Roller Mill Medium	$-.4^{ab}$	-.1	$-.5^{bc}$
Hammermill Fine	$+.3^{a}$	-.1	$+.2^{a}$
Hammermill Medium	0^{a}	0	0^{ab}

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications.

[3] Average initial moisture content 10.7 %WB.

TABLE 14. GRAIN MOISTURE LOSS FOR HIGH MOISTURE GRAIN SORGHUM[1,2,3]

	After Grinding	After Elevation	Total
Grind	---------------	%WB	---------------
Roller Mill Fine	+.5^{a}	-.9^{b}	-.4^{b}
Roller Mill Medium	+.4^{a}	-.2^{a}	+.2^{a}
Hammermill Fine	0^{b}	-.1^{a}	-.1^{b}
Hammermill Medium	+.4^{a}	0^{a}	+.4^{a}

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications (except hammermill fine which is the mean of 6).

[3] Average initial moisture content 15.4 %WB.

appear that atmospheric conditions (like relative humidity) could be responsible for this occurrence; however, since this factor was not monitored during the grinding study, the reason for this occurrence could not be ascertained. No significant differences were noted for the moisture loss during elevation of the low moisture grain sorghum. Moisture loss during elevation was slightly higher for the fine roller mill grind when using high moisture grain sorghum. Total moisture loss for the system was slightly higher for rolled low moisture grain sorghum. Differences in initial moisture content, screen size, or roll gap had no apparent effect on moisture loss for either moisture content.

Moisture loss data for corn is given in Tables 15 and 16. Different accepted procedures for measuring the moisture content of whole kernel and ground corn, as well as relative humidity, could be responsible for moisture gains rather than losses in corn. No significant differences in moisture loss were noted for either moisture level while grinding or during elevation. Very little difference was noted in total moisture losses for the system. Differences in initial moisture content, screen size, or roll gap again do not appear to have any effect on moisture loss.

Temperature Rise

Grain temperature rise while grinding grain sorghum (Tables 17 and 18) indicated that the hammermill produced more heat than the roller mill. Both the temperature rise due to grinding (measured using the collected sample) and the in-stream grain temperature

TABLE 15. GRAIN MOISTURE LOSS FOR LOW MOISTURE CORN[1,2,3]

	After Grinding	After Elevation	Total
Grind	---------------%WB---------------		
Roller Mill Fine	0	-.3	-.3
Roller Mill Medium	0	-.2	-.2
Roller Mill Coarse	+.1	-.4	-.3
Hammermill Fine	-.4	+.1	-.3
Hammermill Medium	-.2	0	-.2
Hammermill Coarse	-.2	-.1	-.3

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[1] Columns means with the same letter are not significantly different $(P < .05)$.

[2] Values are means of 3 replications.

[3] Average initial moisture content 12.8 %WB.

TABLE 16. GRAIN MOISTURE LOSS FOR HIGH MOISTURE CORN[1,2,3]

	After Grinding	After Elevation	Total
Grind	--------------%WB---------------		
Roller Mill Fine	$+.3^{a}$	-.8	$-.5^{ab}$
Roller Mill Medium	$+.1^{ab}$	-.8	$-.7^{c}$
Roller Mill Coarse	$+.1^{ab}$	-.7	$-.6^{bc}$
Hammermill Fine	$-.7^{c}$	-.5	-1.2^{d}
Hammermill Medium	$+.1^{ab}$	-.3	$-.2^{a}$
Hammermill Coarse	$.1^{b}$	.4	$-.5^{ab}$

[1] Columns means with the same letter are not significantly different ($P < .05$).

[2] Values are means of 3 replications (except roller mill medium which is the mean of 4).

[3] Average initial moisture content 15.9 %WB.

TABLE 17. GRAIN TEMPERATURE RISE FOR LOW MOISTURE GRAIN SORGHUM[1,2,3]

	After Grinding		After Elevation	Total
	Sample	In-Stream		
Grind	°C			
Roller Mill Fine	2.7[a]	2.7[a]	-2.7[b]	0
Roller Mill Medium	2.3[a]	2.5[a]	-1.8[b]	.5[a]
Hammermill Fine	11.0[c]	13.3[c]	-5.3[a]	5.7[b]
Hammermill Medium	8.3[b]	9.7[b]	-4.5[a]	3.8[b]

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications.

[3] Average initial temperature 22.8 °C.

TABLE 18. GRAIN TEMPERATURE RISE FOR HIGH MOISTURE GRAIN SORGHUM[1,2,3]

	After Grinding		After Elevation	Total
	Sample	In-Stream		
Grind	--------------------	-----°C-----	--------------------	
Roller Mill Fine	2.3^{a}	3.5^{a}	-2.2^{bc}	.1
Roller Mill Medium	1.3^{a}	2.5^{a}	-1.0^{c}	.3
Hammermill Fine	13.5^{b}	14.3^{b}	-8.8^{a}	4.7
Hammermill Medium	5.2^{a}	6.2^{a}	-4.0^{b}	1.2

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications (except hammermill fine which is the mean of 6).

