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Abstract. *Biomass preprocessing is one of the primary operations in the feedstock assembly system of a lignocellulosic biorefinery. Preprocessing is generally accomplished using industrial grinders to format biomass materials into a suitable biorefinery feedstock for conversion to ethanol and other bioproducts. Many factors affect machine efficiency and the physical characteristics of preprocessed biomass. For example, moisture content of the biomass as received from the point of production has a significant impact on overall system efficiency and can significantly affect the characteristics (particle size distribution, flowability, storability, etc.) of the size-reduced biomass. Many different grinder configurations are available on the market, each with advantages under specific conditions. Ultimately, the capacity and/or efficiency of the grinding process can be enhanced by selecting the grinder configuration that optimizes grinder performance based on moisture content and screen size. This paper discusses the relationships of biomass moisture with respect to preprocessing system performance and product physical characteristics and compares data obtained on corn stover, switchgrass, and wheat straw as model feedstocks during Vermeer HG 200 grinder testing. During the tests, grinder screen configuration and biomass moisture content were varied and tested to provide a better understanding of their relative impact on machine performance and the resulting feedstock physical characteristics and uniformity relative to each crop tested.*

Keywords. preprocessing, grinding, hammer mill, biomass deconstruction, biomass bulk density.

Introduction

Biomass preprocessing is a critical operation in preparing feedstock for use in a lignocellulosic ethanol biorefinery (Figure 1). Without preprocessing, the size, bulk density, and flowability characteristics of harvested biomass would decrease the capacities and efficiencies of the biorefinery conversion processes to the degree that cost targets could not be met (Hamalinck et al., 2005). Loose harvested biomass has a bulk density ranging from only 50 to 120 kg/m^3 depending on the particle size. The bulk density can be increased substantially (~25%) for chopped or ground biomass by vibrating the biomass holder. To increase density further, the biomass must be mechanically compacted into cubes or pellets (Sokhansanj et al., 1999). The objective of preprocessing is to produce a product that (1) improves handling and conveying efficiencies for feedstock storage, transportation, and biorefinery receiving; (2) increases biomass surface areas for improved processing efficiencies (Walker and Wilson, 1991; Mansfield et. al, 1999); (3) reduces particle sizes for improved feedstock uniformity and density; and (4) fractionates structural components for improved compositional quality. In addition, the preprocessing operation has the potential to change traditional methodologies for collection, handling, and transporting biomass, which will enable revolutionary improvements in the feedstock assembly system.

Figure 1. Example of feedstock preprocessing.

The cost of implementing a viable biomass preprocessing operation in the feedstock assembly system is constrained by three basic performance parameters: machine capacity (throughput), operational efficiency, and material output quality. The first two parameters, capacity and efficiency, are primarily dependent on the physical configuration of the equipment and the physical characteristics of the biomass feedstock. Previous Idaho National Laboratory (INL) research has shown that the interaction between machine hardware and the biomass structure can significantly impact the resulting capacity and efficiency of the operation. Therefore, optimization of both capacity and efficiency requires economic trade-offs between machine hardware configurations and the particular biomass being preprocessed.

A standard industrial preprocessing machine has several fundamental hardware components that can be iteratively altered to achieve an optimum design, including the following:

- Fractionation mechanism (hammers, knives, shear plates, etc.)

- Biomass feed system (horizontal conveyer, vertical gravity, pneumatic, etc.)
- Output screen size (diameter and thickness) and shape (square, round, etc.)
- Discharge system (conveyor, auger, pneumatic, etc.)
- Power unit or drive system (electric or diesel).

Similarly, feedstock type and composition are important factors in preprocessing. Different feedstock varieties (wheat straw, corn stover, switchgrass, pine, poplar, etc.) possess different preprocessing parameters that must be considered in the integral design to account for their impacts on machine performance.

The work discussed in this paper builds upon previous INL preprocessing research, which provided specific guidance on possible machine design improvements based on variations in screen configuration and limitations of the feed mechanism. The objective of this study is to analyze the functional relationships between moisture content, biomass type, and screen size in order to optimize the preprocessing unit operation based on capacity, efficiency, and the quality of the output material. It is anticipated that this optimization process will impact not only the stand-alone grinding operation, but also other preprocessing operations in the feedstock assembly system, such as the harvest and collection, storage, and transportation and handling operations.

Safety Emphasis

Like all large-scale grinding equipment, the Vermeer HG-200 has potential hazards associated with its use and maintenance. Prior to operating the grinder, Vermeer provided a one-day, hands-on operator training for equipment users. The HG-200 is designed with safety interlocks to help ensure the safe operation of the grinder. Workers operated in compliance with a safety control document equivalent to a health and safety plan, which identified potential hazards and appropriate mitigation of those hazards. Part of those safety controls included establishing safety zones around the equipment. These zones were established in part to help keep observers at a safe distance. Grinder operators were required to wear hard hats, gloves, safety shoes, and hearing protection. Additionally, because the biomass was dry and produced a large amount of dust during operation, operators were required to wear respirators to reduce the risk of dust inhalation.

Methodologies

INL is tasked with improving the overall efficiency of all unit operations in the feedstock assembly system (harvest and collection, storage, preprocessing [grinding], transportation, and handling) for all feedstock types used in bioethanol or syngas production.

The expected outcomes of this activity were to identify (1) baseline preprocessing performance parameters for wheat straw, corn stover, and switchgrass; (2) preprocessing performance constraints based on screen size; and (3) the effect of moisture content on preprocessing efficiency and quality of the feedstock produced. During this study, three model crops were selected for comparison and testing: wheat straw, corn stover, and switchgrass.

For these grinding or preprocessing tests, a Vermeer HG-200 grinder was used (Figure 2). The HG-200 was powered by a Cummins B3.3 turbo-charged, 85-horsepower diesel engine. The drum had 10 fixed hammers and a drum tip diameter of 22.3 in. (Figure 3).

Figure 2. HG-200 horizontal grinder.

Figure 3. Vermeer fixed grinding cutters.

The efficiency and production rates were determined by measuring the quantities of biomass processed and the time required for processing. The biomass was weighed before and after grinding. A stop watch was used to determine the time it took to complete a grinding test. To determine fuel consumption during the test, the grinder's fuel tank was filled prior to initiating test grinding. An additional portable 5-gallon fuel container was filled with diesel and weighed. Following the completion of the test, the grinder's fuel tank was refilled from the 5-gallon fuel container. The portable fuel container was then reweighed to determine the amount of diesel consumed during the grinding test.

