COMPARISON OF HAMMERMILL AND ROLLER MILL GRINDING AND THE EFFECT OF GRAIN PARTICLE SIZE ON MIXING AND PELLETING

by

STUART A. MARTIN

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Approved by:

Keith C. Behnke

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INTRODUCTION

The objective of grinding is to produce, as economically as possible, a grind that is both optimal for digestion by the consuming animal and suitable for the production of quality finished feeds. Grinding plays a vital role in mixing and pelleting operations. However, very little research has been published relating the particle size reduction required to achieve proper mixing or to optimize pelleting.

Recent increases in energy costs have forced the feed manufacturing industry to look for ways to reduce the energy requirements of processing methods. One method of reducing energy consumption is the substitution of coarse grinding for fine grinding of feed materials. The effect of grind on mixing, segregation, pelleting and customer acceptance must be considered when choosing an appropriate degree of particle size reduction.

The purpose of this study was to compare the efficiency of hammermill and roller mill grinding and to examine the effects of particle size reduction on mixing and pelleting processes. Experiments were designed to determine the amount of energy (Kwh/MT) required by the hammermill and roller mill to grind corn and grain sorghum to various particle sizes, the effect of particle size on mixing uniformity and feed segregation and the effect of particle size on pellet quality, pellet mill efficiency, and production rates.

LITERATURE REVIEW

Particle Size Measurement

The need to accurately express the physical characteristics of ground feedstuffs is essential to understanding the rôle of grinding in feed production. Unfortunately, a substantial amount of the literature devoted to the subject lacks an accurate means of reporting the degree of granulation. Several early publications reported the fineness of grind in terms of the grinding process used or by the appearance of the ground material.

The use of wire mesh sieves to classify ground feedstuffs led to the adoption of the first standard method of quantitatively reporting particle size by the American Society of Agricultural Engineers and the American Society of Animal Science (Pfost and Headley, 1976) in terms of Modulus of Uniformity and Fineness Modulus. The Modulus of Uniformity is a ratio of three numbers representing a coarse fraction, medium fraction, and fine fraction. The Fineness Modulus is calculated by multiplying the overs of each screen by a weighted fineness factor, summing these values, and dividing the total by one hundred.

The usefulness of the Modulus of Uniformity and the Modulus of Fineness is limited due to the difficulty encountered in making statistical comparisons and correlations. Furthermore, the moduli gave no information about total surface area or number of particles. With the application of log-normal particle size distribution techniques to analyze ground cereals, the Modulus of Uniformity and Fineness Modulus became obsolete.

Headley and Pfost (1966) applied techniques previously used in classifying minerals in the mining and glass manufacturing industries (Hatch, 1933) to describe the particle size distribution of certain ground feedstuffs. The authors noted that hammermilled corn and grain sorghum possess non-normal particle size distributions. The logarithm of the particle size, however, closely resembles a normal distribution. From a sieving analysis, one can determine the geometric mean particle diameter (measured in microns) and the geometric standard deviation (a measure of the variability in the distribution geometrically) of a sample by mathematical computation or graphically on logarithmic probability paper (Appendix A).

Given the mean particle diameter, geometric standard deviation, specific density and approximate particle shape of the material, values for the total surface area per gram and the total number of particles per gram can be calculated. The information obtained from log-normal particle size distribution analysis will accurately describe the physical characteristics of certain ground feeds materials. Computer programs can be used to perform the necessary calculations and report the particle size information quickly and accurately.

Effect of Grind on Animal Performance

A review by Lawrence (1972) reported that pigs are unable to masticate whole cereal grains sufficiently. Grinding cereal grains to increased digestibility and improved animal performance in most cases. In general, as particle size decreased, improvements in growth and feed conversion were noticed, however, the differences were not substantial.

Owsley et al (1981) examined the effect of sorghum particle size on digestibility of nutrients in growing-finishing pigs measured over both the terminal ilieum and the total digestive tract. Sorghum used in the preparation of the diets was either dry rolled (coarse), ground through a 6.4 mm hammermill screen (medium), or through a 3.2 mm screen (fine). The fine ground diet resulted in significantly improved ($p < .05$) apparent total digestibility of nitrogen (N), dry matter, starch, and gross energy over the medium and coarse diets. Each successive reduction significantly improved ($p < .05$) the ileal digestibility.

Aubel and Pfost (1961) compared different methods of processing grain sorghum for swine. Results indicated that fine grinding (1.99 M.F.) produced higher daily gains and improved feed conversion over dry rolled (3.72 M.F.), however, the cost of fine grinding was substantially greater than dry rolling. Feeding whole sorghum grain greatly suppressed feed conversion and daily gain indicating that whole grain sorghum should undergo some type of grinding prior to feeding to swine.

√Lawrence (1983) examined the effect of grinding oats on the nutrient digestibility in the finishing pig. Trials comparing diets with oats ground through a hammermill without a screen, with a 4.58 mm screen, and with a 1.56 mm screen showed no significant particle size effects on apparent digestibility of dry matter, modified acid detergent fiber, gross energy, digestible energy, or metabolizable energy. Oats ground without a screen resulted in lower daily gains and poorer feed conversion compared to the other treatments.

Increased incidences of esophagogastric ulcers have been observed in pigs fed diets containing finely ground cereals (Pickett et al, 1969). Although finishing pigs usually do not live long enough to be chronically affected, ulcerations in breeding stock may result in severe health problems (Behnke 1983).

Vohra (1972) noted that under present poultry production methods, cereal grains must be ground sufficiently to make up for the lack of grit available to chickens. Studies reviewed by Vohra (1972) indicated that higher digestibilities are usually associated with fine grinding. Behnke (1983) stated that finely ground wheat and rye may result in decreases in performance due to lower intake. Fine grinds used in poultry diets have also been associated with pasting of beaks.

The literature reporting the effect of grinding cereal grains on the performance of ruminant animals is limited. Morrison (1956) indicated the need to grind corn for dairy cows in order to avoid waste due to whole shelled corn passing through the digestive tract intact. However, Morrison stated that sheep, with a few exceptions, were capable of efficiently digesting whole shelled corn.

Moe et al (1973) studied the effect of physical form of corn on its energy value for lactation. In one experiment, lactating dairy cows were given a diet of 40 percent long alfalfa and 60 percent corn based concentrate. Comparisons were made by using either whole shelled corn, corn ground through a 6.4 mm screen, or cracked corn. In the first experiment, higher digestible, metabolizable and net energy values were associated with the ground corn ($p < .05$). In the second experiment, diets containing ground corn (6.4 mm) resulted in higher digestible and metabolizable energy values than the diets with cracked corn ($p < .05$). The authors cited improved digestibility of cell solubles for the increases in digestible energy in both experiments. Lower milk fat content was observed in treatments using ground corn (6.4 mm) and metabolizable energy was used less efficiently.

In beef cattle trials conducted by Hixon et al (1966), grinding corn for high grain diets did not result in improved digestibility, instead, steers gained more efficiently on diets with whole shelled corn diets. Pendlum et al (1977), examined the effect of grinding corn on nitrogen metabolism in abomasally fistulated Hereford steers. Comparisons were made with diets containing whole shelled corn (5.98 M.F.), cracked corn (4.88 M.F.), and ground corn (3.85 M.F.). Apparent bulk densities of the corn fractions were 665, 613, and 567 grams/liter respectively. No significant effects were observed for abomasal N, NPN, and PN although cracked corn tended to have slightly higher nonprotein nitrogen levels and lower protein nitrogen levels than whole shelled corn or ground corn. Plasma urea N concentrations were significantly (p < .01) higher for cracked corn than for ground corn and whole shelled corn. No differences were found in concentrations of free amino acids reaching the abomasum.

Although the data was not conclusive, differences in the nitrogenous abomasal and plasma levels in steers fed cracked corn were thought to be associated with changes in the time of rumination, rate of feed degradation and passage of digesta from the rumen due to differences in density and particle size of the feed.

