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I am submitting herewith a thesis written by Yuechuan Yang entitled "Image and sieve analysis of biomass particle sizes and separation after size reduction." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Alvin R. Womac, Major Professor

We have read this thesis
and recommend its acceptance:

Douglas G. Hayes

X. Philip Ye

Daniel C. Yoder

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the
Graduate School

(Original signatures are on file with official student records.)

# IMAGE AND SIEVE ANALYSES OF BIOMASS PARTICLE SIZES AND SEPARATION AFTER SIZE REDUCTION

A Thesis Presented for the
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# ABSTRACT

Improved physical separation of biomass concentrates higher-value components, returns unused plant components to the soil, and provides a more efficient platform for downstream industrial users. Sieving and Image Analysis (IA) were studied to evaluate biomass particle sizes, particle size distribution, and potential separation of biomass materials. Switchgrass, wheat straw, and corn stover were used in the study. Particles prepared by a knife mill equipped with various screen sizes were subject to sieving test and IA. Results showed that all three biomass materials would be analyzed using the fast, easy and accurate IA. Biomass particle physical properties, such as length, width, and projected area were obtained through IA. There were 25 to 30 % of switchgrass, prepared by larger knife mill screen, with node sections presented on the 19.0 mm sieve compared with 17.5 % nodal particle population average. This difference suggests that larger screen installed in the knife mill would be used to produce particles with optimum sizes for the nodes separation from the internodes. Results also show that a factor of 4~5 is suggested to apply to the Geometric Mean Diameter (GMD) calculated by standard sieving test to accurately represent the true particle length for grass-like biomass materials. It suggested that standard summary statistics calculated by various consensus standards may not provide the greatest accuracy for biomass.



*Keywords:* biomass material, sieving, particle size distribution, separation, geometric mean diameter, image analysis.

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NOMENCLATURE

| | |
|---|---|
| **ASABE** | American Society of Agricultural and Biological Engineers |
| **ASTM** | American Society for Testing and Materials |
| **CS** | Corn Stover samples |
| **FBS** | Flat-bed Scanner |
| **GMD** | Geometric Mean Diameter |
| **IA** | Image Analysis |
| **KM** | Knife Mill |
| **KMSG** | Knife mill Switchgrass samples |
| **KMWS** | Knife mill Wheat Straw samples |
| **KMCS** | Knife Mill Corn Stover samples |
| **PSD** | Particle Size Distribution |
| **SG** | Switchgrass samples |
| **WS** | Wheat Straw samples |

*Chapter 1*

# INTRODUCTION

World production of biomass is estimated at 146 billion metric tons per year and is mostly from wild plant growth (Balat and Ayar, 2005). There are approximately 1 billion dry tons of biomass feed stock generated per year in the United States (DOE and USDA, 2005). The US Department of Energy (DOE) and the US Department of Agriculture (USDA) have supported biofuel and biomass products as renewable energy to reduce petroleum oil usage (DOE and USDA, 2005). Recently, biomass related energy surpassed hydropower and provided over 3% of the total energy consumption as the largest renewable energy in the United States (DOE and USDA, 2005). However, not all parts of biomass could be used to generate biofuel and biomass related products. Generally, biomass with high glucose content is highly preferable in industrial production. Plant parts high in cellulose, hemicellulose, fructose, or glucose are preferred for feedstock, energy, and bio-based productions, all requiring sugars (Ververis et al., 2007; Karimi et al., 2006; Stumborg and Townley-Smith, 2004; Chandrakant and Bisaria, 1998). On the contrary, lignin is undesirable in the paper industries and it requires extensive procedures to remove the lignin form the pulp before paper can be manufactured. Nearly all biomass related production requires presorting and pre-purification (DOE, 2003; Donahue et al., 1999; Harmond et al., 1968; Karimi et al., 2006; Yu et al., 2003). Pre-sorting or pre-purification

of biomass for conversion can be an advantageous by reducing bulk and waste (Sokhansanj and Turhollow, 2004) as well as facilitate down stream operations.

Physical separation devices, such as straw walkers, lint cleaners, air-screen cleaners, and classifiers are approaches to separate plant components based on biomass physical properties (Kemble et al., 2002; Holt et al., 2000; Wang et al., 1994; Anthony, 2001; Elfverson and Renger, 2000). The main advantage of using physical separation is simplicity and low cost. Sieves have been applied to commercial practice for large-scale particle separation and for use in laboratories to evaluate particle size distributions (Coulson and Richardson, 1991). Due to their simple construction, screens are used in various engineering applications, ranging from separating coal particles to purifying pharmaceutical materials. However, most research studies reported sieve aperture dimensions instead of actual particle sizes retained on the sieves. One reason for this decision is that some particles are geometrically similar to a sphere, with similar dimensions in three orthogonal directions. Most studies focused on the behavior of the homogeneous and uniformly-shaped particles on a screen based on the theoretical passage through an aperture (Feller and Foux, 1976; Gaul et al., 1986; Risse et al., 1991; Li et al., 2003). Behavior of heterogeneous irregular particles on sieves, such as biomass materials, remains unclear. Fowler and Lim (1959) and Gluck (1966) pointed out that the particle shape, moisture content, and tendency for particles to stick together could affect screen efficiency. There is no simple model to address such issues with respect to separation of biomass particles.

Objectives:

The overall objective of this research project was to evaluate the performance of sieve devices with various biomass materials. Specific objectives were to:

a. Determine how biomass particles with a range of physical sizes behave on sieves actuated in vertical versus horizontal planes.
b. Identify separation efficiency of plant parts on sieves exhibiting the potential to separate biomass by comparing nodes versus internodes percentage.
c. Develop an accurate Image Analysis method to rapidly quantify particle size and shape to determine the size distribution of biomass materials retained by particular sieve sizes.
d. Compare standard sieving and Image Analysis to determine the actual biomass particle sizes after size reduction.

*C h a p t e r  2*

# LITERATURE REVIEW

## *1. Biomass physical properties*

Biomass is defined as the plant grown for use as bio power including ethanol, biodiesel, biomass power as well as industrial production of bio-products like fibers and papers. Biomass chemical compositions include cellulose, hemicellulose, lignin, and protein. Cellulose is the polymer of glucose and it forms the primary structural component of green plants as the cell wall. A secondary cell wall is made with a variable amount of lignin. Hemicellulose is present in almost all cell walls along with cellulose. Table 2.1 lists the mass percentage of cellulose, hemicellulose, total lignin, and ash contained in switchgrass, corn stover, and wheat straw. Table 2.2 lists the bulk density for switchgrass particles.

***Table 2.1.*** Switchgrass, corn stover, and wheat straw compositions [1].

| | Percent mass, % | | | |
|---|---|---|---|---|
| | Cellulose | Hemicellulose | Total lignin | Ash |
| Switchgrass (whole) | 33.08 | 25.25 | 17.54 | 6.42 |
| Switchgrass (stem) | 35.78 | 28.76 | 18.86 | 2.54 |
| Corn stover | 34.61 | 22.21 | 17.69 | 10.24 |
| Wheat straw | 32.64 | 22.63 | 16.85 | 10.22 |

[1] http://www1.eere.energy.gov/biomass/feedstock_databases.html

***Table 2.2.*** Bulk switchgrass density [1].

| | Debaler | Baghouse | Truck | Nodes |
|---|---|---|---|---|
| Bulk density ($lb/ft^3$) | 1.3-4.0 | 6.7-15.6 | 14.3 | 13.8-18.3 |
| Bulk density ($kg/m^3$) | 21-64 | 107-250 | 229 | 221-293 |

[1] Amos, 2002.

Internode is defined as the stem between two nodes. The node holds buds that grow into leaves, and flowers. Internodes typically contain a high percentage of cellulose and hemicellulose that are favorable for sugar-based biofuel production. Switchgrass may be accepted as a good source for biofuel production, especially ethanol fuel.

*2. Separation by sieves*

*2.1. Separation of regular-shaped particles*

The sieving process is the basic separation of particles by shapes and sizes. The simplest separation would be separating solid regular-shaped particles that have somewhat uniform dimensions in all orthogonal directions, such as a sphere for instance. Early studies focused on particle size separation efficiency depending on the duration of screening process. Coulson and Richardson (1962) and Feller and Foux (1976) used an equation for determining the change in the mass of particles small enough to pass through a screen (*W, mass)* as a function of screening time (*t*):

$$W=W_0 exp(-\lambda t) \quad (1)$$

Where $W_0$ is the initial mass of passing particles (mass);

$\lambda$ is the passage rate factor, determined experimentally (1/time).

It should be pointed out that this method does not determine the relationship between the particle size and screen aperture sizes.

Screening efficiency is defined as the ratio between the mass of particles that passed through the aperture to the total mass of particles that theoretically could pass through the aperture based on particle and aperture dimensions (Coulson and Richardson, 1962). Feller and Foux (1976) found that the particle size relative to aperture size is a significant factor that can be used as a basis for comparing and predicting passage rates. They predicted the efficiency of the screening (*E, ratio of mass/mass*) as follows:

$$E = 1 - \frac{1}{u}\sum_{i=1}^{j} w_i e^{-\lambda_i t} \tag{2}$$

where $j$=the number of size fractions from the smallest particle up to the screen aperture size D,

$\lambda_i$=the passage rate factor of size fraction $i$, (1/time);

$w_i$=the weight ratio of size fraction $i$, (mass/mass);

$u$=the weight ratio of total undersize particles in the material to be screened (mass/mass).

Fowler and Lim (1959) found that a high level of separation efficiency could be achieved by selecting proper combinations of feeding rate, screen apertures, screen inclinations, and vibration frequency.

*2.2. Separation of irregular-shaped biomass particles*

Irregular shaped particles are defined herein as having non-uniform dimensions in at least one orthogonal direction. Since particle sizes typically have a wide size range and most sieving tests were conducted by measuring weight retained by sieve, it is quite difficult to clarify which aspect of particle size is measured by sieving. For instance, Maerz and Lusher (2001) pointed out that the longest dimension of the particle did not determine whether a particle would pass through a sieve. One explanation is that the sieving processes are measuring the intermediate axis of a particle, not the maximum axis (Fernlund et al., 2007).

There are wide applications of sieving processes of biomass materials, from straw walker / sieve combinations to seed cleaners. Most of these applications were designed for a somewhat narrow range of biomass material. From observation of current equipment that processes biomass, it appears that the advantages of these practices are simplicity and efficiency, while the main disadvantage include a limited ability to separate other biomass materials.

Factors such as particle size, shape, density, size distribution, and moisture content could interact differently with screen apertures as well as affect screen efficiencies (Fowler and Lim, 1959). Mohsenin (1968) pointed out that "It is essential to understand the physical laws governing the response of biological materials so that the machines, processes, and handling operations can be designed for maximum efficiency and highest quality of the end products".

Size and shape are easily specified for regular-shaped particles, such as spheres and cubes, but for irregular-shaped particles (such as sand grains, mica flakes, or biomass particles) the term "size" and "shape" are not so clear. Sphericity $\Phi_s$(length$^3$/length$^3$) may be used to characterize particle shape (McCabe et. al., 1985):

$$\Phi_s = \frac{6v_p}{D_p s_p} \tag{3}$$

where $D_p$=equivalent diameter or nominal diameter of particle, (length);

$s_p$=surface area of one particle, (length$^2$);

$v_p$=volume of one particle (length$^3$).

For example, if the particle sphericity, particle density, and sieve aperture increment (such as the difference in aperture size between top and bottom sieves) is known, the volume-surface mean diameter, mass mean diameter, volume mean diameter, and total population in one mass unit of sample can be calculated (McCabe et al., 1985). One assumption used in the calculation is that the average size of the particles remaining on a sieve is equal to the average aperture size of the top and bottom sieves (McCabe et al., 1985). The extreme situation (particle with small sphericity value) would be long or thin particles. The calculation on such extreme particles should be verified.