[3] Average initial temperature 21.5 °C.

rise were significantly higher for the hammermill. The only exception was for the high moisture medium grind where there was no significant difference. Temperature drops (negative rise) were higher for the hammermilled grain during elevation for all grinds. This could be expected, since the temperature rise while grinding for the hammermill was higher. Total temperature rise for the system was higher for the hammermill. Higher initial moisture content appeared to have little effect on temperature rise. The smaller screen size of the hammermill showed significantly higher temperature rises. Baker (1960) also reported increased temperature rise with smaller screen sizes. No significant differences in temperature rise occurred with changes in roll gap.

The corn data (Tables 19 and 20) showed similar trends to the grain sorghum. The hammermill temperature rise while grinding was significantly higher for all grinds. Temperature loss during elevation was greater for the hammermill in most cases which, again, was expected. Total system temperature rise was, again, higher for the hammermill. Initial moisture content appeared to have little effect on temperature rise as was noted with the grain sorghum. With the hammermill, the temperature rise increased as the screen size was reduced. Different roll gaps, again, showed no significant differences in temperature rise for most cases.

TABLE 19. GRAIN TEMPERATURE RISE FOR LOW MOISTURE CORN[1,2,3]

	After Grinding		After Elevation	Total
	Sample	In-Stream		
Grind	---------------------°C---------------------			
Roller Mill Fine	6.5^{ab}	5.5^{b}	-4.5^{b}	2.0^{a}
Roller Mill Medium	5.8^{ab}	5.0^{ab}	-3.3^{bc}	2.5^{ab}
Roller Mill Coarse	4.8^{a}	3.8^{a}	-3.3^{bc}	1.5^{a}
Hammermill Fine	16.5^{d}	16.5^{e}	-8.5^{a}	8.2^{d}
Hammermill Medium	11.7^{c}	13.0^{d}	-4.3^{b}	7.4^{cd}
Hammermill Coarse	6.5^{b}	11.3^{c}	-1.5^{c}	5.0^{bc}

[1] Columns means with the same letter are not significantly different (P < .05).

[2] Values are means of 3 replications.

[3] Average initial temperature 18.4 °C.

TABLE 20. GRAIN TEMPERATURE RISE FOR HIGH MOISTURE CORN[1,2,3]

	After Grinding		After Elevation	Total
	Sample	In-Stream		
Grind	---------------------°C---------------------			
Roller Mill Fine	5.8^{b}	5.3^{b}	-4.2^{cd}	1.6^{ab}
Roller Mill Medium	4.8^{ab}	4.3^{ab}	-3.0^{de}	1.8^{ab}
Roller Mill Coarse	3.7^{a}	3.3^{a}	-2.5^{e}	1.2^{a}
Hammermill Fine	19.7^{e}	20.0^{d}	-15.3^{a}	4.4^{c}
Hammermill Medium	11.3^{d}	13.2^{c}	-8.3^{b}	3.0^{abc}
Hammermill Coarse	9.0^{c}	11.8^{c}	-5.5^{c}	3.5^{bc}

[1] Columns means with the same letter are not significantly different $(P < .05)$.

[2] Values are means of 3 replications (except roller mill medium which are the mean of 4).

[3] Average initial temperature 27.2 °C.

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SUMMARY

A comparison of hammermill and roller mill grinding of grain sorghum and corn was completed by grinding the grain through 6.4, 3.2, and 1.6 mm hammermill screens and comparable roll gap settings. Efficiencies of both the hammermill and the roller mill were statistically the same in most cases. Net efficiencies and surface area efficiencies were significantly better for the roller mill except for coarse ground corn where no significant differences were found in net efficiencies.

Particle size analysis showed that similar particle sizes could be produced by the roller mill. Product uniformity was nearly the same for both mills with the roller mill being slightly less uniform when grinding high moisture grain; but, in most cases, more surface area/gram was produced by the roller mill. Differences in the number of particles per gram could not be determined from the statistical analysis.

Both production rates and dry matter production rates were significantly lower when grinding with the roller mill. Ground product bulk densities where somewhat lower for the roller mill for both grain sorghum and corn.

No conclusions about moisture loss during grinding or elevation could be determined because of increases in moisture while grinding in almost all instances.

Grain temperature rise while grinding was significantly higher for the hammermill. Larger amounts of heat were lost during elevation of the hammermill product due to the larger temperature rises while grinding.

Additional research is needed to further study the roller mill for grinding feed ingredients. Factors such as roll differential, roll speed, roll cut, roll corrugations, and roll action need to be studied to determine their effects on grinding efficiency. Likewise, the grinding of feed ingredients other than feed grains should also be studied. Despite this, the study shows that the roller mill can be used to fine grind feed grains and do it as efficiently or more efficiently than the hammermill. As a result, feed manufactures could save a great deal of money by using a roller mill to grind their feed grains.