Husted et al (1968) compared the effects of dry rolled and finely ground grain sorghum on the digestibility of dry matter and nitrogen in diets fed to beef cattle. No differences are observed due to the type of grind used. Steam flaking significantly increased dry matter digestibility (p < .05) but had no significant effect on nitrogen digestibility.

Hammermill Grinding

Hammermills have been used to grind cereal grains and forages for many years. Due to the fundamental nature of the grinding process, hammermills are one of the most widely used pieces of equipment in the feed industry.

Hammermills are generally classified as impact grinders. according to the theory of impact grinding (Rumpf, 1959), particle size reduction occurs as a result of high speed collisions between particles and mill surfaces. A particle will rupture if the kinetic energy of impact is greater than the stress the particle is able to withstand. Various equations predicting the energy requirements necessary to grind different materials have been postulated (Bond, 1952). By applying log-normal distribution techniques, Headley and Pfost (1968) were successful in describing the relationship between energy consumption and the production of new surface area of corn and grain sorghum ground by a hammermill.

Corn and milo were ground through 1.64, 3.20, 4.34 and 6.40 mm hammermill screens. Energy consumption was measured in terms of kilowatt-hours per hundredweight (Kwh/cwt) of material ground. Particle size distributions of the ground and whole grains were determined by log-normal particle size analysis. Changes in the total surface area were determined by subtracting the total surface area of the original whole grain from the total surface area of each of the ground grains. Energy consumption was plotted against the change in square feet of surface area. Linear regression analysis performed on the data yielded the following equations:

$$\overline{E}_{corn} = 9.09 \times 10_{-4}(\Delta A_{st}) - 3.57$$

$$\overline{E}_{milo} = 1.54 \times 10_{-4}(\Delta A_{st}) - 0.22$$

where

$\overline{E}$ = energy consumed per unit weight of material ground.

ΔA_{st} = change in surface area of material.

Research has shown that several factors influence hammermill performance and produce granulation such as the type of grain, moisture content of the grain, diameter and shape of screen openings, screen area, peripheral speed, hammer width and design, number of hammers, and hammer tip to screen clearance, feed rate, motor horsepower, and air flow through the mill (Pfost, 1976).

The physical characteristics of the grains will dictate, to some extent, the energy required to grind them. In general, cereal grains with higher amounts of fiber or moisture will require more energy to grind than grains with lower fiber and moisture contents (Baker, 1960). Silver (1932) compared grinding capacities when grinding oats, barley, and corn and found that corn required less energy than barley and barley required less than oats. Several studies indicated that, as the moisture content of the grain rose above 12 to 13 percent, the energy required for grinding increased and grinding capacity decreased (Friedrich, 1959; Baker, 1960; and Silver, 1932).

Product granulation is controlled by hammermill screen selection. The fineness of grind is directly related to the size of screen perforations. The openings are usually round and range in diameter from 1 to about 13 mm. As the diameter increases grinding efficiency increases and particle size decreases (Stevens, 1962a; Baker, 1960; and Thomas, 1960).

The area of screen surface also influences hammermill performance. Large openings result in less screen area for particle collisions and consequently, less particle size reduction and reduced energy consumption. Baker (1960) studied the effect of screen surface area on grinding capacity and particle size reduction by blanking one-half of a 180 degree hammermill screen. Capacity was reduced by approximately 20 percent and a finer particle size was obtained.

O'Callaghan et al (1963) performed similar tests comparing an open 2.38 mm screen to the same screen which subsequently had one quarter, one half, and three quarters of the holes randomly filled with solder. Their results showed a sharp increase in the specific power required to grind after one half of the holes had been blocked. By removing the hammermill screen, the authors showed that only a small portion hammermill grinding is due to the initial impact of the hammers alone.

The energy consumed in hammermill grinding is supplied by the rapidly revolving hammer tips. The peripheral speed of the hammers and the size and number of hammers used are critical factors influencing hammermill performance. Friedrich (1959) stated that peripheral speeds of 70 to 110 meters per second are suitable for grinding feed and problem materials. Silver (1932) reported that speeds above 15,000 feet per minute (76.2 m/s) are inefficient for grinding cereals.

By substituting equal numbers of 1.64 mm wide hammers for 3.2 wide mm hammers, Baker (1960) noted a 15 to 25 percent increase in capacity when grinding through screens of equal sizes. The power required to operate the hammermill without a load was 20 percent less with 1.64 mm wide hammers. Hammer grouping had little effect on grinding capacity. Baker observed that the use of thinner hammers may result in shorter hammer life. Friedrich (1959) found that the number of hammers used affects hammermill performance. He recommended using 3 mm wide hammers spaced at 15 hammers per 100 mm of rotor width.

Stevens (1962a) investigated the influence of hammer tip speed, hammer width and screen selection on particle size reduction and grinding efficiency when grinding corn, oats and grain sorghum. Pfost and Headley (1971) later applied log - normal particle size analysis to Stevens' data. Graphs of the results indicate that the screen opening size had a significant effect on mean particle diameter and grinding efficiency (cwt/Kwh). Hammer width had the greatest effect on efficiency and true efficiency (M^2/watt-hour) when grinding oats. As hammer width increased, efficiency decreased for all speeds. Hammer width had little effect on particle size. True efficiency was greatest with peripheral speeds of about 10,500 feet per minute (53.3 m/s). As the diameter of screen openings increased, true efficiency also increased.

Studies conducted to examine the influence of hammer tip and screen clearance suggest that both particle size and grinding efficiency are largely influenced by hammer and screen clearance. Friedrich (1959) concluded from his tests that a screen clearance of 8 mm was best suited for grinding rye. Prew (1981) found that for a hammermill operating at 17,600 feet per minute increasing the hammer to screen clearance from 15/32" to 1" resulted in a sharp increase in grinding efficiency along with an increased particle size.

The influence of air flow through the hammermill screen was examined by Stevens (1962a). The results showed some improvements in hammermill capacity associated with providing air flow through the hammermill. Prior to the 1960's many hammermills were discharged by negative pressure pneumatic conveying systems. Today, the energy intensive nature of pneumatic conveying has prompted many feed manufacturers to use mechanical conveying systems to carry material away from hammermills.

Several feed producers use air assist systems in the discharge conveyor to help draw air through the hammermill screen (McEllhiney, 1980). Olson (1983) reported that a properly designed air assist system would maximize throughput and lower the power cost of a hammermill grinding system while providing a more uniform particle size with less dust build up.

Roller Mill Grinding

Very little research has been published on the subject of roller mill grinding in the production of livestock feeds. The majority of the literature concerning roller mill performance concerns their use in the flour milling industry.

In flour milling, several roller mills are used to separate the bran and germ from the endosperm of the wheat kernal and gradually reduce the endosperm into flour. Many different roll sizes, corrugations, and differentials are used in this highly refined, gradual reduction process. In feed production, roller mills are used for two purposes - grinding and steam flaking.

Roller mills used to grind cereals for animal feeds are usually operated at speeds of 350 to 600 RPM with roll diameters ranging from 9 to 12 inches. Most cereals require only one reduction to produce a suitable grind with a minimum amount of fines (Naylor and Smith, 1981).

Roll corrugation has significant influence on roller mill grinding. Roll corrugations differ in the number of corrugations per inch, spiral per unit length, and corrugation profile. In feed processing, the type of corrugation used is based on the grain to be ground and the desired granulation. In most instances, a uniform grind with a minimum amount of fines is desired.

Roskamp (1960) studied the effect of roll corrugation and moisture content on grinding corn, oats, milo, barley and soybeans. Results indicated that different roll corrugations were best suited for different grains and different grinds. As moisture content increased, coarser grinds were produced. Roll corrugations cut on a spiral tended to produce more fines than horizontally grooved rolls. Particle size reduction of oats was poor due to the one to one differential used. Roskamp recommended using a two pair high roller mill with the top set of rolls cut with 6 corrugations per inch and the bottom set of rolls cut at 14 or 15 corrugations per inch for greatest versatility. This is based on studies which suggest that the best corrugation for producing coarsely cracked corn is 6 grooves per inch, 11 to 12 for milo, 15 to 16 for crimping oats and 16 to 18 for rolling barley.