Various sieve motions are involved in separation applications. However, there are two basic sieve motions: oscillation in a vertical plane or in a horizontal plane. Figure 2.1 shows oscillation in vertical plane, which results in the vertical movement of particles on the screen surface enabling them to pass through the sieve apertures. The speed of

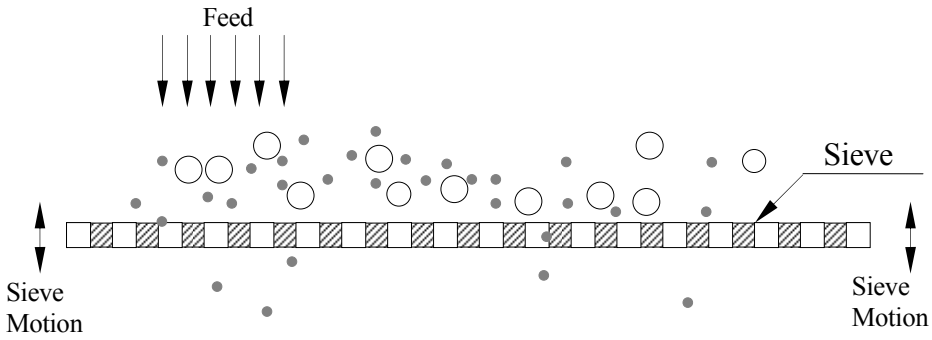



***Figure 2.1.*** Sieve oscillation in vertical plane

oscillation and the amplitude of throw can be adjustable. ASTM standard (E11-95) sieve separation has this vertical motion.

Figure 2.2 shows the oscillation in horizontal motions that results in the horizontal movement of particles on the sieve surface. Compared with vertical sieve motions, horizontal sieve motions cause particles to push each other through the sieve apertures (McCabe et al., 1985).

For the ASABE standard sieving testing that had oscillation in a horizontal plane, the ASABE standard S424.1 (ASAE Standards, 2003) was developed by ASABE Forage Harvesting and Utilization Committee. The standard test is used to determine the particle size distribution of chopped forage materials and to define a method of expressing the material particle size. One unique property of the standard testing sieves is that the sieve materials are made with a relatively thick aluminum, compared to the aperture

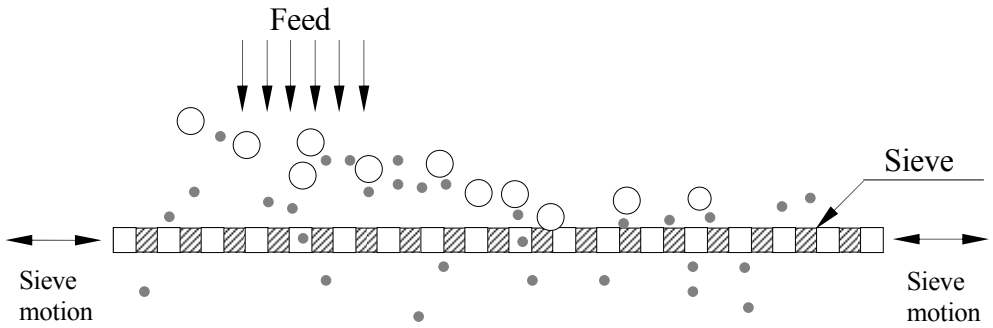



***Figure 2.2.*** Sieve oscillation in horizontal plane

dimensions, and with the thickness decreased from the top sieve (largest aperture) to the bottom sieve (smallest aperture). For instance, the top sieve has the aperture of 19 mm with a thickness of 12.7 mm, while the second sieve has the aperture size of 12.7 mm with a thickness of 9.6 mm. These unique sieve construction features provided a three-dimensional barrier to prevent long and slim particles from passing through. As assumed in the standard, the average length of the particles on a particular sieve is the square root of the product of top and bottom diagonal aperture sizes relative to the sample, except for the top sieve, where the length is the average measured length of the particles on the top sieve. Table 2.3 lists the aperture and thickness dimensions of ASABE sieves. Compared with the ASABE standard sieving test, the ASTM E11 standard sieving test had oscillation in a vertical plane. The ASTM standard was designed for testing purposes of wire cloth and sieves.

***Table 2.3.*** Dimension of squared-hole sieves used in ASABE separator. [1]

| Sieve no. | Nominal aperture size (mm) | Diagonal size (mm) | Sieve thickness (mm) | Open area (%) |
|---|---|---|---|---|
| 1 | 19.0 | 26.9 | 12.7 | 45 |
| 2 | 12.7 | 18.0 | 9.6 | 33 |
| 3 | 6.3 | 8.98 | 4.8 | 33 |
| 4 | 3.96 | 5.6 | 3.1 | 39 |
| 5 | 1.17 | 1.7 | 0.64 | 41.5 |
| Pan | - | - | - | - |

[1] Directly from ASABE standard S424.1.

The change of particle-size distribution on a sieve during the transient process of sieving alters the material size composition at different layers and eventually affects the overall sieving efficiency (Li et al., 2003). For instance, higher separation efficiency would be expected for a wide particle distribution than a narrow particle distribution (Jansen and Glastonbury 1968; Li et al., 2003).

Moisture content of the particles is especially important during sieving. It is much easier for dry particles to travel through screen apertures than damp particles, which are prone to stick to the screen surface and to each other (Fowler and Lim, 1959). Studies by Fowler and Lim (1959) and Gluck (1966) indicated that the particle shape, specific weight, friction coefficient, moisture content, and tendency to stick together could all affect the sieving efficiency.

*3. Image Analysis*

Image Analysis (IA) is a method of extracting information from images. The analysis system is basically composed of two components: hardware and software. Typical hardware is represented by an image capture device, such as a camera or scanner. Typical IA software packages are Windows or Mac based programs, such as Scion or MatLab. Most commonly used two dimension (2-D) IA systems are composed of a personal computer and a flatbed scanner as described by Dalen (2004). Image files are collected from the flatbed scanner in a format that is using compression algorithms without any loss in image quality. This loss-free format is the representative digital file of the original image from the scanner. The applications of IA have been growing rapidly during the past several years, especially combined with pattern reorganization techniques (Gabrielson et al., 2002; Fernlund, 2005; Gonzalez and Woods, 2002).

Flatbed scanning (FBS) was used to determine spray droplet size (Wolf et al., 2000), to analyze air voids in concrete (Peterson et al., 2000), and to quantify microbial growth (Gabrielson et al., 2002). IA has been used for irregular-shaped biomass materials like rice kernels. Dalen (2004) used IA to analyze the size distribution of rice kernels and the percentage of broken rice kernels in the sample.

There are several particle parameters computed from IA data. However, the definitions of size used in the IA processes are different from each other, based on the different softwares. For instance, the Feret's diameter (Al-Thyabat and Miles, 2006; Taylor, 2004) can be used as the dimension of the particles. The Feret's diameter is defined as the maximum distance between any two points in the projected area. The maximum

Feret's diameter is defined as the maximum dimension intersections across the perimeter of the projected area of the particle while the minimum Feret's diameter is defined as the minimum dimension intersections across the perimeter to the projected area of the particle (Fernlund, 2005). However, it is common that the maximum and minimum projected areas are not perpendicular to each other. The particle axes, which are defined as the axes of an equivalent ellipse, can be used in addition to the Feret's diameter (Maerz and Lusher, 2001; Maerz, 1998; Tutumluer et al., 2005).

Studies were conducted on the three dimensional (3-D) analysis for particle sizes and shapes (Maerz, 1998; Maerz and Zhou, 1999; Tutumluer et al., 2005). Compared with 2-D image analysis, 3-D image analysis gave accurate measurement of the dimensions in all three orthogonal directions of the particles, and can be used to accurately determine the volume of the particle (Tutumluer et al., 2005).

*4. Comparison of sieving and Image Analysis for particle sizes*

Compared with traditional sieve analysis, which could not provide the information of actual particle dimensions, IA has been used to determine particle size distribution, particle shape, and particle dimensions (Kwan et al., 1999; Maerz and Lusher, 2001; Tutumluer et al., 2005). It should be pointed out that the results of IA and sieve analysis are not comparable, since IA measures the number of particles or the area of particles, while sieve analysis measures particle weight (Fernlund et al., 2007). Taylor (2002) and Maerz (2004) stated that accurate determination of the volume of the particles would be extremely important to express the particle size distribution using IA with respect to mass. Numerous

studies have shown the importance of determining the volume or weight of the particles along with image analysis to compare the size distribution curves with the mass by sieves (Taylor, 2002; Tutumluer et al., 2005). Mora et al. (1998) and Kwan et al. (1999) used factors of 0.81 to 0.89 times the length of the intermediate axis dimension to convert IA analysis to represent sieve analysis for coarse aggregate.

Most of these image analyses were focused on particles that are regular-shaped or close to regular-shaped, coarse aggregate for instance, because it would be easy to conclude that the measured size is equal to its diameter, and the volume can be calculated from the measured size. Very little information is available for irregular-shaped biomass materials such as chopped forages. The particle analyses of such biomass materials heavily rely on the sieve analysis, which assume that the length or the size of the particles correspond to the screen aperture size.

*C h a p t e r 3*

# MATERIAL AND METHODS

## *1. Materials*

Switchgrass, wheat straw, and corn stover were the test biomass materials used in the study. The moisture content was tested using ASABE standard S358.2. Twenty-five grams of wet samples was weighed, placed in a 103$^{o}$C oven for 24 hours, and weighted again. Particle mass was determined gravimetrically by a scale. The moisture content (wet basis, %) was calculated by:

$$MC = \frac{Loss\ weight \times 100}{weight\ wet\ sample} \tag{4}$$

For determining the density of the switchgrass, nodes and internodes were both cut to the lengths of 12 mm and 3 mm cylindrical particles. Particle length and outside diameter were measured with calipers, and particle mass was measured by laboratory scale. Particle density was determined by:

$$\rho = \frac{m}{v} = \frac{4m}{\pi D^2 L} \tag{5}$$

where $\rho$=particle density, (mass/length$^3$);

$m$=mass of the particle, (mass);

$v$=volume of the particle, (length$^3$);

$D$=diameter of the particle, (length);

$L$=length of the particle, (length).

Cut particle sizes were assumed as uniform cylinders. The volume for calculating true density was determined using a pycnometer (Multipycnometer, Quantachrome Corporation, Boynton Beach, FL).

For the switchgrass, two groups of particles were prepared in the experiment. One group contained hand-cut biomass materials, representing biomass materials with similar size, shape, density, and other physical properties. The switchgrass samples were cut to the lengths of 3.25, 6.35, 12.7, 19.1, and 50.8 mm. The particles were carefully measured twice with a digital caliper.

The second group of switchgrass particles was prepared in a knife mill, representing biomass particles with irregular size, shape, density, and other physical properties. This group of switchgrass shares the same properties with particles that undergo large scale size reduction process in industry.

The corn stover and wheat straw were used as comparison biomass materials. The corn stover and wheat straw were prepared only using knife mill under the same conditions as the switchgrass.

For the knife mill used in the test, various screen aperture sizes (12.4, 19.1, 25.4, and 50.8 mm) were used in combination with various knife mill speeds (250, 322, 400, 450, and 500 rpm). Different feeding rates (1 to 11 kg/min) of biomass materials were also tested.

*2. Sieves: ASABE and ASTM*

ASABE sieves with frame movement were designed using an ASABE Standard (ASABE S424.1). Some modifications were applied to the original ASABE Standard. Basically, it was constructed with two stacks of sieves to balance the weight of reciprocating mass. The first stack contained two sieves (19 mm and 12.7 mm apertures) and a dust pan. The second stack contained three sieves (6.3 mm, 3.96 mm, and 1.17 mm apertures) and a dust pan. After the particles had been separated by the first stack, the particles in the dust pan were transferred to the second stack of sieves for the remaining separation tests. The particles from each sieve were collected carefully, weighed, and subjected to the IA test. The machine was operated for 10 minutes during the tests. It should be noted that the selected time was greater than the time specified in the standards (2 minutes). Additional 8 minutes increased the separation efficiency according to equation (1) and (2). Theoretically, when the separation time approach to infinity, the separation efficiency could be 100% for the particles, which are capable of passing through the sieve apertures, to be separated. Figure 3.1 demonstrates the top view of ASABE sieves.