Biomass samples were collected from the inlet and the outlet of the grinder. These samples were used to determine moisture content of the inflow and outflow material and to determine the particle size distribution and mean particle size for the processed material. The particle size and distribution parameters were determined using a forage particle separator, which is shown in Figure 4. The screen sizes used in the separator were 19 × 19 mm, 12.5 × 12.5 mm, 6 × 6 mm, 4 × 4 mm, 2 × 2 mm, and pan (ANSI/ASAE, 2001a).

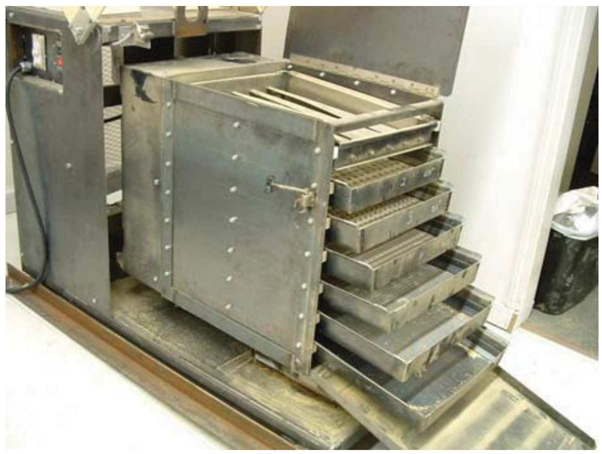

Figure 4. INL forage particle separator.

The crops were ground in the HG-200 using four different screen sizes (3.375 in., 1.75 in., 1.25 in., and 0.75 in.). In general, the bales tested were large 4 × 4 × 8-ft bales, but some 5-ft round bales and some 3 × 4 × 8-ft bales were also tested. In all cases, the bales were de-twined, broken apart, and fed into the grinder by a conveyor. The bales were air dried, and the measured moisture content ranged from 7.04 to 9.55% for switchgrass, 6.60 to 9.05% for corn stover, and 9.95 to 11.19% moisture for wheat straw.

Results

Particle Size Distribution

Three different feedstock varieties (wheat straw, corn stover, and switch grass) were field tested using a Vermeer HG-200 horizontal grinder. These tests showed significant differences in ground material characteristics based on feedstock variety and screen size. The first parameters to show this difference were feedstock particle size and distribution. Two variables, moisture and screen size, were tested to identify particle size and distribution effects.

As expected, the particle sizes decreased with decreasing screen sizes used in the grinder. Interestingly, the corn stover had the broadest range of particles sizes, while switchgrass and wheat straw showed tighter ranges in particle size, with most of the material ending up on the 2-mm sieve and in the pan when tested (see Figures 5 through 8). The wheat straw grinding tests also showed that regardless the screen used, the grinder still produced approximately the same range of particle sizes. In general, 70 to 80% of the wheat straw and switch grass material ended up in the less than 4mm range, while only 30 to 40% of the corn stover fell in that same size range when ground using the 1.75-in screen or larger.

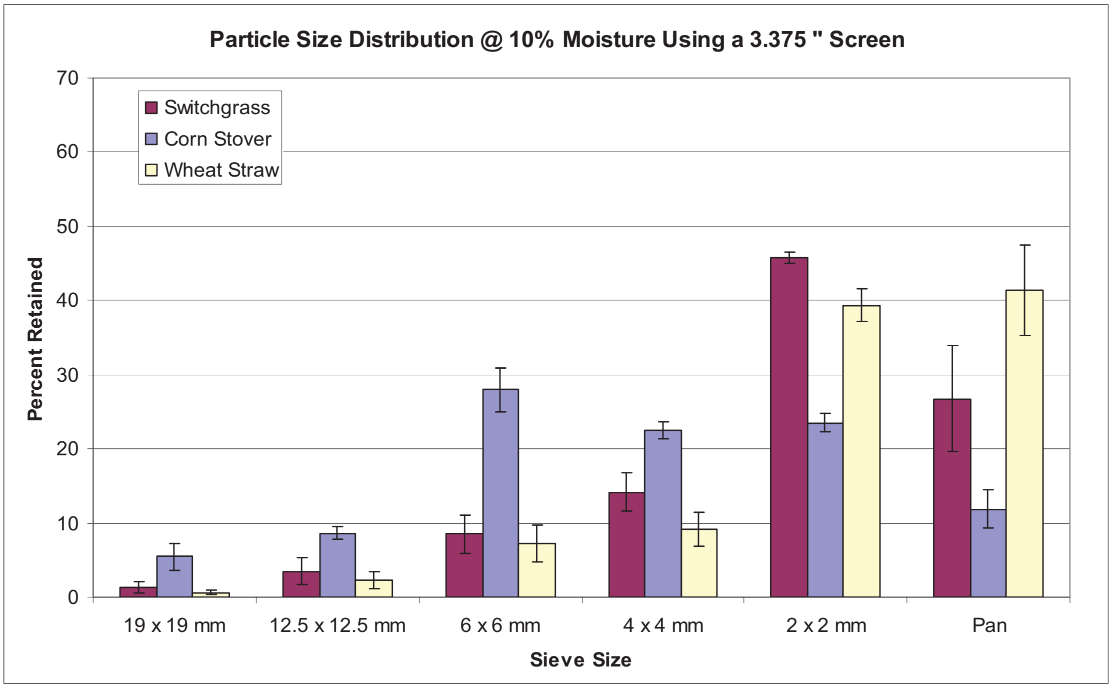

Figure 5. Particle size distribution for switchgrass, corn stover, and wheat straw collected from grinding tests with the HG-200 grinder with a 3.375-in. screen.