Although hammermills are predominantly used for grinding in the feed industry, interest in roller mill grinding has increased due to claims that roller mills require less energy to operate, have lower initial equipment and installation costs, produce less dust, operate quieter, reduce moisture loss and lower maintenance costs (McEllhiney, 1983).

Research comparing roller mill and hammermill grinding efficiency is virtually non-existant. Occasionally, grinding data has been published in conjunction with feeding trials or pelleting trials in which hammermills and roller mills were used in the preparation of the diets, however, that information is specific only to the grinds used in the study.

Aubel and Pfost (1961) reported data (table 1.) that suggested that roller mill grinding of milo is more efficient than hammermill grinding although the particle sizes of the two grinds differ. Stevens (1962b) reported (table 2.) the grinding efficiency of corn and milo ground by hammermill and by roller mill used in a pelleting trial.

An economic comparison of roller mill grinding versus hammermill grinding by Naylor and Smith (1981) reported considerably lower horsepower requirements for rollermill grinding (table 3). Coarse cracked corn (one pass) and fine ground corn (two passes) produced with a roller mill were compared with similar grinds produced on a hammermill with the coarse crack ground through a 6.4 mm screen and the fine ground corn through a 3.2 mm screen. The authors cited advantages in roller mill grinding including lower power requirements, uniform grinds with a lower amount of fines, minimum maintenance and repair, less cost to install, may be installed anywhere and produces less dust. The main disadvantages of roller mills lie in their inability

TABLE 1. COMPARISON OF GRINDING EFFICIENCY AND PARTICLE SIZE OF SORGHUM GRAIN GROUND BY HAMMERMILL AND ROLLER MILL

Processing Method	Efficiency (cwt/Kwh)	Fineness Modulus	Modulus of Uniformity
Finely ground (3.2 mm screen)	2.6	1.99	0:4:6
Dry Rolled	19.4	3.72	0:9:1

Aubel and Pfost (1962)

TABLE 2. THE EFFECT OF SCREEN SIZE, HAMMER SPEED, AND ROLL GAP ON GRINDING EFFICIENCY AND PARTICLE SIZE

Grain	Grind	Hammer Speed (ft/min)	Efficiency (Kwh/ton)	Fineness Modulus	Modulus of Uniformity
Corn	1/8"	14,164	6.26	2.05	0:6:4
	1/4"	14,164	3.54	3.27	1:7:2
	3/16"	7,080	3.44	3.53	1:8:1
	Rolled .02"		4.91	3.89	3:6:1
Milo	1/8"	14,164	2.58	2.69	0:4:6
	1/4"	14,164	1.94	3.00	0:6:4
	3/16"	7,080	1.22	3.19	1:6:3
	Rolled .02"		0.54	2.98	1:6:3

Stevens (1962b)

TABLE 3. COMPARISON OF POWER REQUIREMENTS FOR GRINDING CORN BY HAMMERMILL AND ROLLER MILL

Grind	Power Requirements (kg/hr/hp) Hammermill	Rollermill
Coarse cracked corn	135 - 315	650 - 1150
Fine ground corn	45 - 135	160 - 225

Naylor and Smith (1981)

to grind fiberous products, grinding is limited by the type of roll corrugation, and a roller mill is not capable of producing as fine of grind as a hammermill.

EFFECT OF GRIND ON MIXING

Good mixing has been widely recognized by the feed industry as a critical factor in controlling nutrient variation in finished feeds. Feed manufacturers depend on mixing uniformity in order to meet the nutritional guarantees of the feed they produce. Livestock producers desire a feed mixed so that it will supply optimum levels of all the essential nutrients required by the animal for maximum performance each time the animal feeds.

Over the years, an abundance of research has shown the adverse effect on animal health and performance brought about by failure to supply the animal with one or more essential nutrients, however, very few attempts have been made to examine the value of mixing uniformity on animal performance.

Creager (1957) conducted research simulating the influence that mixing uniformity had on vitamin A metabolism. Diets containing vitamin A were fed intermittently with diets deficient in vitamin A to one group of cockerals while a control group was fed a diet containing constant levels of vitamin A. Although net gain was lower for the cockerals fed intermittent amounts of Vitamin A, questions concerning the retention and subsequent release of vitamin A precluded a clear interpretation of the results. Pfost (1966a) conveyed the general concern of nutritionists that day to day variation of B vitamins would be more critical than that of vitamins A and D because of the animals ability to store fat soluble vitamins.

Research conducted by Henderson and Harris (1949), and Cannon (1947) clearly showed that all of the essential amino acids must be available simultaneously for optimum utilization during protein synthesis. In feeding trials conducted with young chicks, Duncan (1973) showed that increases in the degree of protein variation resulted in decreases in protein consumption and gain although apparent utilization of protein increased.

Although those experiments were helpful in understanding the importance of mixing uniformity, they were of little value in quantifying precisely what adequate mixing entails. Guidelines proposed by Bloom and Livesly (1953) suggest that 95 percent of the daily diet consumed by the animal should contain 90 percent or more of the daily requirements of the ingredient considered. Pfost (1966a) outlined practical criteria to examine when considering the desired degree of mixing:

1. The mix should provide each animal with a given percentage of his daily nutrient requirements.

2. It should be adequate to prevent frequent occurance of toxic levels.

3. It should be adequate to ensure that samples will be within limits set by control organizations.

4. Inaccurate sampling or assay techniques.

5. Loss of material from the mixture.

He further suggested that the total coefficient of variation, measured as the standard deviation of the assay values divided by the mean of the assay values multiplied by 100 should not exceed 20 percent due to the toxicity of some drugs.

Pfost, Duncan, and Waller (1974) listed the following three causes of nutrient variation:

1. Variation of the composition or quality of ingredients from batch to batch or time to time.

2. Errors during weighing and proportioning.

3. Poor mixing or segregation after mixing.

Controlling the amount of variation due to individual ingredients is possible by establishing strict guidelines for evaluating the nutritional profile of ingredients. Chung and Pfost (1976) suggested splitting lots of soybean meal according to protein content as a means of limiting ingredient variation. Errors in weighing and proportioning are easily remedied by proper maintenance of scales and by reducing operator error.

Several factors influence the quality of mixing achieved and the amount of segregation that takes place during handling and delivery. The physical properties of feed ingredients which influence mixing include particle size, particle shape, specific weight, hygroscopicity, susceptability to electrostatic charge and the adhesiveness of the particles (Pfost et al, 1966a).

Very little research has been conducted to determine the effect of grinding on mixing and segregation. Much of the literature devoted to this subject lacks accurate descriptions of the diets, ingredients or analytical procedures.

Pfost et al, (1966b) measured the mixing characteristics of corn, oats and milo which were either ground through a 1/4" hammermill screen or rolled with a 0.010" roll gap. Each grain was mixed with salt as a tracer in a twin screw vertical mixer. Variation was measured by sedimentation tests. Rolled corn, rolled oats and ground oats failed to mix properly. The authors concluded that the large difference in particle size between the salt and rolled corn adversely affected mixing. Differences in particle shapes due to the oat hulls was attributed to the poor mixing characteristics of ground and rolled oats.

Research conducted by Delort-Lavel et al (1971) indicated that the dumping volume ratio (Bruggeman and Niesar, 1962) may be used to indicate the tendancy of a feed to segregate during handling and transportation. The dumping volume is defined by the equation:

$$Vd = C/c \times f/F$$

where:

- Vd = Dumping volume ratio.
- C = Weight of coarse fraction (+ 35 Tyler screen).
- c = Apparent specific weight of coarse fraction.
- F = Weight of fine fraction (- 35 Tyler screen).
- f = Apparent specific weight of fine fraction.