APPENDIX A

Hammermill and Roller Mill Specifications

Hammermill Specifications

Manufacturer: Jacobson Machine Works, Inc. 2445 Nevada Ave. N.,
Minneapolis, Minnesota 55427

Motor: 30 Hp (22.4 Kw)

Motor Speed: 3515 rpm

Rotor Width: 5-1/2 in. (14 cm) outside hammer to outside hammer

Rotor Diameter: 23-3/8 in. (59.4 cm) hammer tip to hammer tip

Peripheral Speed: 21,510 ft/min (6556 m/min)

Screen Type: Full circle teardrop design

Screen Area: 593 in^2 (3825 cm^2)

Hammer Type: Hard surfaced

Hammer Width: 3/16 in. (4.8 mm)

Screens Used:

Coarse Grinds	1/4 in. (6.4 mm)
Medium Grinds	1/8 in. (3.2 mm)
Fine Grinds	1/16 in. (1.6 mm)

Roller Mill Specifications

Manufacturer: Roskamp Mfg. Inc. 2975 Airline Circle
Waterloo, Iowa 50703

Motors: 10 Hp (7.5 Kw) drives top two pair of rolls
5 HP (3.7 Kw) drives bottom pair of rolls

Motor Speeds: 1750 rpm
1750 rpm

Roll Speeds: 1310 ft/min (399 m/min) fast rolls under load
957 ft/min (292 m/min) slow rolls under load

Roll Specifications:

	Top Pair	Middle Pair	Bottom Pair
Corrugation:	8 corr/in.	12 corr/in.	16 corr/in.
Differential:	1:1	1.5:1	1.5:1
Spiral:		1.25in./ft	1.25in./ft
Cut:	Round Bottom V	Sawtooth	Sawtooth
Action:		sharp to sharp	sharp to sharp

Roll Scale[1] and Gap Settings:

	Top Pair	Middle Pair	Bottom Pair
Medium Grain Sorghum	0 - -	6.2 .025 in. .64 mm	6.2 .027 in. .69 mm
Fine Grain Sorghum	0 - -	6.9 .003 in. .08 mm	6.9 .003 in. .08 mm
Coarse Corn	5.6 .050 in. 1.27 mm	6.5 .016 in. .41 mm	0 - -
Medium Corn	6.4 .025 in. .64 mm	6.6 .011 in. .30 mm	0 - -
Fine Corn	6.4 .025 in. .64 mm	6.6 .011 in. .30 mm	6.8 .008 in. .20 mm

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[1] Graduated scale on roller mill used to indicate roll gap.

APPENDIX B

Methods for Calculating Grinding Efficiencies

Electrical Efficiency (EFF):

$$\text{Kwh/Mt} = \frac{I \times E \times \text{Eff} \times PF \times 1.73}{PR \times 1000}$$

Where:

Kwh/Mt = kilowatt hours per metric ton
I = amperage
E = voltage
Eff = motor efficiency factor
PF = power factor
1.73 = correction factor for three phase motor
PR = production rate
1000 = number of watts per kilowatt

Net Electrical Efficiency (NEFF):

The net electrical efficiency was calculated as above except
$I = I\ (\text{loaded}) - I\ (\text{not loaded})$

Where:

I(loaded) = Amperage measured while under a load
I(not loaded) = Amperage measured while not under a load

Surface Area Efficiency (SAEFF):

$$m^2/\text{Wh} = SA\ /\ (\text{Neff} \times 10)$$

Where:

m^2/Wh = square meters per watt hour
SA = surface area per gram (see appendix D)
Neff = net electrical efficiency
10 = combination of conversion factors converting Kwh to Wh, g to Mt, and cm^2 to m^2

APPENDIX C

Method for Determining Bulk Density

The bulk density of the whole grain and ground grain were determined by the following method: A cylindrical metal container with a diameter of 7.8 cm and a height of 11 cm was used as the standard volume container. The sample was placed in the funnel of a standard test weight apparatus and the container placed under it. The funnel was opened allowing the sample to fill the container. A straight edge was then used to strike off the container using three crisscross strokes. The filled container was then weighed using an Ohaus PBI electronic scale accurate to the nearest gram. Using the same sample, the procedure was repeated to obtain an average of two trials. The volume of the container was determined to be 491 cm^3. This was determined by weighing the amount of water required to fill the container to the brim. Since one cm^3 of water weighs approximately one gram, the volume of the container was then equal to the weight of water it held. This method was used because the container was not a perfect cylinder due to a large indentation in the bottom. The density of the grain was then calculated by taking the average weight of the grain and dividing by the volume of the container. The density was then converted from g/cm^3 to kg/m^3.