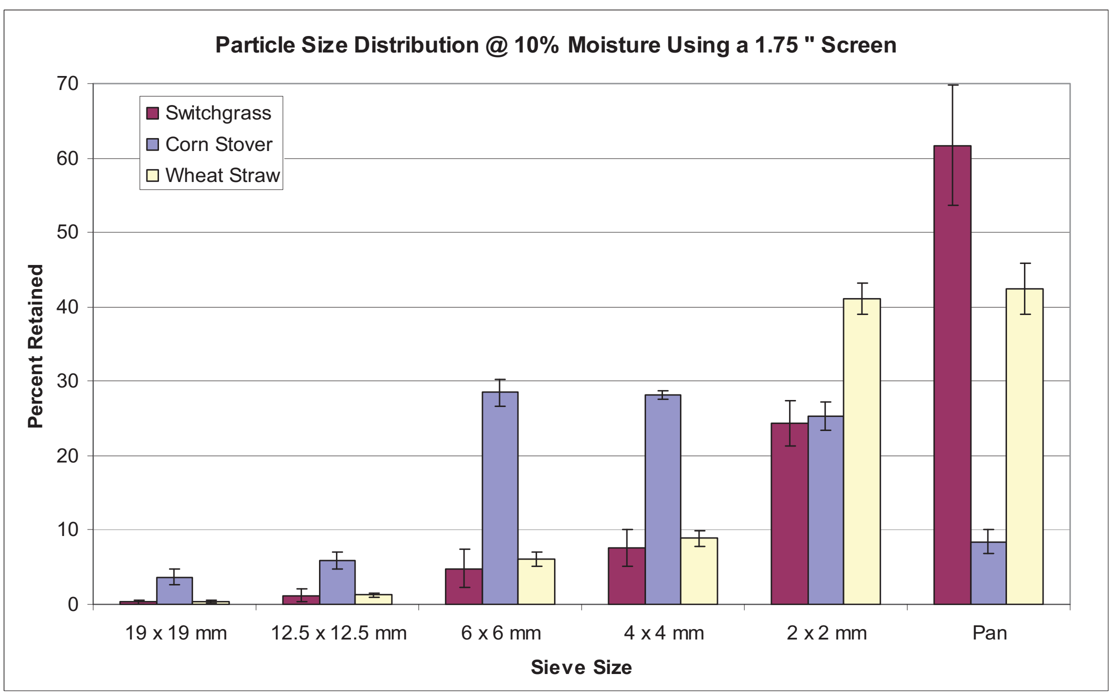

Figure 6. Particle size distribution for switchgrass, corn stover, and wheat straw collected from grinding tests with the HG-200 grinder with a 1.75-in. screen.

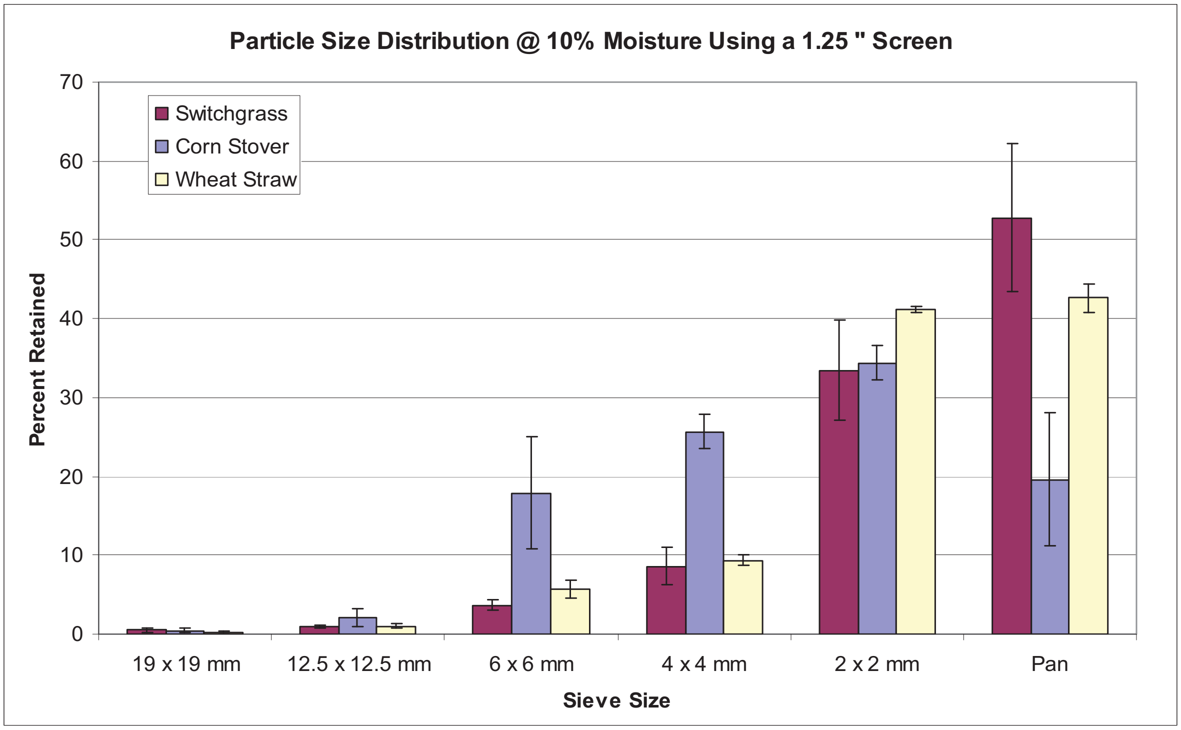

Figure 7. Particle size distribution for switchgrass, corn stover, and wheat straw collected from grinding tests with the HG-200 grinder with a 1.25-in. screen.