In comparison to the ASABE standard separator, the Gilson-brand ASTM testing sieve (TS-1, Lewis Center, OH, USA) was also used in the separation analysis. A low-amplitude shaft with adapter was used in the test. The ASTM sieves (19 mm, 12.7 mm, 6.3 mm, 3.96 mm, 1.17 mm, and dust pan) were chosen to correspond with the sieves used in the ASABE separator. All the sieves used in ASTM separator were made with woven wires according to ASTM standard E11, ISO 565. The machine was also operated for 10 minutes during the tests. Figure 3.2 shows the ASTM separator.

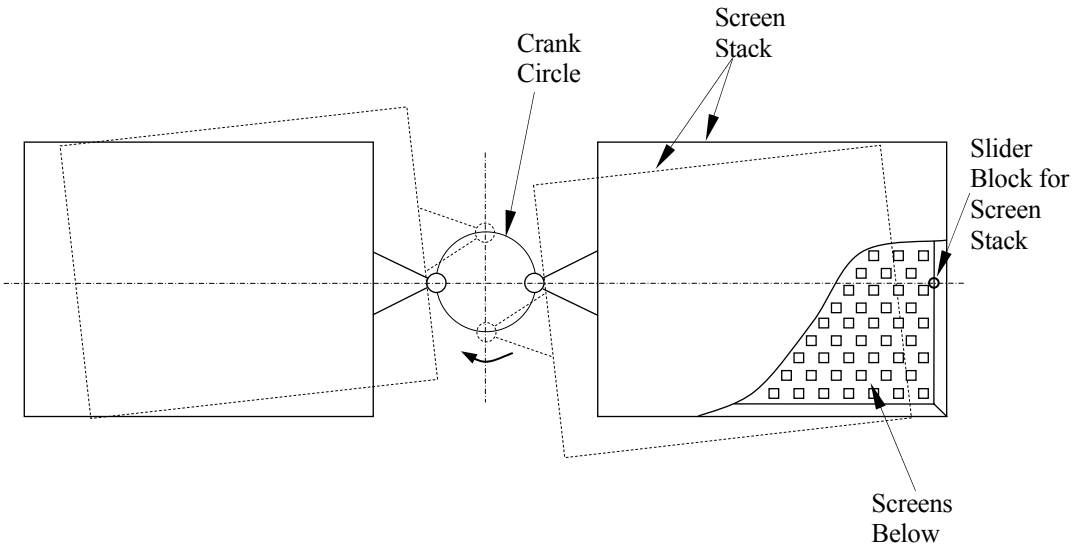



***Figure 3.1.*** Top view of ASABE particle separator showing screen motion.



***Figure 3.2.*** ASTM standard testing sieve TS-1 by Gilson (Lewis Center, OH).

Sample size for both ASABE and ASTM sieving was 50 g for all switchgrass, wheat straw, and corn stover tests. Error analyses were conducted at two extreme conditions: 50.8 mm screen and 12.7 mm screen installed on the knife mill. Switchgrass was prepared by the knife mill as described above. Triplicate ASABE separation experiments were then conducted with materials prepared by the same way. The Geometric Mean Diameter (GMD) and standard variation for each run was calculated as shown in section 4.1. Triplicate ASTM separation experiments and calculations were conducted in the same way as the ASABE separation tests.

*3. Nodes and internodes observations*

Switchgrass particles after sieving analysis were examined for nodes and internodes whether those plant anatomical components were separated. Node particles were defined as any particles with complete or incomplete nodal section by manual observation. Internode particles were defined as any particles without nodal section. Switchgrass particles containing nodal sections were manually selected from each sieve sample and weighed by scale. The weight percentage of nodes particles presented in the sample on each sieve was calculated for each sieve.

Assuming the average length of switchgrass after baling was 900 mm, and the average distance between two nodes was 150 mm. Also assuming the density difference between nodes and internodes particles was negligible. The weight percentage of nodes particles presented in the sample could be calculated by:

$$nodes\,\%(weight) = nodes\,\%(number) = \frac{number\ of\ node}{total\ particles} = \frac{900/150}{900/L} \times 100\% \quad (6)$$

where $L$ =average length of the switchgrass particle after size reduction (mm).

For instance, if the average length of the switchgrass particles after size reduction was 25.4 mm, then the weight percentage of nodes would be:

16.93 %=(900/150)/(900/25.4)×100% (7)

If nodes particles were found having higher percentage than 16.93 %, indicating more nodes particles were presented in the 25.4 mm size group, and vice versa. A theoretical line representing the nodes particle mass fraction in the sample as a function of particle length change could be also calculated using equation (6).

*4. Image Analysis*

*4.1 Image Analysis setup*

Switchgrass, wheat straw, and corn stover particles were analyzed using IA processes. Initial configuration of the IA included an Epson 3490 photo scanner set to 200 dpi with no adjustments (no sharpness, auto contrast, etc.) to the initial scanned images. A black shoe box was also used in the test as described by Dalen (2004). The scanned image was analyzed using ImageJ software operating under Windows XP on a Dell Inspiron 700m laptop computer. (ImageJ is freely available on the web: http://rsb.info.nih.gov/ij/). Macros in ImageJ were used for automatic image analysis (Refer to appendix for code). Table 3.1 summarized the steps and parameters used in the IA.

***Table 3.1.*** List of IA steps and parameters used in the analysis

| Step | Function | Note |
|---|---|---|
| 1 | Read image file into the program | - |
| 2 | Convert the image file into a 8-bit image | Discard the color information and convert the image into discrete 8-bit image [1] |
| 3 | Convert the image file into a 2-bit black and white image | Set the threshold level=35, any level below 35=black; any level above 35=white [2] |
| 4 | Analyze particles | Calculate particle number, projected area size (max and min axis, etc) [3] |

[1] Calculate average of neighboring grey level to generate smooth edge.
[2] Threshold level was determined by the pilot test (Refer to section 4.2 for details).
[3] Refer Figure 3.3 for detailed analysis process.

*4.2 Pilot tests*

Several pilot tests were conducted to determine the optimum parameters to be used in the IA. Particle position difference, threshold level noise difference, and threshold level particle size difference were determined as follows:

A pilot test was conducted to test the position of the switchgrass hand-cut samples, since the switchgrass position on the scanner might affect the projected area in the IA processes. A 50.8 mm hand cut switchgrass sample was used in the test. The length and width were measured by caliper, and the particle was then placed at different angles on the scanner to mimic scattered particles in scanning process.

In the IA processes, there was a step involved with conversion of gray scale image into a binary image (black and white). Different threshold levels would affect the total number of particles in the analysis process (Russ, 1999). For instance, low threshold level

would convert more grey areas to white areas that resulted in high level of noise in the image. To determine the noise level, threshold levels were set at 20, 30, 40, 50, 60, and 70 prior to the particle counting function used in the ImageJ. The total number of particles in the image was determined by ImageJ.

Also, different threshold levels affecting the particle sizes during the binary conversion were tested. For instance, low level of threshold level would generate more white areas around actual particle projected area since there were grey transition area between particles and the black background being converted into white. Very similar to the experiment setup to determine the noise level described above, different threshold levels (20, 30, 40, 50, 60, and 70) were applied prior to the binary conversion. The sizes of the particles from the IA result, including length and width, were compared with hand measurement by the caliper.

*5. Computational methods*

*5.1. Geometric Mean Diameter calculation for sieving tests*

The GMD for sieve analysis (both ASABE and ASTM separation tests) was calculated as follows (ASABE S424.1):

$$X_{gm} = \log^{-1} \frac{\sum \left( M_i \cdot \log \overline{X_i} \right)}{\sum M_i} \tag{6}$$

$$S_{gm} = \log^{-1} \left[ \frac{\sum M_i \left( \log \overline{X_i} - \log X_{gm} \right)^2}{\sum M_i} \right]^{1/2} \tag{7}$$

Where:

$X_i$ is the diagonal of screen apertures of the i[th] screen, length;

$X_{(i-1)}$ is the diagonal of screen apertures in the next larger screen (just above in a set), length;

$X_{gm}$ is the geometric mean length, length;

$\overline{X_i}$ is the geometric mean length of particles on the i[th] screen= $\sqrt{X_i \times X_{i-1}}$ , length;

$M_i$ is the mass on the i[th] screen (actual mass at the conditions of screening of percent of total), mass;

$S_{gm}$ is the standard deviation of $X_{gm}$, length.

For example, the switchgrass sample (KMSG-28) was prepared by the knifemill equipped with 25.4mm screen. The feeding rate was 7kg/min and the knifemill was operated at 400rpm. Then 50g switchgrass sample after grinding was collected for the ASABE sieve analysis. Table 3.2 listed the mass distribution after the standard ASABE sieve analysis.

***Table 3.2.*** Percent mass distribution of the chopped switchgrass sample (KMSG-28).

| Screen No. | Screen diagonal, mm | Mass (g)[1] | Percent total mass on screen, % | Cumulative undersize, % |
|---|---|---|---|---|
| 1 | 26.9 | 1.75 | 6.71 | 93.29 |
| 2 | 18.0 | 5.61 | 10.63 | 82.66 |
| 3 | 8.98 | 11.84 | 21.77 | 60.89 |
| 4 | 5.61 | 12.62 | 33.08 | 27.81 |
| 5 | 1.65 | 10.45 | 18.93 | 8.88 |
| Pan | - | 5.7 | 8.88 | - |
| | | 47.97 | 100.00 | |

[1] Due to sample lost during the test, the total mass was 47.97 g after separation analysis compared with the original 50 g.

The average measured length of the switchgrass particles on the top sieve (No.1) using IA was 82mm. Then $\overline{X_1}$ =82, $\overline{X_2} = \sqrt{18.0 \times 26.9} = 22.0$, $\overline{X_3} = \sqrt{8.98 \times 18.0} = 12.7$, $\overline{X_4} = \sqrt{5.61 \times 8.98} = 7.10$, $\overline{X_5} = \sqrt{1.65 \times 5.61} = 3.04$, $\overline{X_6}$ =0.82.

Using equation (6):

$$X_{gm} = \log^{-1}\left[\frac{0.067 \times \log(82) + 0.106 \times \log(22) + 0.218 \times \log(12.7) + \\ + 0.331 \times \log(7.1) + 0.189 \times \log(3.04) + 0.089 \times \log(0.82)}{0.067 + 0.106 + 0.218 + 0.331 + 0.189 + 0.089}\right]$$

$$= 7.798 mm$$

$$S_{gm} = \log^{-1}\left[\frac{0.067\left[\log\left(\frac{82}{7.798}\right)\right]^2 + 0.106\left[\log\left(\frac{22}{7.798}\right)\right]^2 + 0.218\left[\log\left(\frac{12.7}{7.798}\right)\right]^2 + \\ + 0.331\left[\log\left(\frac{7.1}{7.798}\right)\right]^2 + 0.189\left[\log\left(\frac{3.04}{7.798}\right)\right]^2 + 0.089\left[\log\left(\frac{0.82}{7.798}\right)\right]^2}{0.067 + 0.106 + 0.218 + 0.331 + 0.189 + 0.089}\right]$$

$$= 1.285 mm$$

*5.2. GMD calculation for Image Analysis tests*

Figure 3.3 shows the basic IA process. The data collected form ImageJ analysis was major axis (based on eclipse fit), minor axis (based on eclipse fit), and the area. The conversion factor 0.886 was determined by the ratio of rectangular and fit inside an ellipse. The projected areas of each particle by IA were converted to volume and mass, assuming

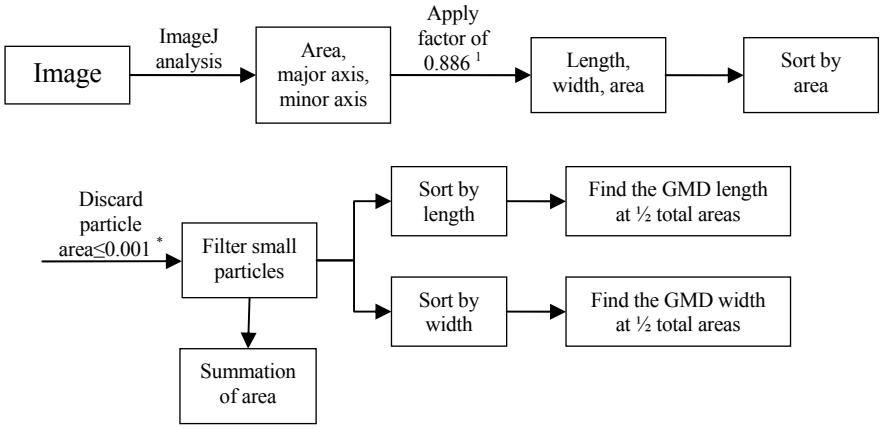



***Figure 3.3.*** IA process flow chart. [1] 0.886 was the conversion factor between eclipse fit for calculating length and width. * 0.001 was the limit of scanner.

each particle has the same third dimension (the height in this case), with the same density as the particles collected from the same sieve. This assumption was made based on observing the particles retained by the sieves during the sieving tests. The GMD for each sieve were calculated by finding the middle point where the length (or the width) at the 50 percentile of mass. For instance, to calculate GMD by length, particles on the same sieve were assumed to have the same particle density and the third dimension (thickness). The assumptions were based on the observations of particles from sieving tests. The total weight was calculated by summing up the individual particle weight. Then the particles were lined up from shortest up to the longest, the representative length GMD was found nearest the 50 percentile of mass.