APPENDIX D

Method for Determining Particle Size[1,2]

The following procedure was used to determine the geometric mean diameter in microns, geometric standard deviation, the surface area per gram, and the number of particles per gram. A set of Tyler eight inch diameter wire cloth sieves (Table 21) and a Tyler[3] Ro-Tap Testing Sieve Shaker Model B were used to sieve the samples. One hundred grams of the sample were placed on the top sieve and sifted for ten minutes. The weight of the sample left on each sieve was determined by using a Mettler PE 6000 electronic scale accurate to the nearest one-tenth of a gram. The weight left on each sieve was then put into a computer program that performed the calculations that follow. See Table 22 for a sample print out. The calculations assume that the grain follows a log-normal distribution. The specific weights for grain sorghum and corn are 1.35 and 1.32 g/cm^3 respectively. The volume shape factor used was 1 and the surface area shape factor used was 6.

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[1] American Society of Agricultural Engineers. Standard S319.1. Method of Determining and Expressing Fineness of Feed Materials by Sieving. In: ASAE Standards 1986. pp. 88-89.

[2] Pfost, H.B. and V.E. Headley. 1976. Methods of Determining and Expressing Particle Size. In: H.B. Pfost (Ed.) Feed Manufacturing Technology. AFMA, Arlington, Virginia. pp. 512-517.

[3] W.S. Tyler Incorporated. Combustion Engineering, Inc. Mentor, Ohio.

Calculations:

$$d_{gw} = \log^{-1} [\Sigma (w_i \log d_i) / \Sigma w_i]$$

$$S_{gw} = \log^{-1} [\Sigma w_i (\log d_i - \log d_{gw})^2 / \Sigma w_i]^{1/2}$$

$$A = [\beta_s S_{gw} (\ln (S_{gw})^{1/2})] / [\beta_v \rho d_{gw}]$$

$$N = [S_{gw} (\ln (S_{gw})^{4.5})] / [\beta_v \rho d_{gw}^3]$$

Where:

A = surface area of particles per gram

β_s = shape factor for calculating surface area of particles

β_v = shape factor for calculating volume of particles

d_i = diameter of sieve openings of the i'th sieve

d_{i+1} = diameter of sieve openings of the next larger sieve

d_{gw} = geometric mean diameter

d_i = geometric mean diameter of particles on i'th sieve or

$d_i = (d_i \times d_{i+1})^{1/2}$

N = number of particles per gram

ρ = specific weight of sample

S_{gw} = geometric standard deviation

w_i = weight fraction on i'th sieve

TABLE D1. SIEVES USED IN PARTICLE SIZE ANALYSIS

Tyler Sieve Number	Nominal opening size (microns)
3.5	5600
4	4750
6	3350
8	2360
10	1700
14	1180
20	850
28	600
35	425
48	300
65	212
100	150
150	106
200	75
270	53
Pan	--

TABLE D2. EXAMPLE COMPUTER PRINT OUT

```
                          PARTICLE SIZE ANALYSIS

TEST NO.: 19              MATERIAL: 1/4 HMC High Corn        DATE: 5-16-87

                                PERCENT              WEIGHT   LOG DIA    WT(LOG
TYLER    WEIGHT                   LESS        LOG       LOG        -     DIA-LOG
SIEVE   (GRAMS)    PERCENT        THAN   DIAMETER  DIAMETER   LOG DGW    DGW)^2

  3.0       .00        .00      100.00      3.865      .000      .925      .000

  4.0       .00        .00      100.00      3.751      .000      .812      .000

  6.0      3.80       3.83       96.17      3.601    13.683      .661     1.662

  8.0     10.70      10.78       85.40      3.449    36.904      .510     2.778

 10.0     13.10      13.19       72.21      3.302    43.252      .362     1.719

 14.0     15.20      15.31       56.90      3.151    47.898      .212      .681

 20.0     14.00      14.10       42.80      2.987    41.825      .048      .032

 28.0     10.50      10.57       32.23      2.841    29.827     -.099      .103

 35.0      9.00       9.06       23.16      2.703    24.329     -.236      .502

 48.0      7.50       7.55       15.61      2.553    19.146     -.387     1.121

 65.0      7.10       7.15        8.46      2.402    17.052     -.538     2.053

100.0      5.00       5.04        3.42      2.251    11.256     -.688     2.368

150.0      1.20       1.21        2.22      2.101     2.521     -.839      .844

200.0      1.70       1.71         .50      1.950     3.315     -.989     1.664

270.0       .30        .30         .20      1.800      .540    -1.140      .390

  PAN       .20        .20         .00      1.689      .338    -1.251      .313

TOTAL     99.30


DGW (MICRONS) =       870.                         SGW =       2.54

SURFACE AREA (CM^2) / GRAM =      80.6          PARTICLES / GRAM =   56852.
```