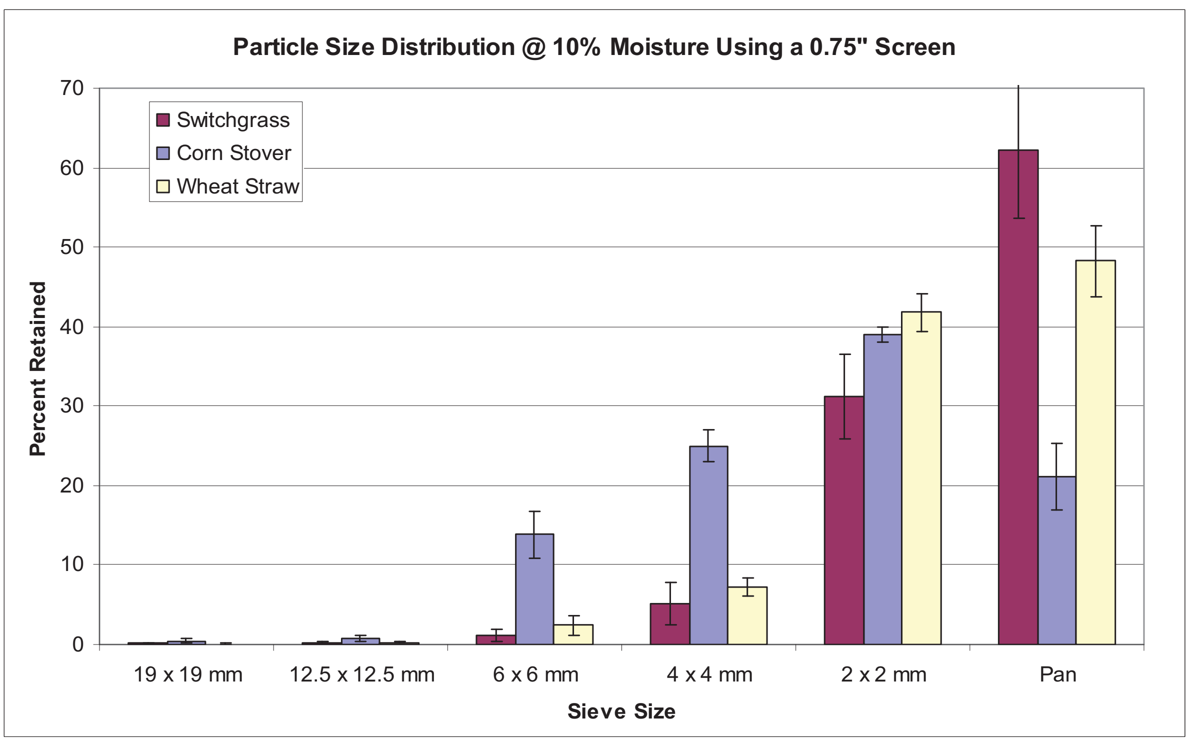

Figure 8. Particle size distribution for switchgrass, corn stover, and wheat straw collected from grinding tests with the HG-200 grinder with a 0.75-in. screen.

Figure 9 shows the mean particle size for each of the crops tested. While there is little difference between the mean particle size of switchgrass and wheat straw, the mean particle size of the ground corn stover is significantly larger than the other two crops, regardless of which screen was used. Changing the screen size had the greatest effect on the switchgrass. Changing the screen size from 3.375-in. to 0.75-in. in the HG-200 resulted in about a 60% reduction in mean particle size in switchgrass. The same change in screens resulted in a 40% reduction in mean particle size in the corn stover, but only a 10% reduction in particle size in the wheat straw.

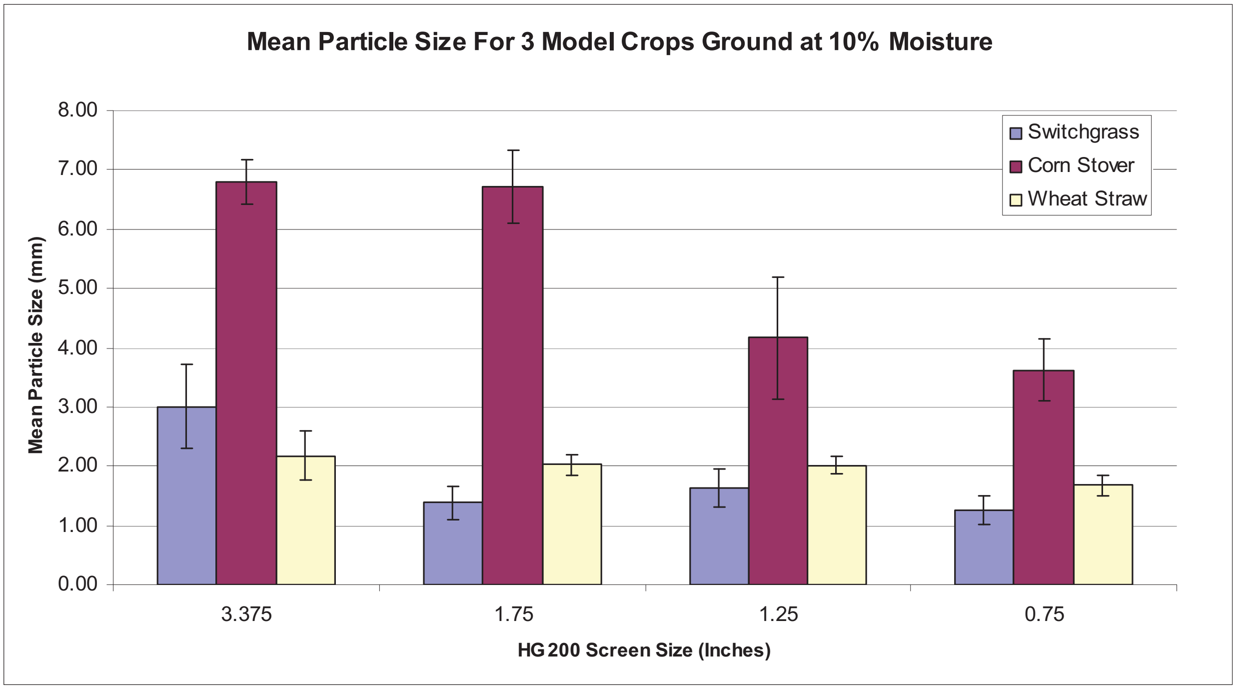

Figure 9. Mean particle size for switchgrass, corn stover, and wheat straw processed using the HG-200.

Moisture had less of an effect on particle size distribution than screen size for each of the model feedstock types. Figures 10 through 12 show the particle size distribution for the three feedstock types ground at four different moisture levels. Each feedstock type shows a decreasing trend related to screen size (as expected), but there is no consistent pattern related to moisture.