Theoretically, no segregation will occur if the dumping volume ratio is less than 0.82, uncertain behavior if Vd is between 0.82 and 1.08, and an increasing tendancy to segregate when Vd is greater than 1.08. Similar tests conducted by Anstaett et al (1971) showed the dumpimg volume ratio to be indicative of segregation tendancies.

Effect of Grind on Pelleting

Pelleting has been defined as "an extrusion type thermoplastic molding operation in which the finely divided particles of a feed ration are formed into a compact, easily handled pellet" (Leaver, Undated).

Grinds described as "medium" or "fine" are usually preferred over "coarse" grinds for pelleting. Medium or fine ground material provides greater surface area for moisture addition during steam conditioning (MacBain, 1966).

Skoch (1979) found that steam conditioning decreased the mechanical friction during pelleting, increased production rates and improved pellet quality. No starch damage occurred as a result of conditioning in pellet mashes conditioned to 80°C in a conditioner with a five second retention time. Furthermore, the addition of steam reduced the amount of starch damage that occurred during pelleting when compared to dry pelleting. Studies conducted by Smith (1962) compared the effect of particle size on pelletibility of a high grain diet. Corn was ground through a 1.64 mm hammermill screen and a 3.2 mm screen prior to mixing and pelleting. Feed rates, die speed, die thickness and pellet mill roll settings were held constant. Trials were conducted comparing the diets with mash conditioned to 160, 180, and 200 °F. Pellet durability and pellet mill motor load were measured. Smith concluded that fine grinding is advantageous in the pelleting process, however, the increased energy costs associated with fine grinding may adversely affect total efficiency.

Pelleting trials conducted by Young (1960) showed no significant differences in pellet durability or production rates associated with particle size of the grain portion of a turkey starter diet. Stevens (1962b) reported that the effect of particle size on pelleting is difficult to evaluate. The benefits associated with pelleting fine grinds must be considered with respect to the added cost of fine grinding.

Large feed particles are undesireable in pellet mashes because they may create natural fissures in the pellet which are susceptable to breaking (MacBain, 1966). Pfost (1966b) found that feed particles undergo some particle size reduction during pelleting. Feeds with greater amounts of large particles undergo more pellet mill grinding than feeds with small particle sizes. Excessive particle size reduction during pelleting will cause the pellet mill die and rolls to wear faster and increase energy requirements.

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Experimental Procedure

Experiments were conducted in the pilot feed mill of the Department of Grain Science, Kansas State University to determine: 1. The effect of particle size on mixing efficiency 2. The effect of particle size on mixing uniformity and segregation. 3. The effect of particle size on pellet quality, pellet mill efficiency, and pelleting production rates.

Diets used in these experiments varied by grain and type of grind. Corn and grain sorghum (No. 2 grade) were ground by either hammermill or roller mill. Two hammermill grinds (3.2 mm and 6.4 mm screens) and two roller mill grinds (fine and coarse rolled) of each grain were used to create eight experimental treatments for each test.

Hammermill grinding was performed with a Jacobson[1] full circle hammermill (for corn) and a Sprout-Waldron[2] full circle hammermill (for grain sorghum). Roller mill grinding was done with a Barnard and Leas[3] single pair high roller mill equipped with 9 x 18 inch rolls cut with 24 corrugations per inch running at a 1:1 speed differential. Corn was rolled twice at different roll settings to obtain the desired particle size.

A stop watch was used to time the length of each grinding run. Weight was measured on a Howe Richardson 454 kg. batch scale. Electrical energy consumption for grinding grains used in the

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[1]Jacobson Machine Works, Minneapolis, Minnesota.

[2]Sprout-Waldron Div., Kopper's Inc., Muncy, Pennsylvania

[3]Barnard and Leas Manufacturing Co. Inc., Cedar Rapids, Iowa.

pelleting experiments was measured using a recording amp-volt recorder. Samples of the ground grains were obtained for particle size analysis (A.S.A.E. 1983, Appendix A).

Mixing Efficiency Study

The effect of particle size reduction on mixing efficiency was studied by measuring the coefficient of variation of salt present in test diets after mixing for periods of 0.5, 1.5, and 3.0 minutes in a 100 kg horizontal double ribbon mixer. Quantab[R] chloride titrators[1] were used to analyze salt content of ten samples obtained after each mixing interval. The grain portion of the diets accounted for 70 percent of the diet. The composition of the diets tested is listed in table 4. The eight treatments were randomly assigned to two blocks prior to mixing. The bulk density of the grain portion of each diet was also determined for each treatment. The sample mean and standard deviation of the salt content of the ten samples were used to calculate the coefficient of variation.

Mixing Uniformity and Segregation Studies

A test to study the effect of particle size on mixing and segregation was conducted in unison with a test to determine the effect of grind on pellet quality and production rates (pellet trial A). The experimental grinds were formulated into a typical swine diet (table 5) containing 0.5 % salt and mixed in a 454 kg mixer for 3 minutes. After mixing, the feed was dis-

1 Ames Division, Miles Laboratories, Inc., Elkhart, Indiana.

TABLE 4. COMPOSITION OF DIETS USED IN MIXING EFFICIENCY STUDY.

Ingredient	International Ref. No.	Diet (%)
Ground Corn or Grain Sorghum	4 - 26 - 023 4 - 20 - 893	70.0
Soybean Meal	5 - 20 - 637	16.7
Wheat Middlings	4 - 05 - 205	10.0
Dicalcium Phosphate	6 - 28 - 335	1.3
Salt	6 - 04 - 152	1.0
Limestone	6 - 02 - 632	1.0

TABLE 5. COMPOSITION OF DIETS USED IN MIXING UNIFORMITY, SEGREGATION AND PELLET TRIAL A STUDIES

Ingredient	International Ref. No.	Diet (%)
Ground Corn or Grain Sorghum	4 - 26 - 023 4 - 20 - 893	59.5
Soybean Meal	5 - 20 - 637	28.0
Dehydrated Alfalfa Meal	1 - 00 - 023	2.5
Dicalcium Phosphate	6 - 28 - 335	2.5
Salt	6 - 04 - 152	0.5
Limestone	6 - 02 - 632	3.0
Oyster Shell	---	3.0
Vitamin and Trace Mineral Premix	---	1.0

charged thru a single outlet into a screw conveyor, transferred a short distance to a bucket elevator, and elevated to mash bins above the pellet mill. The eight experimental diets were assigned to three blocks using a completely randomized block design prior to mixing and pelleting.

During each production run, ten feed samples were obtained from a sampling port between the screw conveyor and the bucket elevator during each mixer discharge, and an additional ten samples were taken from a belt feeder above the conditioning chamber of the pellet mill during pelleting (Fig. 1). Quantab[R] chloride titrators were used to analyze variation in the salt content of each set of samples.

<u>Pelleting Studies</u>

Pelleting was performed on a 25 hp Master model CPM[1] pellet mill equipped with a 50.8 mm x 4.8 mm straight bore die. The die was warmed prior to use. Pellets were cooled in a double pass horizontal cooler. After cooling, the pellets and fines were collected and weighed. The fines were recovered separately. Each production run was timed with a stop watch and weights of the pellets and fines were recorded. The pellet mill was operated at 85 % motor load. Mash was conditoned to 75 °C prior to pelleting. The pellet mill conditioner had a retention time of approximately 5 sec. The electrical energy consumed by the pellet mill was measured with a recording amp-volt recorder. Mash temperature was recorded before and after conditioning and

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[1]California Pellet Mill Co., San Francisco, California

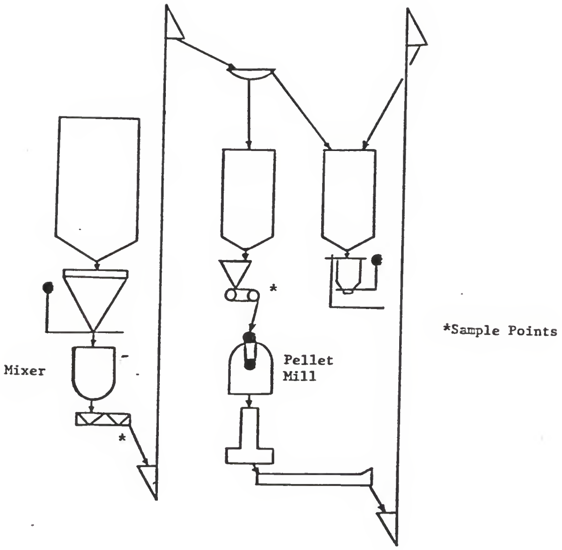

FIGURE 1. SAMPLE POINTS FOR SEGREGATION STUDY.

pellet temperatures were recorded prior to cooling. Steam consumption was calculated from steam tables (Pfost 1976a). Appendix B decribes the methods used to calculate energy efficiency.