APPENDIX E

Original Data

Table E1. GRINDING EFFICIENCY DATA FOR GRAIN SORGHUM

Grind	Rep.	Gross Efficiency Kwh/Mt	Net Efficiency Kwh/Mt	Surface Area Efficiency m^2/Wh
		Low Moisture		
Roller Mill Fine	1	11.29	1.22	10.58
	2	10.46	1.15	11.23
	3	10.10	1.17	8.77
Roller Mill Medium	1	4.28	.41	18.87
	2	3.14	.38	17.91
	3	3.56	.34	23.80
Hammermill Fine	1	6.90	4.48	2.34
	2	7.61	5.01	2.24
	3	8.50	5.73	1.87
Hammermill Medium	1	4.19	2.43	3.94
	2	4.45	2.45	4.01
	3	5.17	2.93	3.28
		High Moisture		
Roller Mill Fine	1	20.30	2.55	5.99
	2	17.15	2.23	5.27
	3	16.60	2.18	6.56
Roller Mill Medium	1	3.95	.82	10.46
	2	4.42	.71	11.78
	3	3.99	.88	8.69
Hammermill Fine	1	9.94	6.62	1.70
	2	7.55	4.75	2.06
	3	11.51	7.11	1.39
	4	15.24	9.63	1.00
	5	12.87	8.89	1.62
	6	13.49	9.31	1.23
Hammermill Medium	1	7.04	4.70	2.29
	2	4.88	2.77	3.05
	3	6.11	3.71	2.29

Table E2. GRINDING EFFICIENCY DATA FOR CORN

		Gross Efficiency	Net Efficiency	Surface Area Efficiency
Grind	Rep.	Kwh/Mt	Kwh/Mt	m^2/Wh
		Low Moisture		
Roller Mill Fine	1	12.96	3.98	2.82
	2	12.63	4.20	2.64
	3	13.01	2.97	3.82
Roller Mill Medium	1	8.00	3.13	2.81
	2	7.13	3.08	2.62
	3	7.36	3.29	2.41
Roller Mill Coarse	1	6.14	2.61	3.44
	2	6.07	2.53	4.19
	3	6.48	2.59	2.93
Hammermill Fine	1	10.71	6.95	1.20
	2	13.07	8.82	.92
	3	14.09	9.00	.90
Hammermill Medium	1	7.51	4.80	1.63
	2	7.38	4.64	1.72
	3	7.47	4.85	1.58
Hammermill Coarse	1	5.14	3.05	2.21
	2	4.98	2.82	2.26
	3	5.35	3.10	2.13
		High Moisture		
Roller Mill Fine	1	13.67	5.19	1.92
	2	14.02	4.32	2.25
	3	13.88	3.54	2.73
Roller Mill Medium	1	11.99	2.40	3.14
	2	10.35	3.12	2.86
	3	8.49	3.51	2.14
	4	8.15	3.88	1.61
Roller Mill Coarse	1	8.60	3.20	2.22
	2	7.31	2.72	2.58
	3	7.70	2.41	3.07
Hammermill Fine	1	25.54	17.03	.58
	2	22.26	15.20	.65
	3	22.96	15.50	.57
Hammermill Medium	1	9.25	6.00	1.56
	2	10.99	7.23	1.07
	3	10.03	6.50	1.20
Hammermill Coarse	1	6.67	3.96	2.04
	2	6.20	3.51	1.82
	3	6.43	3.90	1.65

Table E3. PARTICLE SIZE ANALYSIS DATA FOR GRAIN SORGHUM

Grind	Rep.	Ave. Part. Size μ	Geo. Std. Deviation	Surface Area cm^2/g	Number of Particles per gram
Low Moisture					
Roller Mill Fine	1	414	1.85	129.4	56445
	2	401	1.73	128.9	44886
	3	468	1.48	102.4	14263
Roller Mill Medium	1	738	2.04	77.6	18081
	2	793	1.88	68.5	9035
	3	694	2.00	81.3	19065
Hammermill Fine	1	490	1.72	104.9	23421
	2	462	1.74	112.1	29567
	3	458	1.56	107.0	18697
Hammermill Medium	1	546	1.77	95.8	19844
	2	551	1.88	98.4	26453
	3	550	1.80	96.0	21014
High Moisture					
Roller Mill Fine	1	384	2.10	152.5	156235
	2	476	1.97	117.5	54783
	3	398	2.02	143.0	109213
Roller Mill Medium	1	708	2.21	86.0	35292
	2	735	2.23	83.4	33842
	3	765	2.08	76.1	18651
Hammermill Fine	1	451	1.68	112.9	27227
	2	489	1.47	98.0	12430
	3	487	1.50	99.1	13469
	4	499	1.50	96.6	12499
	5	381	1.91	144.0	89182
	6	441	1.66	114.6	27484
Hammermill Medium	1	526	2.01	107.7	45308
	2	624	1.79	84.3	13955
	3	616	1.77	84.8	13641