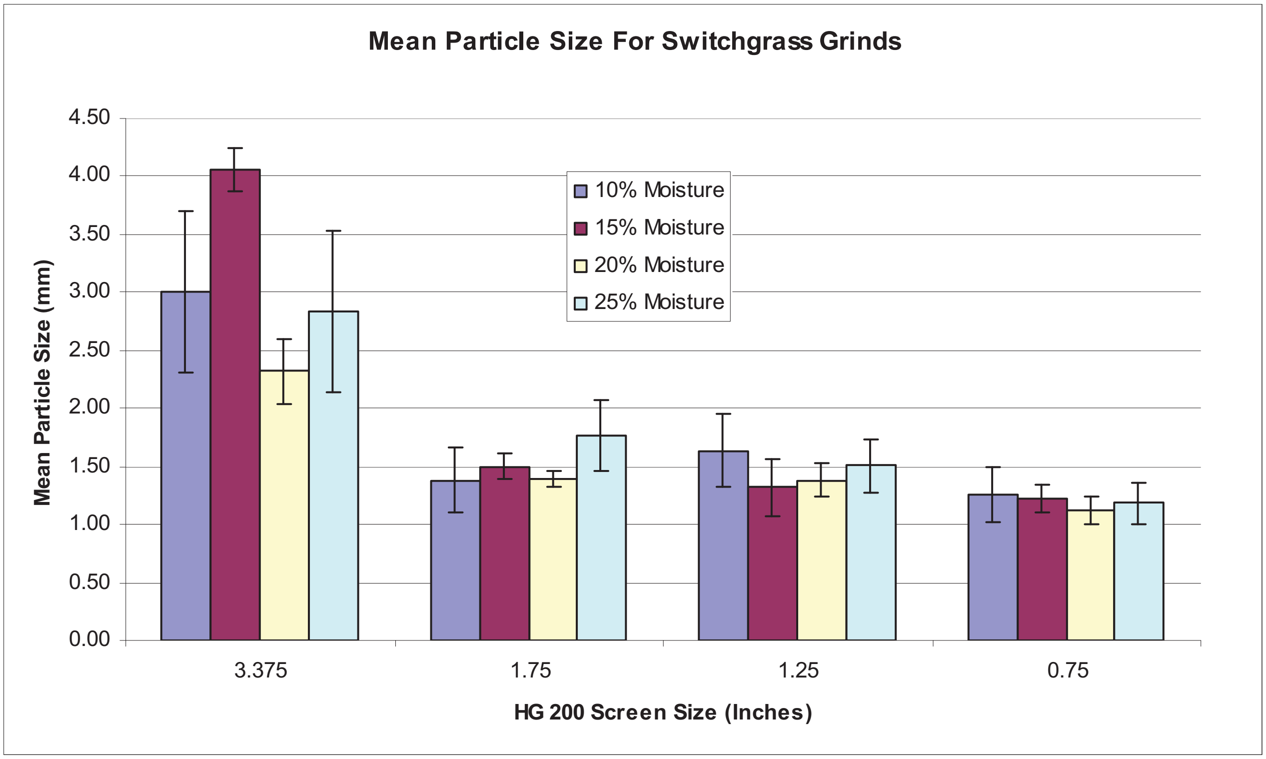

Figure 10. Particle size distribution for switchgrass ground using the HG-200.

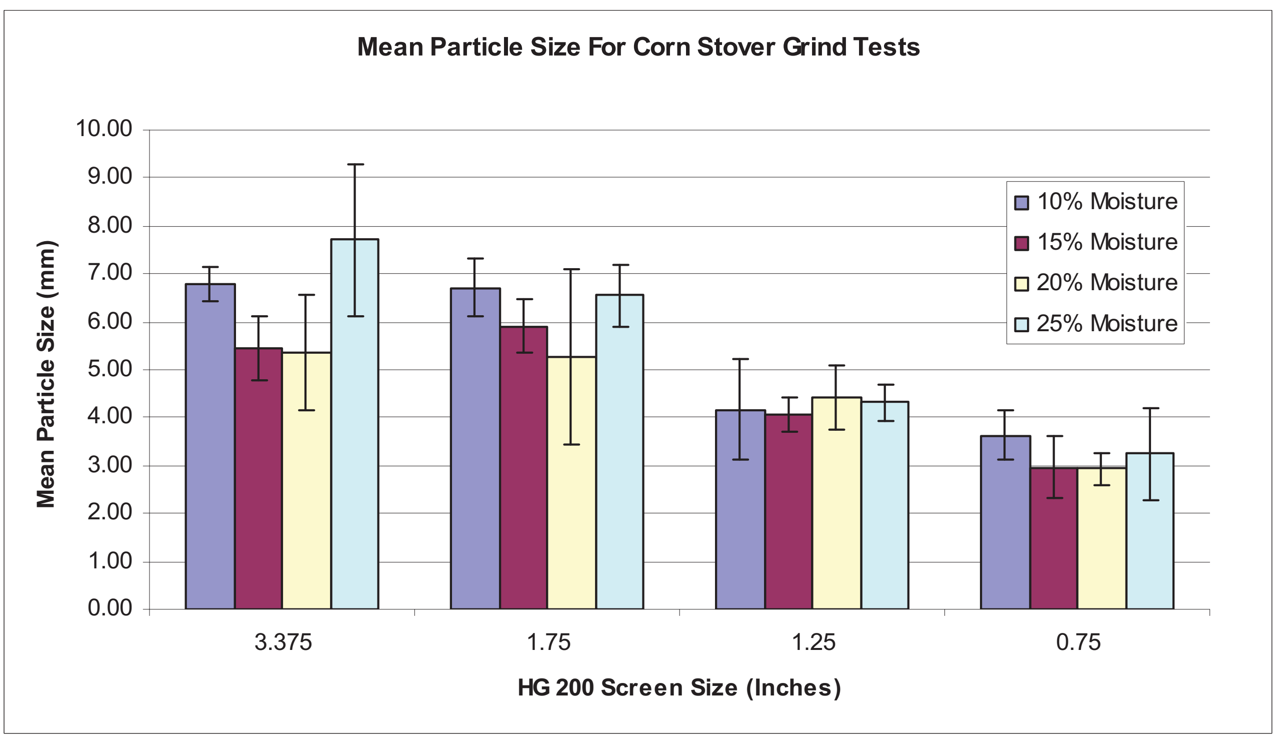

Figure 11. Particle size distribution for corn stover ground using the HG-200.