For example, the switchgrass sample (KMSG-28) was prepared by the knifemill equipped with 25.4mm screen. A small amount of samples were collected from each sieve

after ASABE sieve analysis. Table 3.3 listed the IA data and calculations. The total particles projected area was 7133.31 $mm^2$, half of the total projected area would be 3566.65 $mm^2$. Since the data was sorted by the length, using the column Accumulative Area found the interpolated GMD length=87.4mm by where the area equals to 3566.65 $mm^2$. The calculation was repeated for the rest of the sieves. Table 3.4 summarized the overall GMD calculation for the switchgrass sample. Half of the mass from Table 3.4 was 23.99 g, using the column accumulative mass, the overall GMD was 38.6 mm using interpolation.

Very similar to the error analysis in the separation tests, IA error analysis was conducted using the same switchgrass particles collected from the ASABE tests, but with different positions in the scanning process. All the scanned images were subjected to the analysis using ImageJ under the same conditions. For instance, the particles collected from top sieve were sampled and positioned on the scanner. Then these particles were re-arranged and scanned again. The procedures above were repeated for a total of five (5) replications. The GMD for each run was then calculated as described above.

***Table 3.3.*** IA and calculation for switchgrass particles on first sieve (19mm).

| ID | Area ($mm^2$) | Major[1] (mm) | Minor[2] (mm) | Angle[3] (degree) | Cir. [4] | Feret's Dia (mm) | L (mm) | W (mm) | Project Area[5] ($mm^2$) | Accu. Area[6] ($mm^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 175.48 | 60.5 | 3.7 | 88.2 | 0.157 | 55.2 | 55.2 | 3.3 | 180.27 | 180.27 |
| 2 | 157.42 | 64.6 | 3.1 | 97.6 | 0.120 | 59.2 | 59.2 | 2.7 | 162.56 | 342.83 |
| 3 | 303.23 | 54.1 | 7.1 | 86.8 | 0.077 | 59.3 | 59.3 | 6.3 | 375.22 | 718.04 |
| 4 | 210.97 | 65.8 | 4.1 | 70.3 | 0.145 | 60.0 | 60.0 | 3.6 | 216.11 | 934.16 |
| 5 | 144.52 | 69.2 | 2.6 | 12.3 | 0.092 | 63.5 | 63.5 | 2.3 | 148.62 | 1082.78 |
| 6 | 159.35 | 63.2 | 3.2 | 2.7 | 0.093 | 67.4 | 67.4 | 2.9 | 192.52 | 1275.30 |
| 7 | 65.81 | 61.6 | 1.4 | 35.0 | 0.031 | 75.8 | 75.8 | 1.2 | 92.17 | 1367.47 |
| 8 | 129.68 | 64.9 | 2.5 | 43.8 | 0.053 | 76.6 | 76.6 | 2.3 | 172.40 | 1539.87 |
| 9 | 85.16 | 57.4 | 1.9 | 35.9 | 0.038 | 77.9 | 77.9 | 1.7 | 131.48 | 1671.35 |
| 10 | 176.77 | 84.4 | 2.7 | 99.4 | 0.072 | 78.6 | 78.6 | 2.4 | 185.82 | 1857.17 |
| 11 | 203.23 | 86.4 | 3.0 | 52.9 | 0.087 | 79.1 | 79.1 | 2.7 | 210.04 | 2067.21 |
| 12 | 333.55 | 78.6 | 5.4 | 33.6 | 0.104 | 83.2 | 83.2 | 4.8 | 398.62 | 2465.83 |
| 13 | 187.74 | 90.2 | 2.6 | 57.3 | 0.071 | 83.8 | 83.8 | 2.3 | 196.24 | 2662.07 |
| 14 | 161.29 | 60.1 | 3.4 | 62.3 | 0.048 | 84.4 | 84.4 | 3.0 | 256.43 | 2918.49 |
| 15 | 213.55 | 89.2 | 3.0 | 41.9 | 0.083 | 85.5 | 85.5 | 2.7 | 230.82 | 3149.31 |
| 16 | 128.39 | 60.5 | 2.7 | 85.4 | 0.046 | 85.9 | 85.9 | 2.4 | 204.92 | 3354.23 |
| 17 | 100.64 | 39.7 | 3.2 | 101.3 | 0.036 | 87.7 | 87.7 | 2.9 | 250.52 | 3604.75 |
| 18 | 389.68 | 93.4 | 5.3 | 45.0 | 0.130 | 87.8 | 87.8 | 4.7 | 413.12 | 4017.87 |
| 19 | 119.35 | 36.5 | 4.2 | 89.1 | 0.035 | 94.7 | 94.7 | 3.7 | 349.48 | 4367.35 |
| 20 | 161.29 | 53.1 | 3.9 | 38.2 | 0.043 | 97.8 | 97.8 | 3.4 | 336.88 | 4704.23 |
| 21 | 449.03 | 90.4 | 6.3 | 7.3 | 0.085 | 102.3 | 102.3 | 5.6 | 573.31 | 5277.54 |
| 22 | 446.45 | 100.2 | 5.7 | 74.2 | 0.088 | 105.3 | 105.3 | 5.0 | 528.49 | 5806.03 |
| 23 | 563.87 | 119.6 | 6.0 | 20.6 | 0.106 | 112.9 | 112.9 | 5.3 | 599.77 | 6405.80 |
| 24 | 252.26 | 47.2 | 6.8 | 104.0 | 0.044 | 120.6 | 120.6 | 6.0 | 727.51 | 7133.31 |

[1] Major axis, where was the longest axis from the ellipse fit.
[2] Minor axis, where was the shortest axis from the ellipse fit.
[3] The angle between horizontal line and major axis, degree.
[4] Circularity.
[5] Project area of each particle, it was calculated by length × width, assuming rectangular shaped particles.
[6] Accumulative area.

***Table 3.4.*** Overall GMD calculation for switchgrass sample (KMSG-28).

| ID | Sieve size (mm) | GMD by IA (mm)[1] | Mass (g)[2] | Accu. Mass (g) |
|---|---|---|---|---|
| 1 | 19.0 | 87.4 | 1.75 | 1.75 |
| 2 | 12.7 | 63.4 | 5.61 | 7.36 |
| 3 | 6.3 | 42.5 | 11.84 | 19.2 |
| 4 | 3.96 | 32.2 | 12.62 | 31.82 |
| 5 | 1.17 | 23.1 | 10.45 | 42.27 |
| 6 | Dustpan | 21.9 | 5.7 | 47.97 |
| | | | 47.97 | |

[1] GMD was based on particle length.
[2] Mass data was obtained from ASAEB sieve analysis.

*C h a p t e r  4*

# RESULTS AND DISCUSSIONS

## *1. Sieving*

For the dry samples used in the tests, the MC for each biomass group was 5% on a wet basis. Density analysis shows true density determined by the pyncometer compared with particle density by hand measurements. Since the calculations of particle density assumed solid cylindrical switchgrass particles, it averaged the weight through the hollow part of the internode and resulted in lower density as shown in Table 4.1.

Table 4.2 shows the repeated hand measurements of the same hand cut switchgrass particles using calipers. These repeated measurements show very small variations, with standard deviations ranging from 0.02 to 0.05 mm for the length, and 0.02 to 0.07 mm for the width.

***Table 4.1***. Particle density of nodal and internodes section from switchgrass[1]

| | Density of nodes ($g/cm^3$) | | Density of internodes ($g/cm^3$) | |
|---|---|---|---|---|
| | 12 mm Cut | 3 mm Cut | 12 mm Cut | 3 mm Cut |
| Particle density [3] | 0.63±0.13 | 0.80±0.11 | 0.24±0.04 | ND[2] |
| True density [4] | 0.68±0.11 | 1.24±0.13 | 1.22±0.17 | ND[2] |

[1] Moisture content for the switchgrass was 5%. Standard deviation was calculated from 10 samples.
[2] ND=not determined.
[3] Volume by calculation using equation (5).
[4] Volume determined by pyncometer.

***Table 4.2.*** Duplicated manual measurements by calipers for hand cut switchgrass particles assuming each particle with cylinder shape.

| ID | 1st measurement (mm) | | 2nd measurement (mm) | | Δ L (mm) | Δ D (mm) | Standard Dev.(mm) | |
|---|---|---|---|---|---|---|---|---|
| | L | D | L | D | | | L | D |
| 1 | 12.80 | 3.96 | 12.85 | 3.94 | 0.05 | 0.03 | 0.04 | 0.02 |
| 2 | 12.80 | 4.01 | 12.75 | 3.94 | 0.05 | 0.10 | 0.04 | 0.07 |
| 3 | 13.23 | 4.46 | 13.28 | 4.42 | 0.05 | 0.05 | 0.04 | 0.04 |
| 4 | 25.35 | 4.06 | 25.43 | 4.11 | 0.08 | 0.08 | 0.05 | 0.05 |
| 5 | 26.31 | 3.66 | 26.29 | 3.73 | 0.02 | 0.08 | 0.02 | 0.07 |
| 6 | 26.04 | 3.86 | 26.11 | 3.81 | 0.07 | 0.05 | 0.05 | 0.05 |
| 7 | 39.29 | 3.86 | 39.32 | 3.84 | 0.03 | 0.03 | 0.02 | 0.02 |
| 8 | 38.35 | 3.86 | 38.43 | 3.86 | 0.08 | 0.00 | 0.05 | 0.00 |
| 9 | 38.86 | 3.89 | 38.94 | 3.94 | 0.08 | 0.08 | 0.05 | 0.05 |
| 10 | 50.80 | 3.17 | 50.88 | 3.10 | 0.08 | 0.10 | 0.05 | 0.07 |
| 11 | 50.83 | 3.35 | 50.80 | 3.40 | 0.03 | 0.08 | 0.02 | 0.05 |
| 12 | 51.36 | 4.29 | 51.28 | 4.23 | 0.08 | 0.05 | 0.05 | 0.04 |

Figures 4.1 and 4.2 show the results of triplicate ASABE separation experiment results. As shown in the figures, there were about 2 to 5% weight differences during the sieving test, depending on the screen installed in the knife mill. Standard deviations of weight percentages among sieves (26.9, 18.0, 8.9, 5.6, 1.7 mm, and dust pan) in the stack were 1.55, 1.44, 2.12, 0.72, 1.54, and 0.64 %, respectively, for switchgrass samples prepared with the knife mill equipped with a 50.8 mm screen (Figure 4.1). Standard deviations among sieves (26.9, 18.0, 8.9, 5.6, 1.7 mm, and dust pan) in the stack were 0.15, 0.06, 0.13, 2.08, 0.36, and 2.82 %, respectively, for switchgrass samples prepared with the knife mill equipped with a 12.7 mm screen (Figure 4.2). In comparison tests of ASTM separator, standard deviations among sieves (26.9, 18.0, 8.9, 5.6, 1.7 mm, and dust pan) in