Table E4. PARTICLE SIZE ANALYSIS DATA FOR CORN

		Ave. Part. Size	Geo. Std. Deviation	Surface Area	Number of Particles
Grind	Rep.	μ		cm^2/g	per gram
Low Moisture					
Roller Mill Fine	1	528	2.06	112.0	54860
	2	501	1.89	111.0	37062
	3	490	1.88	113.4	39123
Roller Mill Medium	1	674	2.07	88.0	27020
	2	744	2.11	80.6	22404
	3	834	2.38	79.3	38123
Roller Mill Coarse	1	743	2.40	89.8	58525
	2	751	2.89	106.1	280234
	3	794	2.12	75.9	19129
Hammermill Fine	1	576	1.39	83.3	6465
	2	590	1.40	81.5	6136
	3	591	1.39	81.2	6008
Hammermill Medium	1	668	1.69	78.1	8797
	2	655	1.69	79.7	9375
	3	669	1.62	76.4	7260
Hammermill Coarse	1	865	2.03	67.5	11155
	2	935	2.09	63.8	10685
	3	889	2.05	66.1	10934
High Moisture					
Roller Mill Fine	1	574	1.97	99.7	31871
	2	580	1.92	97.0	26556
	3	580	1.91	96.7	25657
Roller Mill Medium	1	756	1.95	75.2	13097
	2	607	1.81	89.3	16615
	3	858	2.30	75.1	27685
	4	965	2.13	62.6	10971
Roller Mill Coarse	1	966	2.47	70.8	33339
	2	873	2.16	70.0	16421
	3	802	2.07	73.9	16071
Hammermill Fine	1	518	1.60	98.1	14865
	2	511	1.57	98.5	14300
	3	559	1.50	88.3	9075
Hammermill Medium	1	613	1.97	93.4	26295
	2	682	1.71	77.0	8675
	3	690	1.78	77.9	10415
Hammermill Coarse	1	870	2.54	80.6	56852
	2	907	2.01	64.0	9170
	3	921	2.06	64.1	10267

Table E5. PRODUCTION RATE AND DENSITY FOR GRAIN SORGHUM

		Production Rate	Dry Matter Production Rate	Bulk Density Before Grinding	Bulk Density After Grinding
Grind	Rep.	Kg/hr	Kg/hr	Kg/m^3	Kg/m^3
			Low Moisture		
Roller Mill Fine	1	308	273	692	500
	2	333	296		507
	3	338	302		522
Roller Mill Medium	1	801	710	692	551
	2	1123	992		551
	3	965	855		500
Hammermill Fine	1	3155	2836	701	564
	2	2938	2665		563
	3	2771	2510		558
Hammermill Medium	1	4355	3941	701	603
	2	3839	3478		595
	3	3418	3103		604
			High Moisture		
Roller Mill Fine	1	169	144	690	482
	2	201	170		490
	3	208	177		470
Roller Mill Medium	1	959	809	690	517
	2	807	680		519
	3	961	812		495
Hammermill Fine	1	2310	1954	688	559
	2	2728	2305		577
	3	1739	1475		568
	4	1467	1247		480
	5	1921	1637		493
	6	1832	1554		492
Hammermill Medium	1	3259	2747	688	579
	2	3616	3049		587
	3	3177	2681		549

Table E6. PRODUCTION RATE AND DENSITY FOR CORN

		Production Rate	Dry Matter Production Rate	Bulk Density Before Grinding	Bulk Density After Grinding
Grind	Rep.	Kg/hr	Kg/hr	Kg/m^3	Kg/m^3
Low Moisture					
Roller Mill Fine	1	468	409	756	474
	2	499	438		474
	3	418	365		480
Roller Mill Medium	1	507	443	756	492
	2	611	534		499
	3	608	533		495
Roller Mill Coarse	1	699	611	756	501
	2	698	611		509
	3	636	556		504
Hammermill Fine	1	2033	1779	756	543
	2	1801	1576		552
	3	1503	1314		557
Hammermill Medium	1	2821	2462	756	553
	2	2792	2437		560
	3	2914	2550		555
Hammermill Coarse	1	3664	3213	756	616
	2	3548	3104		607
	3	3413	2986		591
High Moisture					
Roller Mill Fine	1	513	433	684	433
	2	448	380		444
	3	421	356		444
Roller Mill Medium	1	270	229	684	447
	2	358	304		464
	3	520	441		475
	4	607	515		498
Roller Mill Coarse	1	479	405	684	463
	2	563	478		473
	3	489	414		463
Hammermill Fine	1	899	768	680	526
	2	1084	922		543
	3	1025	876		508
Hammermill Medium	1	2354	1984	680	504
	2	2035	1720		494
	3	2172	1831		499
Hammermill Coarse	1	2825	2387	680	529
	2	2847	2412		550
	3	3021	2556		529

Table E7. MOISTURE LOSS DATA FOR GRAIN SORGHUM (%WB)