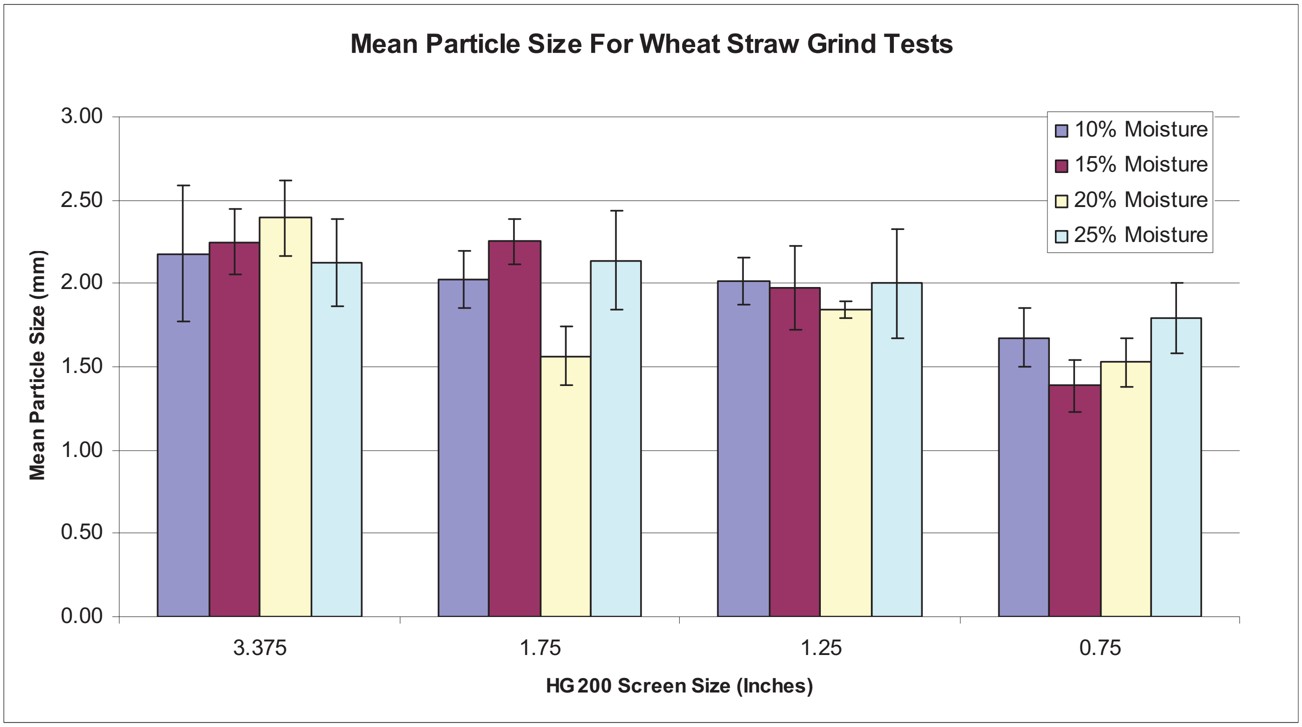

Figure 12. Particle size distribution for wheat straw ground using the HG-200.

Grinder Capacity and Efficiency

In addition to particle size, the efficiency and production rates of the grinder were measured. Fuel consumption was measured while grinding a predetermined amount of biomass for a measured period of time. The moisture level of the biomass was determined and moisture levels were compared between the crop types. The efficiency for switchgrass, as measured by tons of biomass ground per gallon of diesel consumed, is presented in Figure 13. For the switchgrass, there is a noted decrease in efficiency as moisture is increased. The screen size also impacts the efficiency, with a decrease in screen size typically resulting in decreased efficiency. Efficiency while grinding switchgrass was reduced by 40 to 50% as a result of increasing the moisture content in the biomass from 10% to 25%.

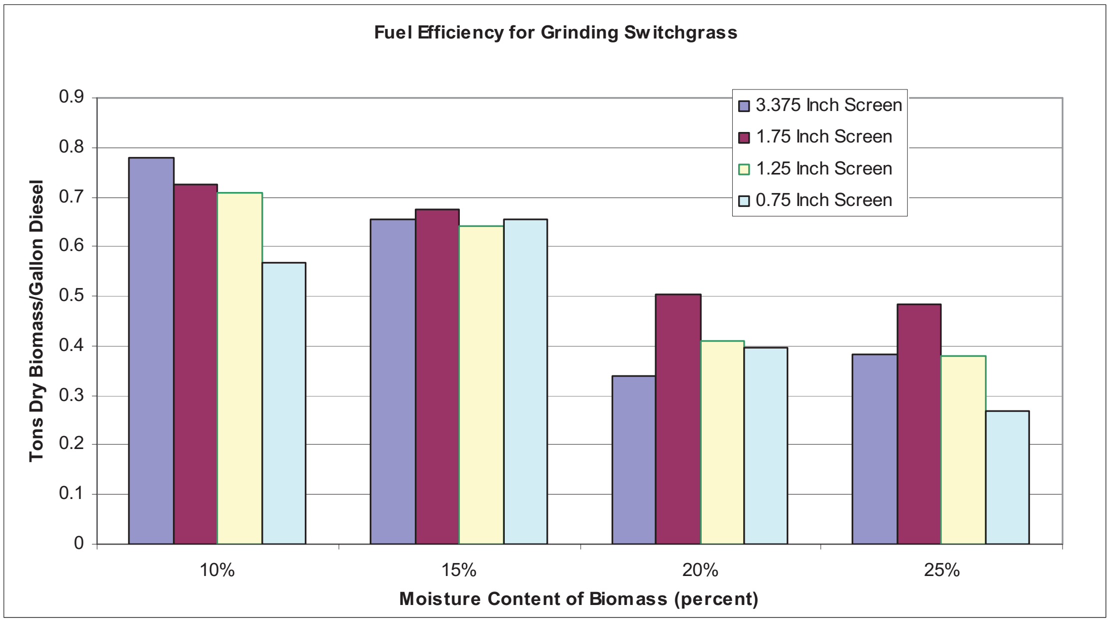

Figure 13. Measured fuel efficiency while grinding switchgrass with the HG-200.

Similar trends were observed while grinding the corn stover (Figure 14). Increases in moisture resulted in decreases in efficiency. Screen size also had a significant impact on efficiency. The efficiency when ground with the 3.375-in. screen was higher than when ground using a 0.75-in. screen at each moisture level tested. A 30 to 40% reduction in efficiency was observed when the moisture of the biomass was increased from 10% to 25% in the corn stover.

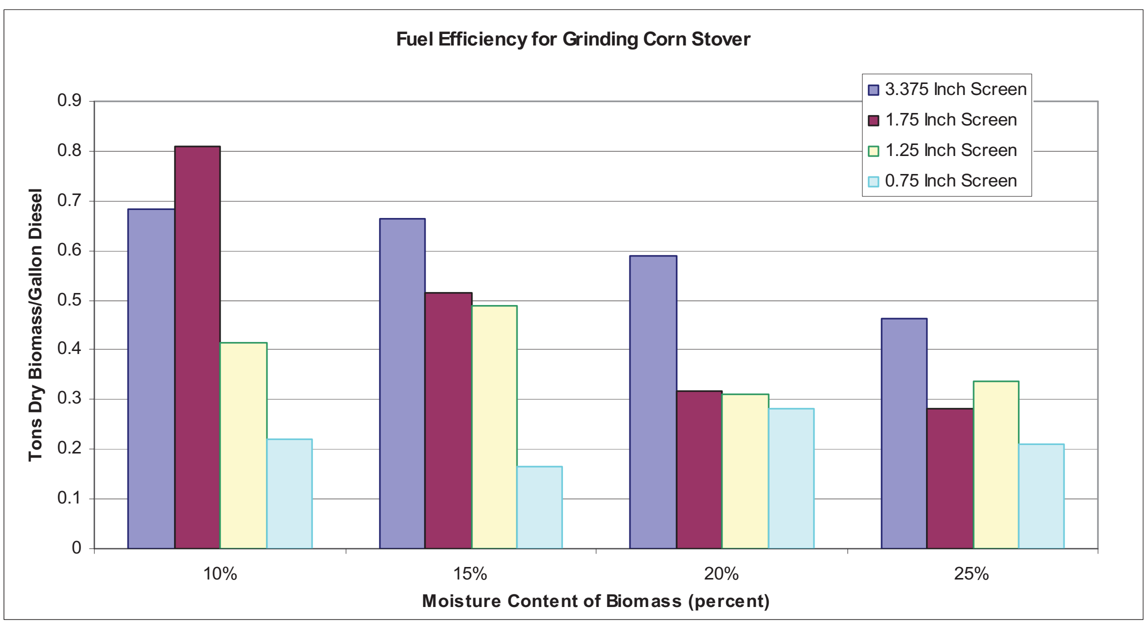

Figure 14. Measured fuel efficiency while grinding corn stover with the HG-200.