Samples of the meal were taken before and after conditioning for moisture analysis (A.A.C.C. 1975). Samples of pellets for durability testing were taken prior to entering the cooler and cooled at room temperature. Pellet durability was measured by tumbling cold pellets in a cannister according to the method described by Pfost (1976b). Total energy requirements for pelleting were calculated by summing the amount of energy required to grind the grain portion of the diet to the energy required for conditioning and pelleting.

A similar pelleting trial (pellet trial B) was conducted with the same experimental grinds included in a layer ration. The composition of the diet is given in Table 6. The same pellet die, motor load, and conditioning temperature were used in both trials. Each treatment was completely randomized in two replications.

Statictical Analysis

Results obtained from particle size analysis were statistically analyzed for differences due to type of grind using analysis of variance (ANOVA) protected by Duncan's multiple range test (SAS Institute, 1979). No attempt was made to compare corn to grain sorghum data. The results of the mixing and pelleting studies were statisticaly analyzed for differences due to particle size using analysis of variance (ANOVA) protected by Duncan's multiple range test (Ibid.).

TABLE 6. COMPOSITION OF DIETS USED IN PELLET TRIAL B

Ingredient	International Ref. No.	Diet (%)
Ground Corn or Grain Sorghum	4 - 26 - 023 4 - 20 - 893	68.0
Soybean Meal	5 - 20 - 637	27.5
Dicalcium Phosphate	6 - 28 - 335	2.0
Salt	6 - 04 - 152	0.5
Limestone	6 - 02 - 632	1.0
Vitamin and Trace Mineral Premix	---	1.0

RESULTS AND DISCUSSION

Grinding

Hammermill grinding required more energy and produced a finer grind than roller mill grinding (table 7,8 and 9). As particle size decreased, the amount of energy increased significantly. Energy consumed in grinding ranged from 1.15 Kwh/MT for coarse rolled grain sorghum to 8.4 Kwh/MT for corn ground through an 3.2 mm screen.

Type of grind produced significant differences in mean particle diameters for all grinds. Significant differences were observed for surface area and particle numbers with the exception of 6.4 mm vs. fine rolled corn and grain sorghum in the mixing uniformity, segregation and pellet trial A . As the mean particle size increased, the geometric standard deviation of the particle size distribution increased in hammermill grinds and decreased in roller mill grinds.

The various grinds produced some differences in apparent bulk density (table 10 and 11). Roller mill grinds tended to produce lower bulk densities than hammermill grinding. Those differences may affect the mixing and pelleting properties of the diets.

Mixing Efficiency

The results obtained in the mixing efficiency studies followed the normal pattern for this particular test (table 10). After 0.5 minutes, a high coefficient of variation was measured, indicating insufficient mixing, in each test. Samples analyzed after mixing for 1.5 minutes had less variation than samples taken

TABLE 7. PARTICLE SIZE ANALYSIS OF CORN AND GRAIN SORGHUM USED IN MIXING EFFICIENCY STUDY[1,2]

Type of Grind	Mean Particle Diameter (μ)	Geo. Std. Dev.	Surface Area (cm^2/gm)	Particles Per Gram
- - - Corn - - -				
Hammermill				
(3.2 mm)[3]	554[a]	2.18[a]	81[a]	63000[a]
(6.4 mm)[3]	861[b]	2.23[a]	58[b]	30000[b]
Roller mill				
(fine)	908[c]	2.20[a]	53[c]	26000[c]
(coarse)	1414[d]	1.92[b]	40[d]	4000[d]
- - - Grain Sorghum - - -				
Hammermill				
(3.2 mm)[3]	502[a]	1.94[ab]	93[a]	83000[a]
(6.4 mm)[3]	706[b]	2.06[b]	78[b]	45000[b]
Roller mill				
(fine)	834[c]	2.04[b]	67[c]	29000[c]
(coarse)	1250[d]	1.88[a]	43[d]	4000[d]

[1]Values are means of two replications.

[2]Corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

TABLE 8. PARTICLE SIZE ANALYSIS AND GRINDING EFFICIENCY OF CORN AND GRAIN SORGHUM USED IN MIXING UNIFORMITY AND SEGREGATION STUDY AND PELLET TRIAL A[1,2]

Type of Grind	Particle Diameter (μ)	Geo. Std. Dev.	Surface Area (cm^2/gm)	Particles Per Gram	Grinding Efficiency (Kwh/MT)
			Corn		
Hammermill					
(3.2 mm)[3]	595[a]	2.13[ab]	89[a]	49000[a]	3.40[a]
(6.4 mm)[3]	876[b]	2.19[ab]	71[b]	31000[b]	4.95[b]
Roller mill					
(fine)	916[c]	2.24[b]	67[b]	27000[b]	4.37[c]
(coarse)	1460[d]	2.01[a]	39[c]	7000[c]	2.73[d]
			Grain Sorghum		
Hammermill					
(3.2 mm)[3]	508[a]	2.18[a]	101[a]	68000[a]	6.04[a]
(6.4 mm)[3]	741[b]	2.17[a]	77[b]	24000[b]	4.64[b]
Roller mill					
(fine)	974[c]	2.14[a]	61[c]	19000[b]	3.20[c]
(coarse)	1387[d]	2.01[b]	46[d]	9000[c]	1.15[d]

[1]Values are means of three replications.

[2]Corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

TABLE 9. PARTICLE SIZE ANALYSIS AND GRINDING EFFICIENCY OF CORN AND GRAIN SORGHUM USED IN PELLET TRIAL B[1,2]

Type of Grind	Particle Diameter (μ)	Geo. Std. Dev.	Surface Area (cm^2/gm)	Particles Per Gram	Grinding Efficiency (Kwh/MT)
- - - Corn - - -					
Hammermill					
(3.2 mm)[3]	612^a	2.23^{ab}	102^a	59000^a	8.22^a
(6.4 mm)[3]	900^b	2.35^a	73^b	27000^b	5.05^b
Roller mill					
(fine)	1045^c	2.20^{ab}	59^c	11000^c	4.26^c
(coarse)	1494^d	2.10^b	40^d	2700^d	2.47^d
- - - Grain Sorghum - - -					
Hammermill					
(3.2 mm)[3]	552^a	1.85^a	97^a	24000^a	5.76^a
(6.4 mm)[3]	676^b	1.91^a	81^b	15800^b	4.79^b
Roller mill					
(fine)	1146^c	2.20^b	53^c	3000^c	2.92^c
(coarse)	1444^d	1.89^a	38^d	1500^d	1.18^d

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

TABLE 10. EFFECT OF PARTICLE SIZE ON COEFFICIENT OF VARIATION OF CHLORIDE IONS IN MIXING EFFICIENCY STUDY[1,2]

Type Of Grind	Mean Particle Diameter (μ)	Bulk Density (kg/M^3)	Coefficient of Variation (%)		
			0.5 min.	1.5 min.	3.0 min.
- - - - - Corn - - - - -					
Hammermill					
(3.2 mm)[3]	554	640^{a}	40.0^{a}	7.7^{a}	8.4^{a}
(6.4 mm)[3]	861	608^{ab}	42.3^{a}	11.0^{b}	7.7^{a}
Roller mill					
(fine)	908	577^{b}	35.7^{a}	10.8^{b}	9.3^{a}
(coarse)	1414	592^{b}	63.2^{b}	17.3^{c}	14.2^{b}
- - - - - Grain Sorghum - - - - -					
Hammermill					
(3.2 mm)[3]	502	657^{a}	30.2^{a}	8.8^{a}	9.2^{ab}
(6.4 mm)[3]	706	657^{a}	42.0^{b}	9.7^{a}	7.8^{a}
Roller mill					
(fine)	834	592^{b}	45.0^{bc}	10.3^{a}	10.5^{ab}
(coarse)	1250	608^{b}	51.5^{c}	14.8^{b}	11.2^{b}

[1]Values are means of two replications.