Grind	Rep.	After Grinding	After Elevation	Total
Low Moisture				
Roller Mill Fine	1	-0.5	-0.1	-0.6
	2	-0.5	-0.2	-0.7
	3	-1.5	0.0	-1.5
Roller Mill Medium	1	-0.2	-0.4	-0.6
	2	-0.4	+0.1	-0.3
	3	-0.7	+0.1	-0.6
Hammermill Fine	1	+0.7	0.0	+0.7
	2	-0.1	0.0	-0.1
	3	+0.2	-0.2	0.0
Hammermill Medium	1	+0.1	0.0	+0.1
	2	+0.1	-0.1	0.0
	3	-0.2	0.0	-0.2
High Moisture				
Roller Mill Fine	1	+0.6	-1.1	-0.5
	2	+0.4	-0.7	-0.3
	3	+0.4	-0.8	-0.4
Roller Mill Medium	1	+0.2	0.0	+0.2
	2	+0.5	-0.2	+0.3
	3	+0.4	-0.3	+0.1
Hammermill Fine	1	+0.3	-0.2	+0.1
	2	+0.2	0.0	+0.2
	3	+0.2	-0.3	-0.1
	4	-0.3	0.0	-0.3
	5	-0.2	-0.3	-0.5
	6	-0.1	0.0	-0.1
Hammermill Medium	1	+0.5	-0.1	+0.4
	2	+0.3	+0.1	+0.4
	3	+0.4	-0.1	+0.3

Table E8. MOISTURE LOSS DATA FOR CORN (%WB)

Grind	Rep.	After Grinding	After Elevation	Total
----------Low Moisture----------				
Roller Mill Fine	1	+0.3	-0.5	-0.2
	2	-0.2	-0.4	-0.6
	3	-0.1	+0.1	0.0
Roller Mill Medium	1	-0.2	0.0	-0.2
	2	+0.3	-0.4	-0.1
	3	-0.1	-0.3	-0.4
Roller Mill Coarse	1	+0.2	-0.4	-0.2
	2	0.0	-0.4	-0.4
	3	+0.1	-0.4	-0.3
Hammermill Fine	1	-0.6	+0.3	-0.3
	2	-0.3	0.0	-0.3
	3	-0.2	0.0	-0.2
Hammermill Medium	1	0.0	-0.1	-0.1
	2	-0.1	0.0	-0.1
	3	-0.4	+0.1	-0.3
Hammermill Coarse	1	-0.5	0.0	-0.5
	2	0.0	-0.3	-0.3
	3	-0.2	-0.1	-0.3
----------High Moisture----------				
Roller Mill Fine	1	+0.3	-0.6	-0.3
	2	+0.4	-1.0	-0.6
	3	+0.3	-0.9	-0.6
Roller Mill Medium	1	+0.1	-0.8	-0.7
	2	0.0	-0.9	-0.9
	3	+0.3	-1.0	-0.7
	4	-0.2	-0.6	-0.8
Roller Mill Coarse	1	+0.3	-0.7	-0.4
	2	-0.1	-0.7	-0.8
	3	+0.2	-0.8	-0.6
Hammermill Fine	1	-0.2	-1.1	-1.3
	2	-1.0	0.0	-1.0
	3	-0.8	-0.5	-1.0
Hammermill Medium	1	0.0	-0.2	-0.2
	2	+0.2	-0.6	-0.4
	3	0.0	-0.2	-0.2
Hammermill Coarse	1	0.0	-0.4	-0.4
	2	-0.2	-0.4	-0.6
	3	0.0	-0.5	-0.5

Table E9. TEMPERATURE RISE DATA FOR GRAIN SORGHUM (^{o}C)

Grind	Rep.	After Grinding		After Elevation	Total
		Sample	In-Stream		
		Low Moisture			
Roller MIll	1	3.0	3.0	-3.0	0.0
Fine	2	2.0	2.0	-3.5	-1.5
	3	3.0	3.0	-1.5	1.5
Roller Mill	1	2.0	2.0	-1.5	0.5
Medium	2	2.5	2.5	-2.0	0.5
	3	2.5	3.0	-2.0	0.5
Hammermill	1	10.5	12.5	-5.0	5.5
Fine	2	10.0	12.0	-5.0	5.0
	3	12.5	15.5	-6.0	6.5
Hammermill	1	9.0	10.0	-4.0	5.0
Medium	2	9.0	10.0	-5.5	3.5
	3	7.0	9.0	-4.0	3.0
		High Moisture			
Roller Mill	1	2.0	1.5	-3.0	-1.0
Fine	2	2.0	2.5	-2.0	0.0
	3	3.0	3.5	-1.5	1.5
Roller Mill	1	2.0	3.5	-0.5	1.5
Medium	2	1.0	3.5	-1.0	0.0
	3	1.0	3.5	-1.5	-0.5
Hammermill	1	10.5	11.0	-7.0	3.5
Fine	2	7.5	7.5	-7.5	0.0
	3	8.5	7.5	-7.0	1.5
	4	19.0	22.0	-11.0	8.0
	5	16.5	19.0	-9.5	7.0
	6	19.0	19.0	-11.0	8.0
Hammermill	1	5.5	8.0	-4.5	1.0
Medium	2	5.5	7.5	-3.5	2.0
	3	4.5	3.0	-4.0	0.5