The efficiency of grinding wheat straw was much less susceptible to changes in moisture and screen size. There was a lot more variability in the data when grinding wheat straw. In some cases, the 1.75-in. screen performed the best, and in other cases, such as grinding at 25% moisture (Figure 15), there was little difference in efficiency with respect to screen size.

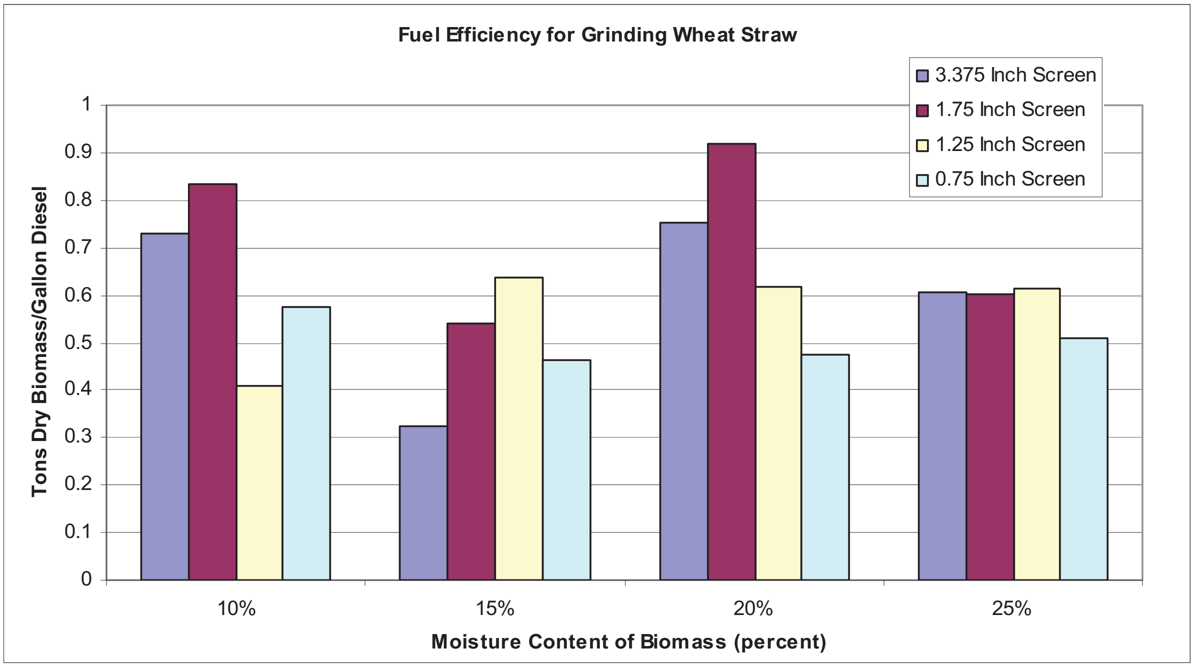

Figure 15. Measured fuel efficiency while grinding wheat straw with the HG-200.

Production rate, reported as tons of biomass processed per hour, was also measured. The data was collected and reported on a dry ton basis. Figure 16 shows a general trend of decreasing production rate with increasing moisture for switchgrass. Oddly enough, production rate tends to increase when screen size is reduced. One explanation is that the larger material produced with the larger screens did not move through the grinder and conveyors as easily as the smaller material. Additionally, some plugging behind the screens was noted while using the larger screen sizes.

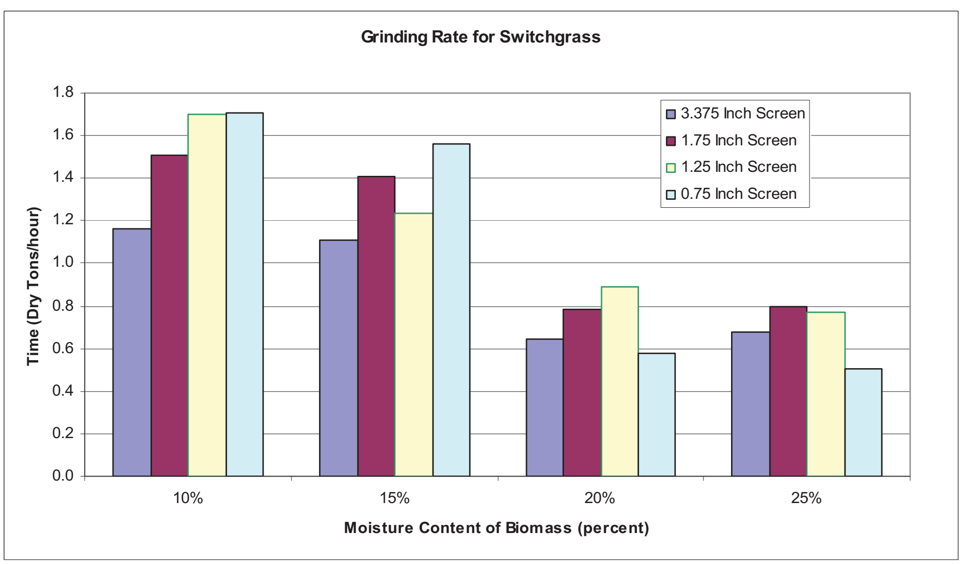

Figure 16. Measured production rate while grinding switchgrass with the HG-200.

The production rate for grinding corn stover is shown in Figure 17. Like the switchgrass, the production rates decrease as moisture content increases. The production rate while using the

0.75-in. screen was almost always lower than with the larger screen at all moistures tested, with one exception at 20% moisture, where the 1.75-in. screen had the lowest production rate.