[2]Diets containing corn and grain sorgum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

after 0.5 minutes with the finer grinds showing adequate mixing (coefficient of variation less than 10%). After mixing for 3.0 minutes, all of the test diets had coefficients of variation less than 10 percent except for the coarse rolled diets and the fine rolled grain sorghum diets. Of these, only the coarse rolled corn diet had a coefficient of variation substantially higher than 10 percent. These results indicate that coarser grinds tend to require more time to mix than finer grinds.

Mixing Uniformity and Segregation

Analysis of samples taken after mixing and prior to pelleting indicated that no substantial amount of segregation occurred during transfer (table 11). Diets containing fine rolled grains had the greatest amount of variation prior to pelleting. The greater amount of segregation occurring in the fine rolled diets may be related to the lower bulk density of the grains used.

Pelleting

Increases in particle size had little effect on pellet quality and pelleting efficiency in either pelleting trial. Diets containing corn or grain sorghum ground through a 3.2 mm hammermill screen generally produced the most durable pellets with the least amount of energy (table 12 and 14). Although some differences were observed in electrical energy used during pelleting, those differences were minor when considering the great differences in grinding efficiency (table 8 and 9). The energy required to condition the diet (table 13 and 15) was considerably higher than the electrical energy required for pelleting. No significant differences in

TABLE 11. THE EFFECT OF PARTICLE SIZE ON MIXING UNIFORMITY AND SEGREGATION[1,2]

Type Of Grind	Mean Particle Diameter (μ)	Diet Bulk Density (kg/M^3)	Coefficient of Variation (%)	
			Mixer Discharge	Prior To Pelleting
- - - Corn - - -				
Hammermill				
(3.2 mm)*	595	494^{a}	6.42^{a1}	7.72^{a1}
(6.4 mm)*	876	515^{a}	6.08^{a1}	11.00^{b2}
Roller mill				
(fine)	916	485^{a}	7.78^{a1}	13.94^{b2}
(coarse)	1460	508^{a}	10.23^{b1}	13.56^{b2}
- - - Grain Sorghum - - -				
Hammermill				
(3.2 mm)*	508	520^{a}	6.12^{a1}	8.55^{a1}
(6.4 mm)*	741	513^{a}	7.36^{ab1}	11.54^{b2}
Roller mill				
(fine)	974	506^{a}	9.50^{b1}	17.33^{c2}
(coarse)	1387	531^{a}	10.43^{b1}	13.17^{b1}

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

*Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

[1,2]Row means with the same superscripts are not significantly different ($p < .05$).

TABLE 12. THE EFFECT OF PARTICLE SIZE ON PELLET QUALITY AND PELLETING EFFICIENCY IN PELLET TRIAL A[1,2]

Type of Grind	Mean Particle Diameter (μ)	Pellet Durability Index (%)	Production Rate (kg/hr)	Electrical Efficiency (Kwh/MT)
- - - Corn - - -				
Hammermill				
(3.2 mm)[3]	595	92.5[a]	1800[a]	9.63[a]
(6.4 mm)[3]	876	92.3[a]	1764[a]	9.77[a]
Roller mill				
(fine)	916	91.3[a]	1758[a]	9.88[a]
(coarse)	1460	91.3[a]	1730[a]	10.08[a]
- - - Grain Sorghum - - -				
Hammermill				
(3.2 mm)[3]	508	92.9[a]	1745[a]	9.88[a]
(6.4 mm)[3]	741	91.6[a]	1728[a]	10.03[a]
Roller mill				
(fine)	974	91.9[a]	1688[a]	9.77[a]
(coarse)	1387	91.6[a]	1699[a]	10.21[a]

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

steam consumption due to particle size were noticed.

Total energy requirements of the pellet trials are listed in tables 16 and 17. Total efficiency was calculated by combining the energy required to grind the grain portion of the diet with the energy required to condition and pellet the diet. Diets containing corn ground through a 3.2 mm hammermill screen had the highest energy requirements in each trial. Diets containing the coarse rolled grains generally had the lowest total energy requirement.

Results from this study indicate that it is possible to lower total feed production costs by substituting coarser, more economical grinds for finer grinds in certain types of feeds. However, caution must be taken when using larger particle sizes due to their mixing and segregation characteristics. Further research in this area is needed to evaluate the potential for using coarser grinds in different types of feed.

TABLE 13. MOISTURE CONTENT AND TEMPERATURE OF MASH BEFORE AND AFTER CONDITIONING AND THE EFFECT OF PARTICLE SIZE ON STEAM EFFICIENCY IN PELLET TRIAL A[1,2]

Grind	Mean Particle Diameter (μ)	Moisture Content (%) Before Cond.	Moisture Content (%) After Cond.	Temp. (C) Before Cond.	Temp. (C) After Cond.	Steam Efficiency (Kwh/MT)
Corn						
Hammermill						
(3.2 mm)[3]	595	11.63	14.54	26.0	75.0	27.65[a]
(6.4 mm)[3]	876	11.41	14.68	25.7	75.0	27.82[a]
Roller mill						
(fine)	916	11.26	14.65	25.7	75.0	27.82[a]
(coarse)	1460	11.16	14.73	25.3	75.0	28.04[a]
Grain Sorghum						
Hammermill						
(3.2 mm)[3]	508	10.94	14.32	25.7	75.0	27.82[a]
(6.4 mm)[3]	741	11.27	14.54	25.3	75.0	28.04[a]
Roller mill						
(fine)	941	10.94	14.22	25.3	75.0	28.04[a]
(coarse)	1387	11.27	14.23	25.3	75.0	28.04[a]

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

TABLE 14. EFFECT OF PARTICLE SIZE ON PELLET QUALITY AND PELLETING EFFICIENCY IN PELLET TRIAL B[1,2]

Type of Grind	Mean Particle Diameter (μ)	Pellet Durability Index (%)	Production Rate (kg/hr)	Electrical Efficiency (Kwh/MT)
Corn				
Hammermill				
(3.2 mm)[3]	612	93.4^{a}	1362^{a}	10.85^{a}
(6.4 mm)[3]	900	92.3^{a}	1426^{a}	10.56^{a}
Roller mill				
(fine)	1044	92.9^{a}	1334^{a}	11.26^{a}
(coarse)	1494	93.1^{a}	1450^{a}	10.38^{a}
Grain Sorghum				
Hammermill				
(3.2 mm)[3]	552^{a}	93.4^{a}	1256^{a}	11.96^{a}
(6.4 mm)[3]	676^{b}	92.2^{a}	1503^{b}	10.05^{b}
Roller mill				
(fine)	1146^{c}	92.4^{a}	1511^{b}	10.14^{b}
(coarse)	1444^{d}	92.2^{a}	1359^{ab}	11.28^{ab}

[1]Values are means of three replicates.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

TABLE 15. MOISTURE CONTENT AND TEMPERATURE OF MASH BEFORE AND AFTER CONDITIONING OF MASH AND STEAM EFFICIENCY OF PELLET TRIAL B[1,2]