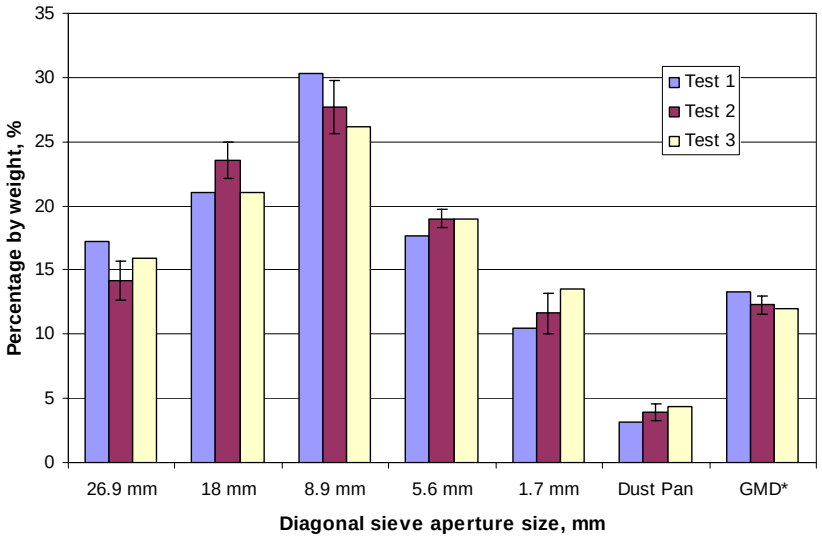



***Figure 4.1.*** Triplicate tests of switchgrass particles mass distribution by a 50.8 mm screen in the knife mill in the ASABE separation analysis. (*GMD is in the unit of mm and the error bar is the standard deviation).

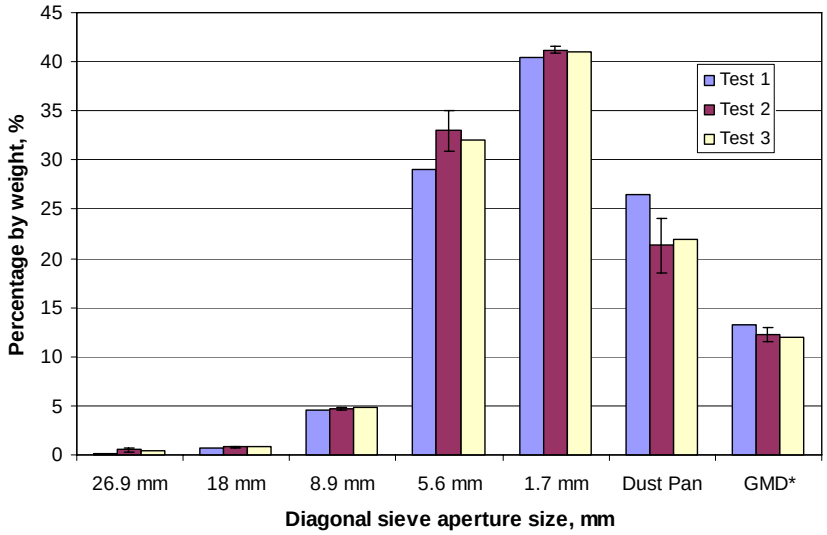



***Figure 4.2.*** Triplicate tests of switchgrass particles mass distribution by a 12.7 mm screen in the knife mill in the ASABE separation analysis. (*GMD is in the unit of mm and the error bar is the standard deviation).

the stack were 3.44, 1.62, 3.91, 4.08, 3.55, and 0.92 % respectively for switchgrass samples prepared with knife mill equipped with 50.8 mm screen (Figure 4.3).

These variations in the experiments could come from a sample-collection difference, the separation test, or the weighing procedure. Also, there was about 2 to 5 % of the sample lost in the separation process that contributed to the variations. Figure 4.4 shows the randomness of the weight variation in the sieving analysis.

Figure 4.5 shows the difference in the separation analysis using both ASTM and ASABE standard sieves for the same switchgrass sample. As shown in the figure, ASTM separator tends to capture switchgrass particles in lower sieves, while the ASABE separator has a somewhat more uniform particle distribution. This could be explained by the different

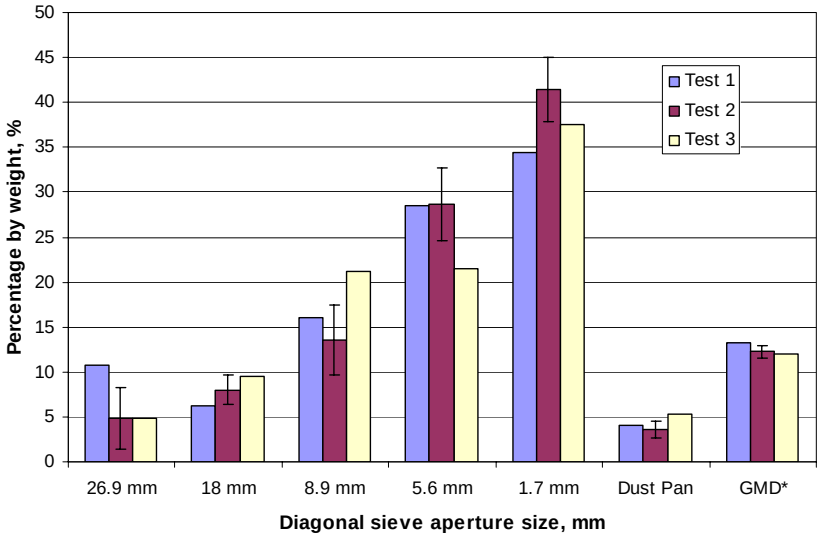



***Figure 4.3.*** Triplicate tests of switchgrass particles mass distribution by a 50.8 mm screen in the knife mill in the ASTM separation analysis. (*GMD is in the unit of mm and the error bar is the standard deviation).

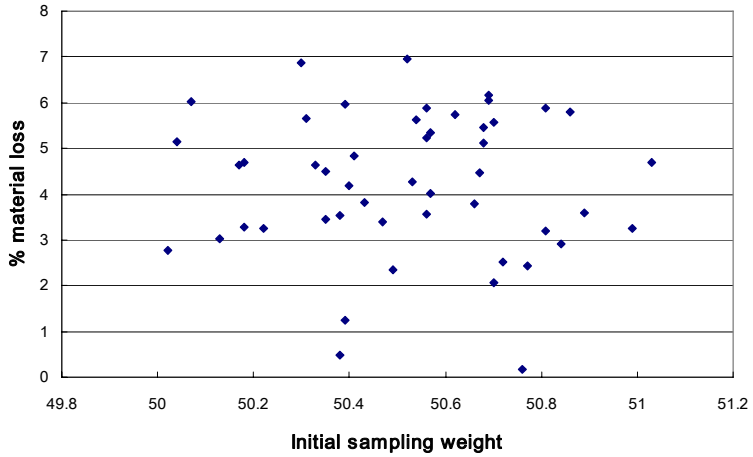



***Figure 4.4.*** Weight percent variations versus initial sampling weight.

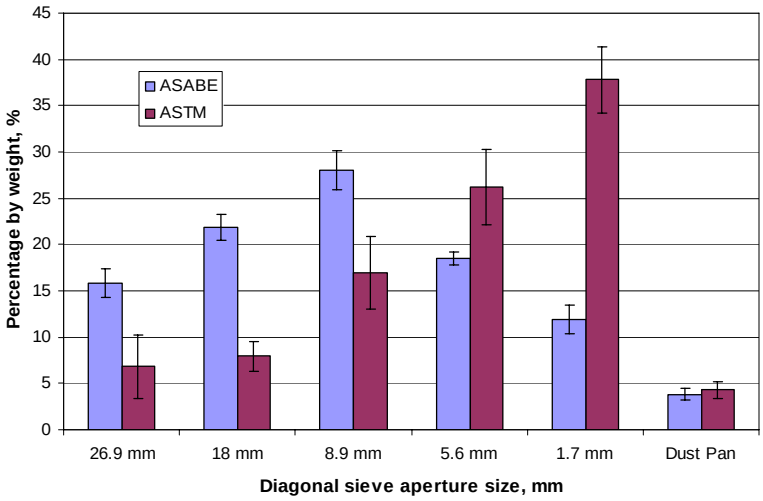



***Figure 4.5.*** Mass distribution comparison of parallel tests of ASABE and ASTM sieves using switchgrass sample prepared by the 50.8 mm screen in the knife mill (the error bar is the standard deviation for triplicate measurements).

sieving motion applied to the separators, as well as by the sieve construction itself. The ASTM method uses a vertical motion and woven-wire sieve that allows slim particles to pass through, while the ASABE separator employs a horizontal motion and a thick sieve, which prevents long and slim particles from passing through.

Using the different screens installed in the knife mill gave similar results: larger screens generated larger particles, while smaller screens generated smaller particles during the grinding process. Figure 4.6 demonstrates the relationship between cumulative mass percent for switchgrass prepared by a knife mill using 12.7, 25.4, and 50.8 mm screens. At 50 % cumulative mass, the sizes of switchgrass particles for 12.7, 25.4, and 50.8 mm screen are 1.2, 5.4, and 7.8 mm respectively.

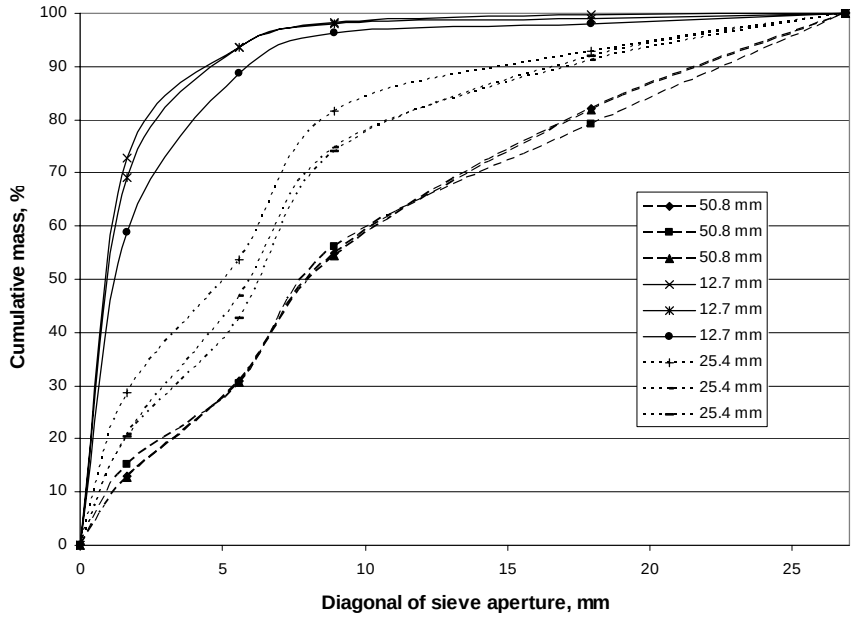



***Figure 4.6.*** Plot of cumulative mass percent as a function of diagonal sieve aperture size for switchgrass particles prepared using 12.7, 25.4, and 50.8 mm screen in the knife mill.

*2. Sieve separation of nodes and internodes*

Figure 4.7 shows the weight difference in the separation of switchgrass nodes and internodes particles from hand cut samples. There are 25% more nodes by weight trapped on the upper sieve than on the lower sieve, which indicates that the nodes could be separated from internodes using the ASABE separator.