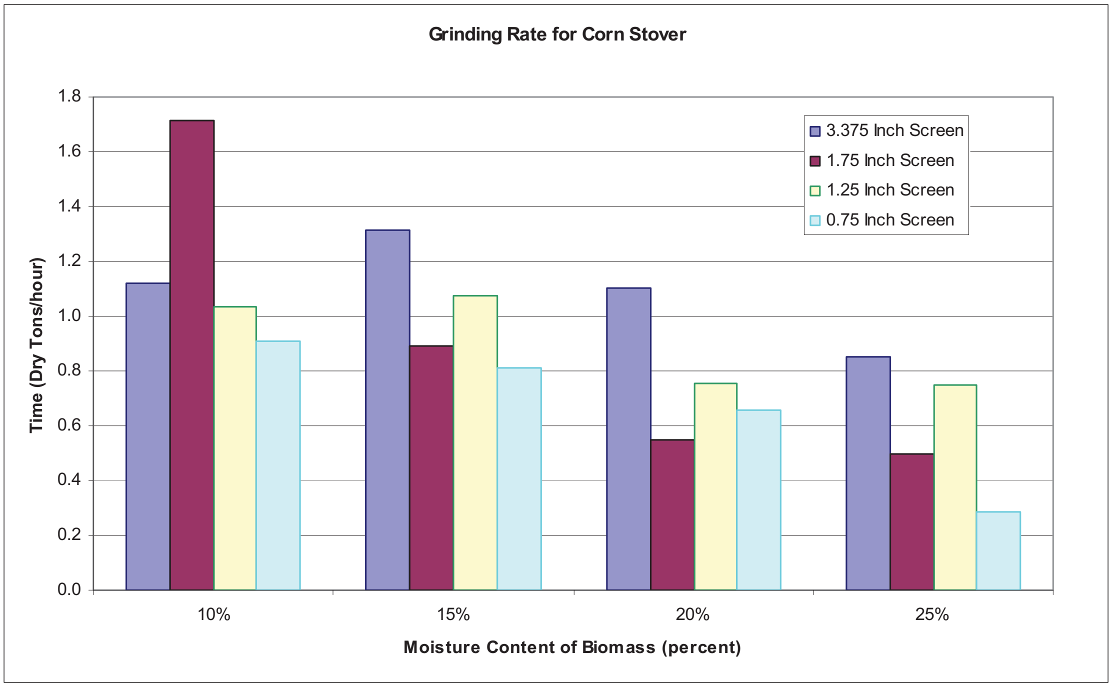

Figure 17. Measured production rate while grinding corn stover with the HG-200.

There was a great degree of variability noted in the production rate for grinding wheat straw (Figure 18). There were no clear trends observed based on screen size or moisture content relative to the production rate for grinding wheat straw.

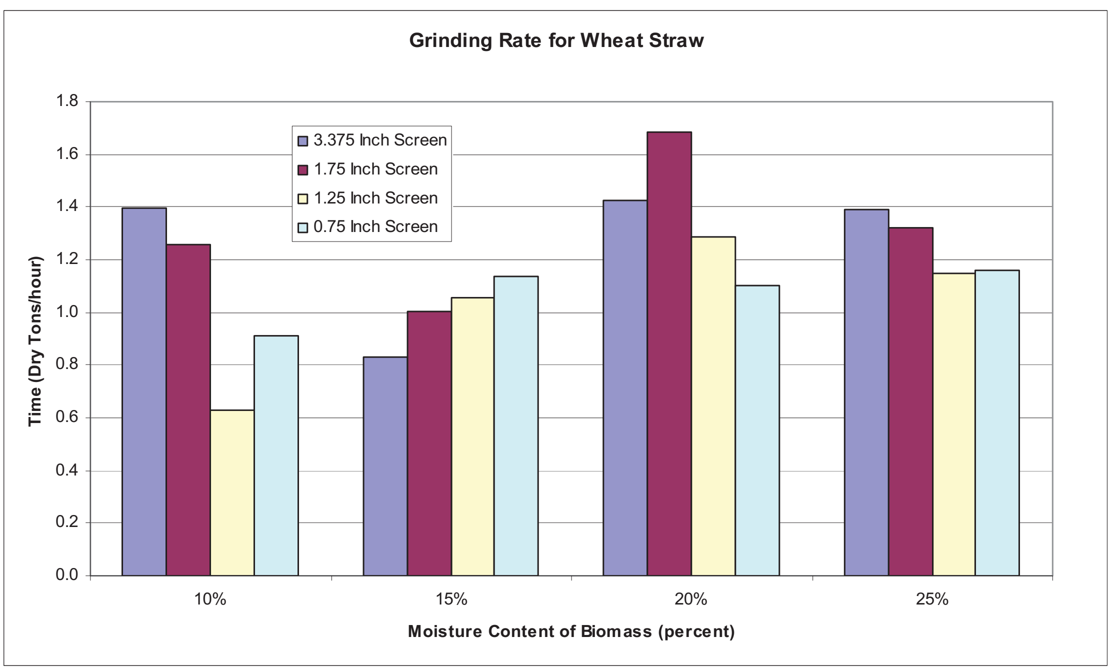

Figure 18. Measured production rate while grinding wheat straw with the HG-200.

Discussion and Conclusions

Some general trends were observed during the grinding tests using the HG-200 with two variables being tested: moisture and screen size. The moisture content for the grinding tests ranged from approximately 10 to 25%. No moisture-induced effect on particle size was observed for the crops that were tested. Moisture did, however, affect efficiency and production rate. Both efficiency and production rates were reduced by increasing the moisture content of the biomass being processed.

By decreasing the size of the screens used in the HG-200, the mean particle size also decreased, but decreasing the screen size also resulted in decreased efficiency.

It is important to understand the particle size requirements for the production of biofuel. Typically, a smaller particle size of biomass is more desirable for the infeed for biorefinery conversion. Smaller particle size equates to larger surface area and greater rate or chemical and biological reaction. Although it is simple enough to reduce the screen size in the grinder to produce the smallest particle size required, the power input that will be required to achieve that size also needs to be considered to determine what the best and most economical particle size will be.

Future Grinder Research Challenges

Due to the number of grinder manufacturers and grinding technologies/options, it is extremely challenging to identify the best possible options for improving grinder capacities and efficiencies while improving feedstock physical and chemical characteristics. The objective of INL's full-scale equipment field testing over the past 4 years has been to establish baseline performance parameters for multiple feedstock varieties and grinder configurations in order to identify or guide the development of the best preprocessing technologies. The goal of the project discussed in this paper was to analyze the effects of screen size and moisture content on particle size, efficiency, and production rates. Many other parameters will also affect these same factors. Future testing will be conducted to identify parameters (hammer type, hammer configuration, screen configuration, etc.) that will increase efficiency and productivity and overall product quality.

Acknowledgements

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