Type of Grind	Mean Particle Diameter (μ)	Moisture Content (%) Before Cond.	Moisture Content (%) After Cond.	Temp. (C) Before Cond.	Temp. (C) After Cond.	Steam Efficiency (Kwh/MT)
Corn						
Hammermill						
(3.2 mm)[3]	612	11.33	14.41	26.5	75.0	27.37[a]
(6.4 mm)[3]	900	11.50	14.72	27.5	75.0	27.11[a]
Roller mill						
(fine)	1044	11.41	14.74	25.5	75.8	28.42[a]
(coarse)	1494	10.99	14.58	27.0	75.5	27.39[a]
Grain Sorghum						
Hammermill						
(3.2 mm)[3]	552	11.29	14.55	27.0	75.0	27.00[a]
(6.4 mm)[3]	676	11.18	14.31	26.5	75.0	27.37[a]
Roller mill						
(fine)	1146	11.36	14.64	26.0	75.0	27.65[a]
(coarse)	1444	11.19	14.22	25.0	75.0	28.21[a]

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$)

TABLE 16. SUMMARY OF ENERGY REQUIREMENTS FOR PELLET TRIAL A[1,2]

Type of Grind	Mean Particle Diameter (μ)	Grinding Efficiency (Kwh/MT)	Pelleting Efficiency (Kwh/MT)	Steam Efficiency (Kwh/MT)	Total Efficiency (Kwh/MT)
- - - Corn - - -					
Hammermill					
(3.2 mm)[3]	595	5.38	9.64	27.65	43.17[a]
(6.4 mm)[3]	876	3.47	9.77	27.82	41.06[b]
Roller mill					
(Fine)	916	3.06	9.88	27.82	40.76[b]
(Coarse)	1460	1.91	10.08	28.04	40.03[b]
- - - Grain Sorghum - - -					
Hammermill					
(3.2 mm)[3]	508	4.23	9.88	27.82	41.93[a]
(6.4 mm)[3]	741	3.25	10.03	28.04	41.32[ab]
Rollermill					
(Fine)	974	2.24	9.77	28.04	40.05[ab]
(Coarse)	1387	0.81	10.21	28.04	39.06[b]

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

TABLE 17. SUMMARY OF ENERGY REQUIREMENTS FOR PELLET TRIAL B[1,2]

Type of Grind	Mean Particle Diameter (μ)	Grinding Efficiency (Kwh/MT)	Pelleting Efficiency (Kwh/MT)	Steam Efficiency (Kwh/MT)	Total Efficiency (Kwh/MT)
Corn					
Hammermill					
(3.2 mm)[3]	612	4.89	10.85	27.37	43.11[a]
(6.4 mm)[3]	900	3.00	10.56	27.11	40.67[bc]
Roller mill					
(Fine)	1044	2.53	11.26	28.42	42.21[ab]
(Coarse)	1494	1.47	10.38	27.39	39.24[c]
Grain Sorghum					
Hammermill					
(3.2 mm)[3]	552	3.43	11.96	27.08	42.47[a]
(6.4 mm)[3]	676	2.85	10.05	27.37	40.27[b]
Roller mill					
(Fine)	1146	1.74	10.14	27.65	39.53[b]
(Coarse)	1444	0.70	11.28	28.21	40.19[b]

[1]Values are means of three replications.

[2]Diets containing corn and grain sorghum were analyzed separately.

[3]Diameter of hammermill screen openings.

[abcd]Column means with the same superscripts are not significantly different ($p < .05$).

SUMMARY

The effect of particle size reduction on mixing and pelleting quality and production rates was investigated in a series of experiments in which corn and grain sorghum were ground to various degrees of fineness by hammermill (3.2 mm and 6.4 mm screen) and by roller mill (fine and coarse). Energy usage in grinding ranged from 1.15 Kwh/MT (coarse rolled grain sorghum) to 8.4 Kwh/MT (corn, 3.2 mm screen).

The effect of particle size on mixing efficiency was determined by measuring the variation in salt content of diets containing the same types of grinds at time intervals of 0.5, 1.5, and 3.0 minutes. Finer grinds required less time to mix throughly than coarser grinds. However, a suitable degree of mixing uniformity was obtained with all grinds after mixing 3.0 minutes. Feed samples taken from the mixer discharge and samples taken prior to entering the pellet mill conditioner were analyzed for uniformity of mix. Diets containing coarse ground grains tended to segregate more than diets containing finer ground grains.

Two pelleting trials were conducted which indicated that particle size reduction had little effect on pellet durability and pelleting production rates. Diets containing corn or grain sorghum ground by hammermill with a 3.2 mm screen produced slightly more durable pellets than coarser grinds, however, the energy consumed in grinding through a 3.2 mm screen would appear to offset the improved pellet quality.

APPENDIX A

Method of Determining Log-Normal Particle Size Distribution Parameters[1]

The following procedure was used to determine the mean particle size (μ), geometric standard deviation, total surface area (cm^2/gram), and total number of particles (particles/gram) of ground grains and feedstuffs.

Equipment

A set of Tyler 8 inch diameter woven-wire cloth sieves (Table 18) and a Tyler Ro-Tap testing sieve shaker (Model B) were used to isolate the particles into different sized fractions. An Ohaus Dial-A-Gram[R] balance was used to weigh the sieved fractions. Sieve agitators were used to ensure proper sieving action. A wire sieve brush and a triangle pan were used to collect sieve fractions.

Sieving Procedure

A sample of approximately 100 grams was placed on the the top sieve in the stack. The sample was then sifted for exactly ten minutes. The weight of sample remaining on each sieve and in the pan was determined to the nearest one-tenth of a gram.

Calculations

The following calculations are made based on the assumption that the weight distribution of ground cereal grains and feed ingredients are logarithmically normal. In order to perform these calculations, one must know the specific density of the sample (1.32

[1]ASAE. 1983. Method of determining and expressing fineness of feed materials by sieving. ASAE Standard S319, In Agricultural Engineers Yearbook of Standards, ASAE p. 325.

TABLE 18. SCREENS USED IN SIEVE ANALYSIS

Tyler Sieve Number	Nominal Sieve Opening (μ)
3.5	5660
5	4000
6	3360
8	2380
10	1680
14	1190
20	841
28	595
35	420
48	297
65	210
100	149
150	105
200	74
270	53
Pan	--

and 1.35 g/cm^3 for corn and milo, respectively), and the cubic shape factors (values of 6 for surface area and 1 for volume). Mean particle diameter (d_{gw}), geometric standard deviation (S_{gw}), total surface area (A_{st}), and total number of particles (N_t) are obtained as follows:

$$d_{gw} = \log^{-1} [\Sigma(W_i \log \bar{d}_i) / \Sigma W_i]$$

$$S_{gw} = \log^{-1} [\Sigma W_i (\log \bar{d}_i - \log dgw)^2 / \Sigma W]^{1/2}$$

$$A_{st} = \frac{\beta_s W_t S_{gw}}{\beta_v \rho d_{gw}} (\ln(S_{gw})^{.05}$$

$$N_t = \frac{W_t S_{gw}}{\beta_v \rho d_{gw}^3} (\ln(Sgw)^{4.5})$$

where:

A_{st} = total surface area of particles

β_s = shape factor for calculating surface area of particles

β_v = shape factor for calculating volume of particles

d = particle size or diameter

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

d_{i+1} = diameter of openings in next larger i'th sieve in set

d_{gw} = geometric mean particle diameter

$\bar{d}_i$ = geometric mean diameter of particles on i'th sieve $= (d_i \times d_{i+1})^{1/2}$

N_t = total number of particles per sample

ρ = specific weight of sample

S_{gw} = geometric standard deviation

W_i = weight fraction on i'th sieve

W_t = unit of weight used in A_{st} and N_t calculations

Example

Table 19 details the information obtained from a sieve analysis of corn ground through a 6.4 mm hammermill screen. Figure 2 illustrates how the results from the same sieve analysis may be found graphically.