Table E10. TEMPERATURE RISE DATA FOR CORN (^{o}C)

Grind	Rep.	After Grinding		After Elevation	Total
		Sample	In-Stream		
		Low Moisture			
Roller Mill Fine	1	5.0	4.0	-6.0	-1.0
	2	6.5	5.5	-4.0	2.5
	3	8.0	7.0	-3.5	4.5
Roller Mill Medium	1	6.0	5.5	-4.0	2.0
	2	6.0	5.0	-4.0	2.0
	3	5.5	4.5	-2.0	3.5
Roller MIll Coarse	1	5.5	3.5	-5.0	0.5
	2	4.0	3.0	-4.0	0.0
	3	5.0	5.0	-1.0	4.0
Hammermill Fine	1	16.0	16.0	-9.0	7.0
	2	16.5	16.5	-8.5	8.0
	3	17.0	17.0	-8.0	9.0
Hammermill Medium	1	12.0	13.0	-5.0	7.0
	2	10.0	12.5	-3.0	7.0
	3	13.0	13.5	-5.0	8.0
Hammermill Coarse	1	6.5	10.5	-2.5	4.0
	2	6.0	11.0	-1.5	4.5
	3	7.0	12.5	-0.5	6.5
		High Moisture			
Roller Mill Fine	1	5.5	5.0	-4.0	1.5
	2	6.0	5.0	-4.5	1.5
	3	6.0	6.0	-4.0	2.0
Roller MIll Medium	1	5.0	4.0	-3.0	2.0
	2	5.5	4.5	-4.0	1.5
	3	4.5	5.0	-3.0	1.5
	4	4.0	3.5	-2.0	2.0
Roller Mill Coarse	1	3.0	2.5	-2.5	0.5
	2	4.0	3.5	-3.0	1.0
	3	4.0	4.0	-2.0	2.0
Hammermill Fine	1	17.0	18.0	-15.0	2.0
	2	21.0	20.0	-17.0	4.0
	3	21.0	22.0	-14.0	7.0
Hammermill Medium	1	12.5	13.5	-8.5	4.0
	2	10.0	12.0	-9.0	1.0
	3	11.5	14.0	-7.5	4.0
Hammermill Coarse	1	9.5	12.0	-6.5	3.0
	2	8.5	11.5	-5.0	3.5
	3	9.0	12.0	-5.0	4.0

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COMPARISON OF HAMMERMILL AND ROLLER MILL GRINDING OF GRAIN SORGHUM AND CORN

by

Walter B. Appel

B.S., Kansas State University, 1986

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Grain Science and Industry

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1987

ABSTRACT

Grain sorghum and corn were used to study differences in hammermill and roller mill grinding of feed grains. Hammermill screens used in the study where 6.4, 3.2, and 1.6 mm. Roll gap settings were chosen in an attempt to produce particle sizes comparable to the hammermill. Grinding efficiency results indicated that the efficiency was nearly the same for both mills with the fine rolled grain sorghum being the least efficient. Net efficiency and surface area efficiency were significantly better for the roller mill, with the exception of coarse ground corn, where the net efficiency of the roller mill was not significantly different.

Particle sizes produced by both mills varied, but indicated that similar particle sizes could be produced. The uniformity of both mills was nearly the same with the roller mill being slightly less uniform when grinding high moisture grain. Rolled grain showed more surface area per gram in most instances. Differences in particles per gram could not be determined from the statistical analysis.

Production rates and dry matter production rates were considerably lower for the roller mill. The lowest production rates occurred with the high moisture grain. Bulk density of the ground grain was slightly lower for the roller mill in most instances.

No conclusions could be drawn about moisture loss, because in most cases moisture was gained rather than lost. Data for the

moisture loss during elevation of the ground grain could not be statistically analyzed.

The hammermill produced significantly higher grain temperature rises than the roller mill while grinding in most instances. As a result significantly higher temperature losses were also noted when the ground product was elevated.

Additional research is needed to further study the roller mill for grinding feed ingredients. The effects of factors such as roll speed, roll differential, roll cut, roll corrugations, and roll action on grinding efficiency need to be determined. grinding of feed ingredients other than feed grains should also be studied. Despite the need for additional research, the study indicates that the roller mill can be used for fine grinding feed grains. It also indicates that, the roller mill will fine grind as efficiently or more efficiently than the hammermill. As a result, feed manufactures could be saving a great deal of money by using a roller mill to grind their feed grains.