Figure 4.8 demonstrates the comparison of switchgrass mass percent between 50.8, 25.4, 19, and 12.7 mm screens used in knifemill. The theoretical line in the figure was calculated by the percentage of nodes present in a particular size group. For instance, assuming the switchgrass before grinding was 900 mm long and the distance between the

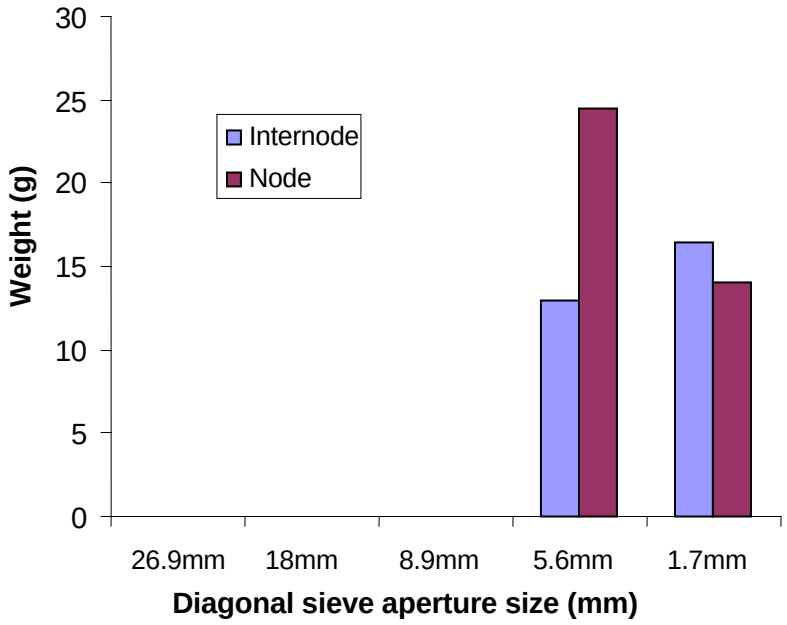



***Figure 4.7.*** Comparison of internode and node cut switchgrass samples by the ASABE standard sieve.

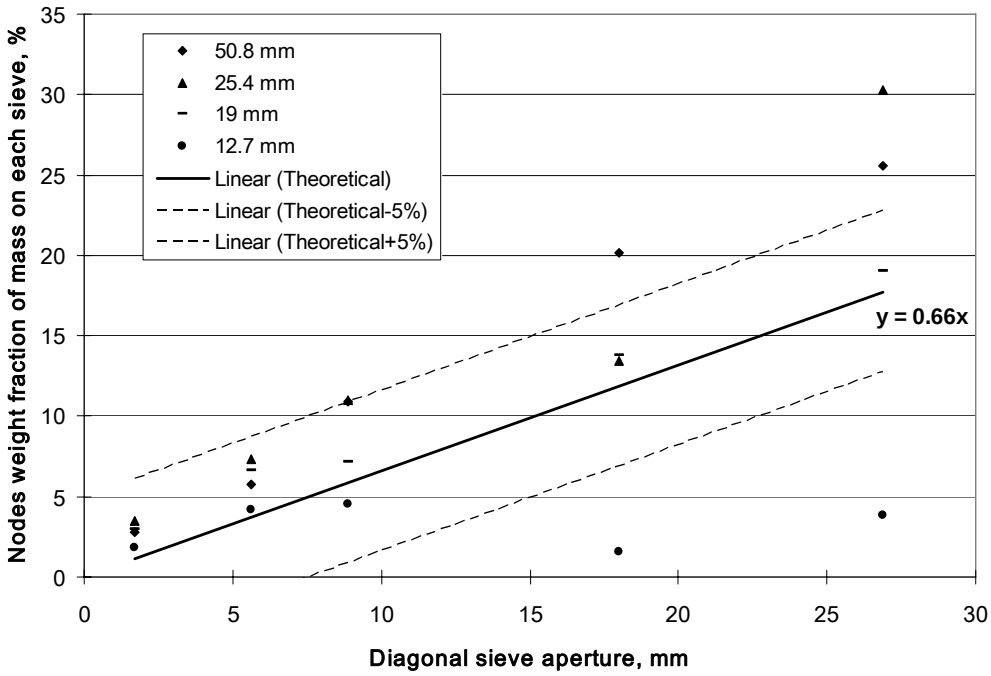



***Figure 4.8.*** Switchgrass node mass percentage comparison between 50.8, 25.4, 19, and 12.7 mm screens installed in the knife mill.

nodes was 150 mm. If all particles generated were 25.4 mm, then there would be 16.93% of the particles containing nodes section, based on the number of nodes compared to the total number of particles:

16.93 %=(900/150)/(900/25.4)×100%

The equation above shows the percentage of the particles containing nodes presented in the sample based on the number. There are two extreme situations: extreme small particles and extreme large particle. As to the extreme small particles, the weight of individual particle containing node section differs from the weight of individual particle without node (refer to table 4.1). However, since there was small number of such particles with nodes, the weight

fraction of the particles containing nodes could be represented by the fraction based on the number of the particles. As to the extreme large particles, the weight difference between particles with or without nodes is minimized due to the long internodes section between the nodes. So the weight fraction of particles with nodes could be represented by the fraction based on the number. In either case showed above, the fraction of particles with nodes based on number could be used for the weight fraction of such particle containing nodes.

The dashed line in the figure presents the ±5% error range by assumption. Any points above the +5% line represent more nodes particles by weight in the sample after separation and any points below -5% line represent less nodes particles by weight in the sample. As illustrated in the figure 4.8, switchgrass particles prepared by 50.8 mm knife mill screen had 25.6% of node particles on the top sieve with diagonal sieve aperture of 26.9 mm, and 20.2% of node particles on the second sieve with diagonal sieve aperture of 18.0mm. However, switchgrass particles prepared by 12.7 mm knife mill screen had lower node percentage in the upper two sieves with the nodes percentage of 3.8% and 1.6% respectively. For most of the nodes percentages, they were within the ±5% error range. From the figure 4.8, more percentage of particles with nodes section presented in the upper 2 sieves for the switchgrass particles prepared by the 50.8 mm and 25.4 mm screen installed in the knife mill. This difference also was demonstrated in Table 4.3. This shows the agreement with some previous studies that indicate the particles of different shape even they have the same volume, will pass through a sieve at different rate (Feller and Foux, 1976).

***Table 4.3.*** Comparison of percentage mass of switchgrass nodes for each sieve after ASABE sieve analysis.

| ID | KM Screen Size (mm) | KM speed (rpm) | ASABE sieve analysis by sieve (mm) | | | | | | Manual nodes observation (gram) | | | | | | Nodes mass percentage by each sieve (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 19mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm | Pan | 19mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm | 19mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm |
| KMSG-13 | 12.7 | 508 | 0.17 | 0.60 | 2.17 | 9.83 | 19.13 | 14.94 | 0.00 | 0.00 | 0.03 | 0.39 | 0.38 | 0.0 | 0.0 | 1.4 | 4.0 | 2.0 |
| KMSG-14 | 12.7 | 508 | 0.51 | 0.45 | 2.04 | 11.75 | 20.90 | 12.26 | 0.00 | 0.00 | 0.16 | 0.47 | 0.42 | 0.0 | 0.0 | 7.8 | 4.0 | 2.0 |
| KMSG-17 | 12.7 | 400 | 0.94 | 0.45 | 2.64 | 12.91 | 17.64 | 12.48 | 0.18 | 0.00 | 0.18 | 0.64 | 0.30 | 19.1 | 0.0 | 6.8 | 5.0 | 1.7 |
| KMSG-18 | 12.7 | 462 | 0.68 | 0.75 | 2.47 | 13.13 | 19.74 | 10.82 | 0.00 | 0.06 | 0.08 | 0.69 | 0.35 | 0.0 | 8.0 | 3.2 | 5.3 | 1.8 |
| KMSG-20 | 12.7 | 504 | 0.10 | 0.27 | 1.76 | 11.20 | 21.04 | 13.25 | 0.00 | 0.00 | 0.06 | 0.30 | 0.34 | 0.0 | 0.0 | 3.4 | 2.7 | 1.6 |
| KMSG-49 | 19 | 454 | 0.27 | 1.12 | 9.01 | 15.90 | 14.87 | 6.55 | 0.05 | 0.01 | 0.56 | 0.62 | 0.27 | 18.5 | 0.9 | 6.2 | 3.9 | 1.8 |
| KMSG-50 | 19 | 403 | 1.15 | 2.28 | 10.04 | 15.12 | 12.94 | 6.16 | 0.26 | 0.09 | 0.83 | 1.14 | 0.49 | 22.6 | 3.9 | 8.3 | 7.5 | 3.8 |
| KMSG-51 | 19 | 319 | 0.56 | 1.35 | 8.74 | 15.62 | 14.52 | 7.03 | 0.08 | 0.20 | 0.83 | 0.95 | 0.36 | 14.3 | 14.8 | 9.5 | 6.1 | 2.5 |
| KMSG-52 | 19 | 319 | 0.55 | 1.07 | 7.90 | 15.43 | 14.28 | 7.78 | 0.00 | 0.25 | 0.45 | 0.93 | 0.32 | 0.0 | 23.4 | 5.7 | 6.0 | 2.2 |
| KMSG-55 | 19 | 319 | 1.79 | 2.01 | 9.10 | 15.49 | 13.15 | 5.92 | 0.28 | 0.49 | 0.85 | 1.44 | 0.41 | 15.6 | 24.4 | 9.3 | 9.3 | 3.1 |
| KMSG-23 | 25.4 | 262 | 4.25 | 7.96 | 13.53 | 12.47 | 7.64 | 2.44 | 1.86 | 1.77 | 1.03 | 0.92 | 0.29 | 43.8 | 22.2 | 7.6 | 7.4 | 3.8 |
| KMSG-24 | 25.4 | 262 | 3.86 | 8.60 | 14.97 | 10.68 | 6.68 | 3.05 | 1.40 | 2.30 | 1.46 | 0.63 | 0.23 | 36.3 | 26.7 | 9.8 | 5.9 | 3.4 |
| KMSG-26 | 25.4 | 318 | 4.98 | 6.09 | 15.01 | 10.02 | 8.09 | 4.43 | 1.39 | 1.08 | 1.65 | 0.76 | 0.28 | 27.9 | 17.7 | 11.0 | 7.6 | 3.5 |
| KMSG-29 | 25.4 | 468 | 3.52 | 6.14 | 13.37 | 11.58 | 9.81 | 3.96 | 1.46 | 0.99 | 1.68 | 0.89 | 0.34 | 41.5 | 16.1 | 12.6 | 7.7 | 3.5 |
| KMSG-30 | 25.4 | 470 | 4.42 | 7.87 | 13.44 | 12.33 | 7.62 | 2.86 | 1.12 | 1.02 | 1.17 | 0.79 | 0.20 | 25.3 | 13.0 | 8.7 | 6.4 | 2.6 |
| KMSG-32 | 25.4 | 504 | 4.12 | 6.04 | 16.70 | 12.81 | 7.61 | 3.39 | 1.93 | 0.97 | 1.49 | 0.89 | 0.22 | 46.8 | 16.1 | 8.9 | 6.9 | 2.9 |
| KMSG-33 | 25.4 | 504 | 5.96 | 8.34 | 14.54 | 11.23 | 6.68 | 3.39 | 2.43 | 0.60 | 1.57 | 0.58 | 0.22 | 40.8 | 7.2 | 10.8 | 5.2 | 3.3 |
| KMSG-4 | 50.8 | 320 | 8.87 | 13.34 | 11.89 | 8.85 | 4.95 | 1.43 | 3.02 | 3.23 | 0.83 | 0.53 | 0.27 | 34.0 | 24.2 | 7.0 | 6.0 | 5.5 |
| KMSG-9 | 50.8 | 502 | 10.70 | 11.13 | 12.78 | 7.92 | 4.46 | 1.62 | 2.92 | 2.38 | 1.40 | 0.30 | 0.04 | 27.3 | 21.4 | 11.0 | 3.8 | 0.9 |
| KMSG-10 | 50.8 | 502 | 6.31 | 11.76 | 14.36 | 9.45 | 4.96 | 1.66 | 1.34 | 2.49 | 1.22 | 0.43 | 0.07 | 21.2 | 21.2 | 8.5 | 4.6 | 1.4 |
| KMSG-11 | 50.8 | 507 | 8.58 | 10.83 | 12.81 | 8.90 | 5.43 | 2.05 | 2.31 | 1.51 | 2.00 | 0.60 | 0.16 | 26.9 | 13.9 | 15.6 | 6.7 | 2.9 |
| KMSG-12 | 50.8 | 508 | 7.88 | 13.66 | 12.78 | 8.14 | 4.45 | 1.68 | 1.46 | 2.75 | 1.61 | 0.62 | 0.15 | 18.5 | 20.1 | 12.6 | 7.6 | 3.4 |

This difference indicates that a larger sieve size screen might provide optimal isolation of nodes from the biomass materials. Larger screen apertures used in the knife mill may result in higher percent of particles containing un-broken nodes. Due to the differences between particles with or without nodal sections, they may be trapped by different sieves due to different passing rates. Small screen apertures used in the milling processes result in smaller particles, and also reflect broken nodal sections. This was verified by the observation that with smaller knife mill screens, e.g. the screen with 12.7 mm aperture, there was increased percentage of broken nodal sections compared to the tests with the 50.8 mm aperture screen installed for the knife mill.