TABLE 19. METHOD OF CALCULATING PARTICLE SIZE ANALYSIS DATA

Tyler Screen No.	Screen opening (μ)	$\log \bar{d}_i$	W_i (grams)	$W_i \log \bar{d}_i$	$W_i(\log \bar{d}_i - \log d_{gw})^2$
3	6730	3.903	0	0	0
4	4760	3.753	0	0	0
6	3360	3.602	2.1	7.564	.818
8	2380	3.452	9.6	33.139	2.159
10	1680	3.301	13.5	44.564	1.410
14	1190	3.149	17.5	55.108	.513
20	841	3.000	14.3	42.900	.007
28	595	2.849	10.7	30.484	.178
35	420	2.699	10.7	28.879	.832
48	297	2.549	10.4	26.510	1.912
65	210	2.398	3.8	9.078	1.317
100	149	2.248	1.2	2.698	.639
150	105	2.097	.9	1.887	.698
200	74	1.944	.3	.583	.321
270	53	1.799	.2	.360	.278
Pan	--	1.643*	.2	.320	.356
		Summation	95.4	284.074	11.716

$$\log d_{gw} = \frac{\Sigma(W_i \log \bar{d}_i)}{\Sigma W_i} = 2.978 \qquad d_{gw} = 950 \text{ microns}$$

$$\log S_{gw} = [\Sigma W_i(\log \bar{d}_i - \log d_{gw})^2 / \Sigma W_i]^{1/2} = .343 \qquad S_{gw} = 2.21$$

$$\rho = 1.32 \qquad \beta_v = 6 \qquad \beta_s = 1 \qquad W_t = 1 \text{ gram}$$

$$A_{st} = \frac{\beta_s W_t S_{gw}}{\beta_v \rho d_{gw}} (\ln(S_{gw})^{.05} = 65.7 \text{ cm}^2/\text{gram}$$

$$N_t = \frac{W_t S_{gw}}{\beta_v \rho d_{gw}^3} (\ln(S_{gw})^{4.5}) = 15400 \text{ particles/gram}$$

* Material passing thru a Tyler sieve no. 270 shall be considered to have a mean diameter of 44 microns.

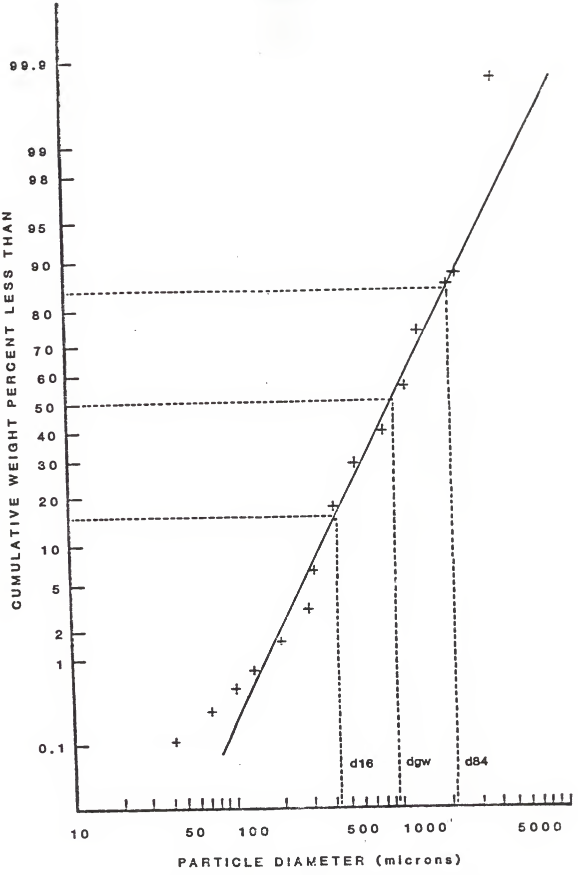

FIGURE 2. GRAPHICAL SOLUTION OF PARTICLE SIZE ANALYSIS DATA.

Appendix B

Methods for Calculating Steam and Electrical Energy Consumed in Grinding and Pelleting

Electrical Efficiency Calculations:

$$Kwh/MT = \frac{I \times E \times EFF \times P.F. \times 1.73}{(MT/hr) \times 1000}$$

where Kwh/MT = kilowatt hours per metric ton

I = amperage

E = voltage

EFF = efficiency factor

P.F. = power factor

1.73 = correction factor for three phase motor

MT/hr = metric tons per hour

1000 = number of watts per kilowatt

Steam Efficiency Equivalent Calculations[1]:

Kwh/MT of steam required for pelleting was determined by calculating the amount of heat required to generate the steam necessary to raise the temperature of the meal from its original temperature to its temperature after conditioning. The following assumptions were made in these calculations:

1. Steam injected during conditioning was used efficiently. Therefore, the heat removed from the steam was equal to the heat added to the meal.
2. Steam quality at the conditioner was equal to 90 %.
3. The specific heat of the product was equal to .4 BTU/lb F.
4. Boiler feedwater had a temperature of 50 °F.

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[1]Pfost, H.B. 1976. Principles of Heat and Moisture Transfer. In: H. B. Pfost (Ed.) Feed Manufacturing Technology. pp 59-70. AFMA, Arlington, Virginia.

Given the following definitons:

T_1 = temperature of meal before conditioning (F)

T_2 = temperature of meal after conditioning (F)

T_3 = temperature of boiler feed water.

h_f = enthalpy or heat content, BTU/lb in saturated liquid

h_{fg} = latent enthalpy (BTU/lb)

h_g = total enthalpy (BTU/lb)

h_1 = enthalpy of original steam

h_2 = final enthalpy of steam (after cond.)

q = heat required to raise the temperature of the meal

C = specific heat of the meal (BTU/lb F)

W = weight of steam (lb)

Q = total amount of heat required from boiler per metric ton of meal

The following method was used to calculate the energy consumed in steam conditioning:

Let T_1 = 26 °C (78.8 F)

T_2 = 75 °C (167 F)

Steam entered the conditioner at 90 psig (105 psia). Enthalpy values from steam tables are:

At 105 psia : h_f = 302

h_{fg} = 886

h_g = 1188

At 14.7 psia: $h_f = 180$

$h_{fg} = 970$

$h_g = 1150$

Original steam enthalpy (90 % steam quality):

$$h_1 = h_f + (h_{fg} \times .90 \%)$$

$$= 302 + (886 \times .90) = 1099.4 \text{ BTU/lb}$$

Final steam enthalpy will be:

$$h_2 = t_2 - 32$$

$$= 167 - 32 = 135 \text{ BTU/lb}$$

The heat required to raise the temperature of the meal:

$$q = 1 \text{ lb} \times C \times (T_2 - T_1)$$

$$= 1 \times 0.4 \times (167 - 79) = 35.3 \text{ BTU/lb}$$

The weight of steam required per pound of mash:

$$W = q/(h_1 - h_2)$$

$$= 35.3/(1099.4 - 135) = 0.037 \text{ lb steam/lb mash}$$

Total heat required from boiler per metric ton of meal is calcluated by:

$$Q = W(2204.6 \text{ lb/MT})(h_f - (T_3 - 32 \text{ F}) + h_{fg})$$

$$= 0.037(2204.6)(302 - 18 + 886) = 94360 \text{ BTU/MT}$$

Steam efficiency in Kwh/MT is calculated by:

$$\text{Kwh/MT} = 94360 \text{ (BTU/MT)}/3413 \text{ BTU/Kwh} = 27.65 \text{ Kwh/MT}$$

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COMPARISON OF HAMMERMILL AND ROLLER MILL GRINDING
AND THE EFFECT OF GRAIN PARTICLE SIZE
ON MIXING AND PELLETING

by

STUART A. MARTIN

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