*3. Image Analysis*

Figure 4.9 shows the relationship between the number of total particles in the image and threshold level. There were actual 35 switchgrass particles on the scanner, with the

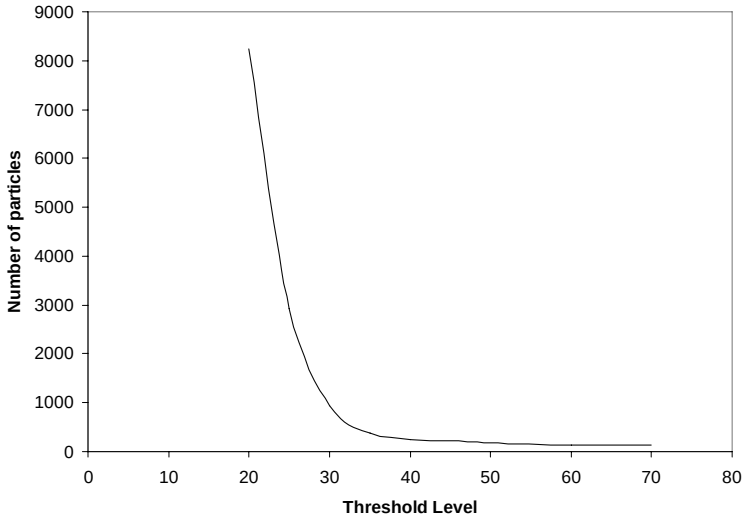



***Figure 4.9.*** Plot of total particles as a function of threshold level change in the IA.

average 82.7 mm in length. As indicated in this figure, the number of particles approaches a constant value when the threshold level reached 30, while a further increase the threshold level above 30 did not dramatically drop the noise level.

Figures 4.10 and Figure 4.11 demonstrate the effect of threshold level on the IA of particle length and width, respectively. As seen in Figure 4.10 a threshold level equal to 35 gave the best prediction of particle length, while IA seemed to always overestimate particle width (Figure 4.11). One explanation of this is that the particles prepared by knife mill were not perfectly straight, and a bend or curve shape would result in overestimation of

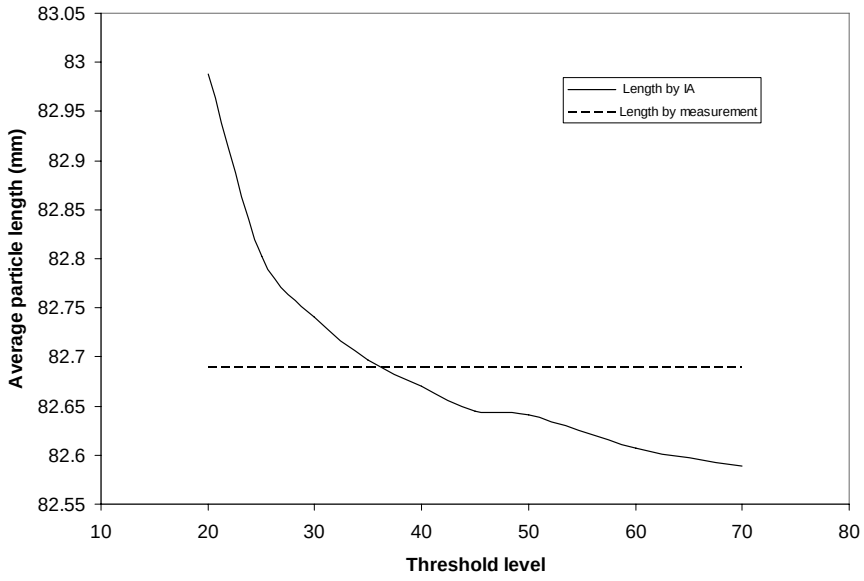



***Figure 4.10.*** Plot of particle length change as a function of threshold level change in the IA. The dashed line presents the manual measurement of particle by a caliper (There were actual 35 switchgrass particles on the scanner).

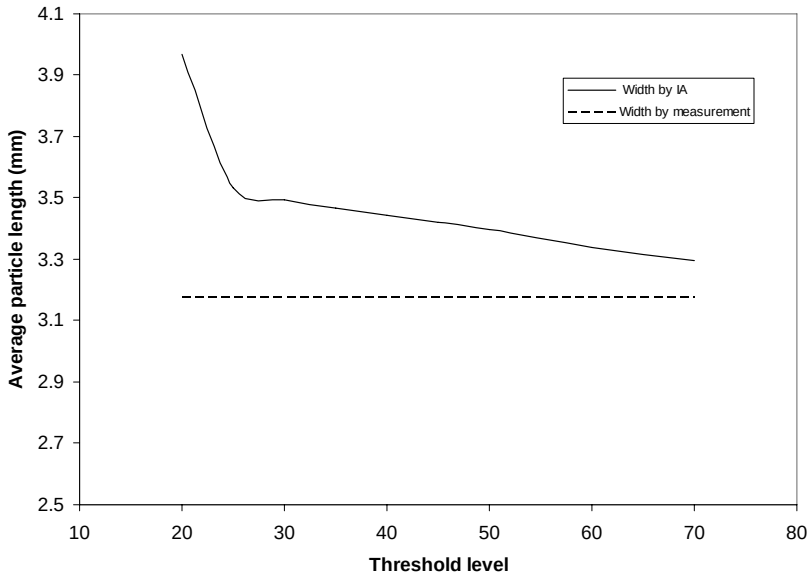



***Figure 4.11.*** Plot of particle width change as a function of threshold level change in the IA. The dashed line presents the manual measurement of particle by a caliper (There were actual 35 switchgrass particles on the scanner).

width during the IA process. Table 4.4 demonstrates a result of a switchgrass sample using IA. The geometric mean diameter used in the ASABE calculation for each sieve falls between the GMD of length and width calculated by the IA process. The total number of the particles on a particular sieve were calculated by the number count from IA times the weight fraction of samples.

Table 4.5 shows the percent of cumulative mass by particle length using IA for KMSG-4 (50.8 mm screen aperture in knife mill). The GMD by length indicated in the table corresponds to the 50 percentile of cumulative mass by particle length.

***Table 4.4.*** Comparisons of the geometric mean for screened switchgrass particles and IA determination of switchgrass particles prepared using the knife mill.

| Sieve size (mm) | Number of particles | Geometric mean diameter by ASABE standard (mm) | GMD by IA (mm) | |
|---|---|---|---|---|
| | | | Length | Width |
| 19.0 | 1 | 96.8[1] | 96.8 | 2.21 |
| 12.7 | 7 | 22.0 | 32.25 | 3.11 |
| 6.3 | 33 | 12.7 | 19.39 | 2.78 |
| 3.96 | 643 | 7.10 | 19.42 | 1.75 |
| 1.17 | 3970 | 3.04 | 14.61 | 1.69 |
| Pan | 4845 | 0.82 | 6.78 | 1.00 |
| Overall | 9499 | 3.05 | 10.08 | 1.30 |

[1] The average measured length of the particles on sieve with 19.0 mm aperture was 96.8 mm.

***Table 4.5.*** Accumulate weight (%) by particle length using IA[1].

| Sieve size (mm) | GMD by ASABE (mm) | GMD by length (mm) | GMD by width (mm) | Cumulative weight (%) by particle length (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | <10.16 | 12.70 | 15.24 | 17.78 | 20.32 | 22.86 | 25.40 | 50.80 | 76.20 | 101.60 |
| 19.0 | - | 104.14 | 4.27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9.27 | 42.45 |
| 12.7 | - | 83.57 | 4.37 | 0.17 | 0.44 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 6.4 | 34.06 | 77.85 |
| 6.3 | - | 55.63 | 3.40 | 0.31 | 0.52 | 1.06 | 1.34 | 1.34 | 2.31 | 3.10 | 36.88 | 83.92 | |
| 3.96 | - | 35.31 | 3.25 | 0.19 | 0.19 | 0.42 | 3.47 | 5.33 | 9.10 | 13.68 | 70.79 | 97.56 | |
| 1.17 | - | 29.72 | 1.83 | 2.48 | 3.89 | 6.25 | 10.65 | 17.02 | 23.76 | 32.98 | 95.08 | | |
| Pan | - | 26.92 | 1.65 | 5.43 | 6.90 | 10.89 | 16.77 | 20.13 | 29.11 | 35.67 | 96.22 | | |
| All | 16.17 | 51.43 | 3.37 | - | - | - | - | - | - | - | - | - | - |

[1]Assumptions:

1. The image analysis calculates the two major dimensions of the particle (length and width), and the third dimension (thickness) is much smaller than the two major dimensions.
2. All particles on the same sieve have the same third dimension (particle thickness).
3. All particles on the same sieve have the same density.
4. GMD by length and GMD by width are calculated by IA (Refer Figure 3.3 for details).
5. 50 percent tile is determined by interpolation assuming linear relationship (Refer to Chapter 3, section 5.2 for calculation example).

Different angle of the particle positioned on the scanner did not affect the IA result, and this has been verified in the repeated IA analysis as shown in Table 4.6 and Table 4.7. The standard deviation for the repeated measurements ranged from 0.04 mm up to 0.31 mm.

Table 4.8 shows the visual comparison of sieving results for the different screens installed in the knife mill. The ASABE sieves were constructed in a unique way that the thickness of the sieves equals to about ¾ of sieve nominal aperture sizes, which prevented the long slim particles passing through the sieves. This unique characteristic may have been a determining factor in particle passage through the sieves. Compared with ASABE sieves, most woven wire sieves are constructed in a way that longest dimension cannot be used to determine whether a particle will pass through a sieve (Maerz and Lusher, 2001).

***Table 4.6.*** GMD comparison of different positions using the same switchgrass particles by IA.

| Sieve size (mm) | GMD by Length (mm) | | | | | Average GMD (mm) | Standard deviation (mm) |
|---|---|---|---|---|---|---|---|
| | 1st Scan | 2nd Scan | 3rd Scan | 4th Scan | 5th Scan | | |
| 19.0 | 95.61 | 95.53 | 95.78 | 95.66 | 95.63 | 95.64 | 0.09 |
| 12.7 | 61.47 | 61.21 | 60.96 | 61.67 | 61.67 | 61.40 | 0.31 |
| 6.3 | 41.00 | 41.43 | 41.48 | 41.45 | 41.55 | 41.38 | 0.22 |
| 3.96 | 33.88 | 33.81 | 33.91 | 33.88 | 33.91 | 33.88 | 0.04 |
| 1.17 | 18.36 | 18.26 | 18.26 | 18.29 | 18.31 | 18.30 | 0.04 |
| Dustpan | 24.94 | 24.89 | 24.97 | 24.97 | 24.89 | 24.93 | 0.04 |

***Table 4.7.*** Pilot test of switchgrass particles in the IA process.

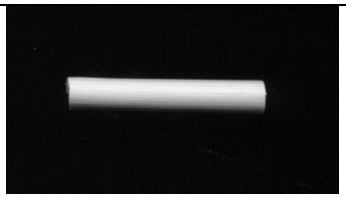
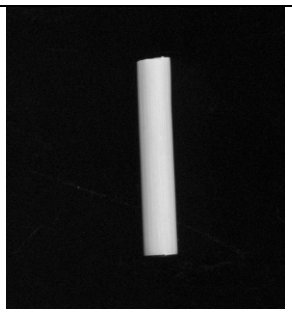
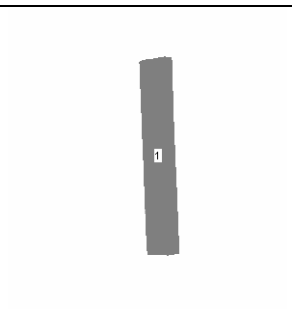
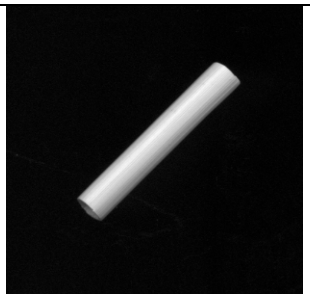
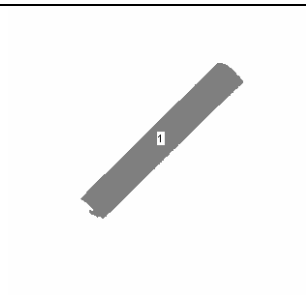
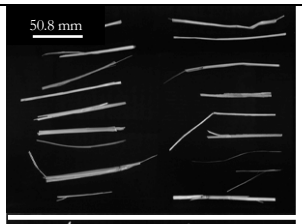
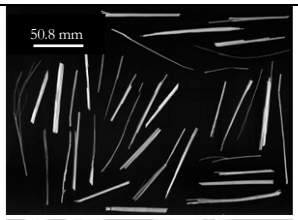
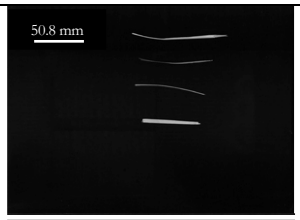
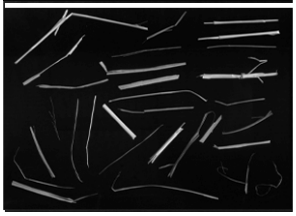
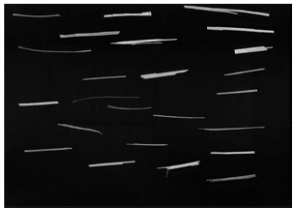
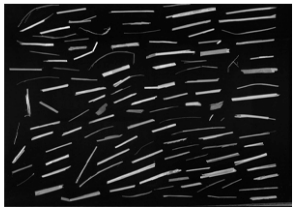
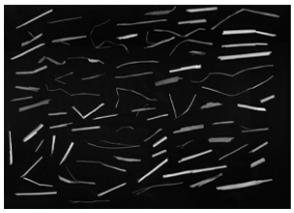
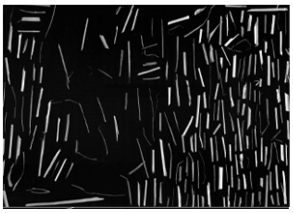
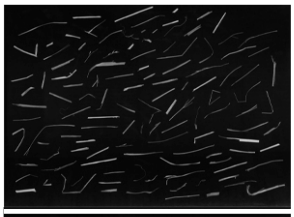
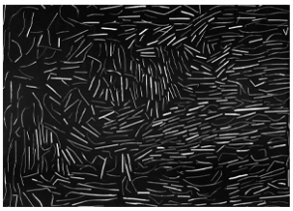
| | Hand measurement | IA Results |
|---|---|---|
| Horizontal |  |  |
| Length (mm) | 25.55 | 25.67 |
| Width (mm) | 4.14 | 4.81 |
| Area ($mm^2$) | 105.78 | 123.47 |
| Vertical |  |  |
| Length (mm) | 25.55 | 25.67 |
| Width (mm) | 4.14 | 4.83 |
| Area ($mm^2$) | 105.78 | 123.98 |
| Diagonal |  |  |
| Length (mm) | 25.55 | 25.86 |
| Width (mm) | 4.14 | 4.57 |
| Area ($mm^2$) | 105.78 | 118.18 |

***Table 4.8.*** Visual comparison of switchgrass by different knife mill screens after ASABE sieving analysis.

| Sieve size | 50.8 mm KM screen[1] | 25.4 mm KM screen[2] | 12.7 mm KM screen[3] |
|---|---|---|---|
| Sieve 1 (19 mm) |   |   |   |
| Sieve 2 (12.5 mm) |  |  |  |
| Sieve 3 (6.3 mm) |  |  |  |
| Sieve 4 (4 mm) |  |  |  |
| Sieve 5 (1.18 mm) |  |  |  |
| Dust Pan |  |  |  |

[1] Presented by KMSG-4 sample; [2] Presented by KMSG-6 sample; [3] Presented by KMSG-13 sample. All figures were shown by the same scale.

*4. Comparison of sieving and Image Analysis*

Figure 4.12 shows the percent of cumulative mass by particle length to the three materials using both sieve analysis and IA. The sieve analysis shows similar results for the three biomass materials. At 50 % cumulative mass (i.e. 50 percentile for GMD), the sieve-determined sizes of switchgrass, wheat straw, and corn stover particles are 8.9 mm, 8.4 mm, and 8.3 mm respectively. All IA results indicated larger particle sizes than sieve analysis. The IA results demonstrate reduced particle sizes for the corn stover, which can be explained by the fact that large amount of dust particles are generated during the grinding processes for corn stover. Also, due to the curved particles generated in the grinding process for corn stover, the particle lengths estimated by the IA process were smaller. Compared with the cumulative mass by the sieve data, the difference might be

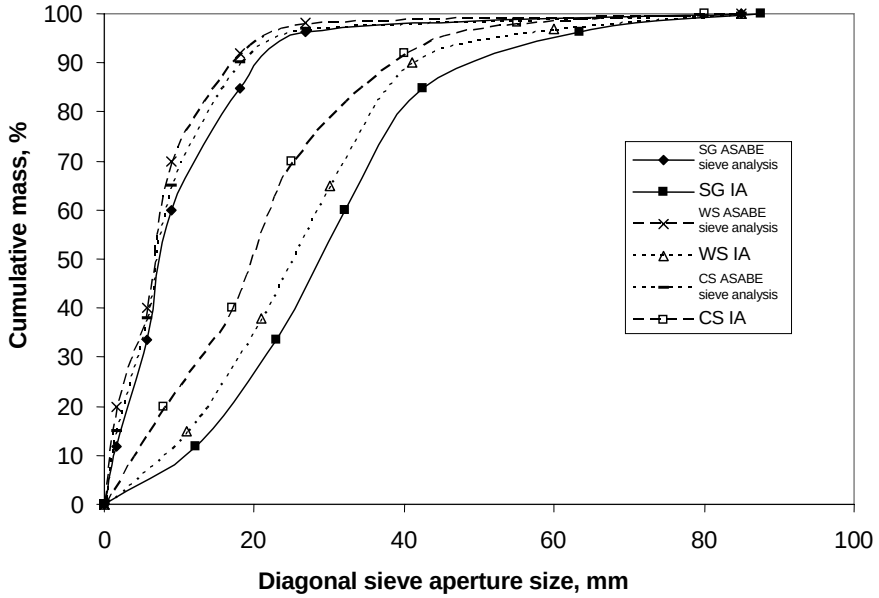



***Figure 4.12.*** Comparison of % cumulative mass by IA and sieve analysis for switchgrass (SG), wheat straw (WS), and corn stover (CS) particles by 12.7 mm knife mill screen.

explained by the two assumptions: 1. the projected areas are the particle volume and mass in the volume-mass conversion by IA and 2. particle sizes equal to the square root of upper and lower sieve sizes instead of actual particle sizes in the sieve analysis.

Figure 4.13 shows the relationship for switchgrass between GMD calculated by the ASABE standard with the GMD calculated based on length in the IA tests. It is interesting to point out that there is a factor of about 5 between the GMD by sieve and GMD by major dimension (length) from IA analysis, while there is a factor of about 1/5 between the GMD by sieve and GMD by minor dimension (width, Figure 4.14) from IA analysis. The GMD calculated based on the standard ASABE tests may not provide truly representative particle sizes, especially for irregular shape biomass particles. ASABE sieve tests were based on the mass of particles on sieves, which is independent of particle size or shape.

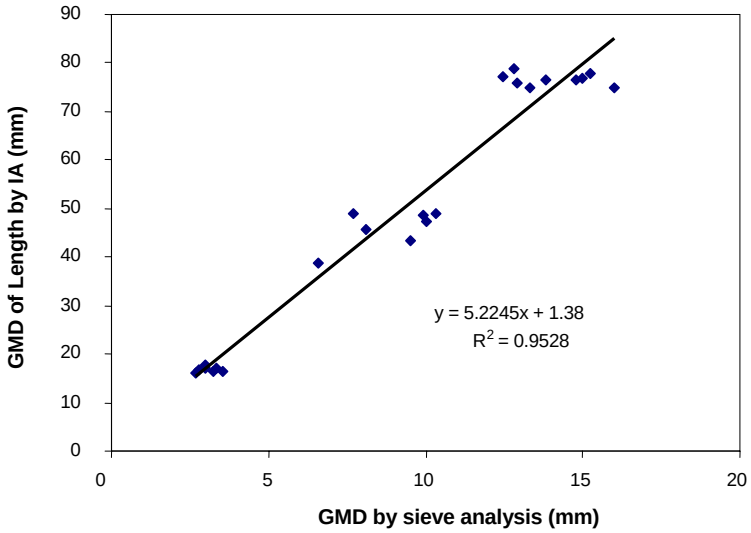



***Figure 4.13.*** Plot of GMD length by IA as a function of GMD by sieve analysis for switchgrass (x=GMD by sieve analysis; y=GMD length by IA).

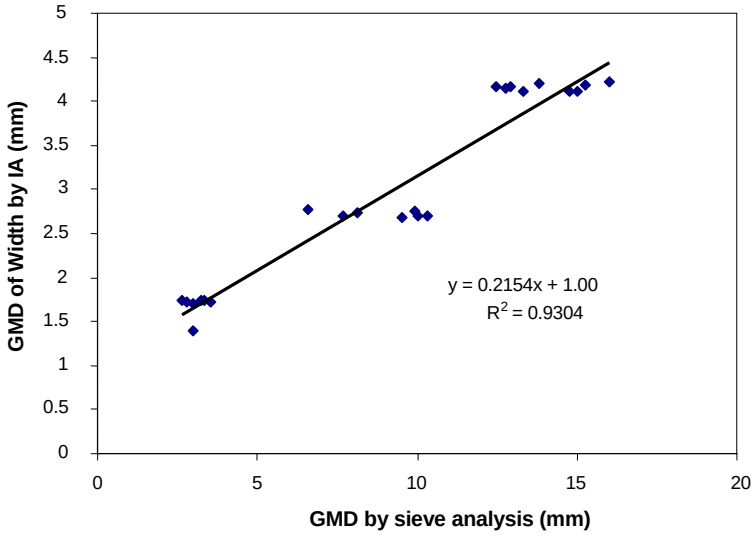



***Figure 4.14.*** Plot of GMD width by IA as a function of GMD by sieve analysis for switchgrass (x=GMD by sieve analysis; y=GMD width by IA).

However, IA takes into account individual particle factors, such as size and shape, and all the calculations were based on individual particles, though assumptions of the 3rd orthogonal dimension and subsequent mass could vary for IA. The variation in the GMD by sieve analysis could come from the different knife mill speeds as well as different feeding rate of switchgrass material.

Figures 4.15 and 4.16 show the relationship between GMD calculated by the ASABE standard with that calculated based on length and width in the IA tests for wheat straw. It is interesting to point out that there is a factor of about 4 between the GMD by weight and GMD by major dimension (length) from IA analysis, and a factor of about 1/4 between the GMD by weight and GMD by minor dimension (width) from IA analysis.

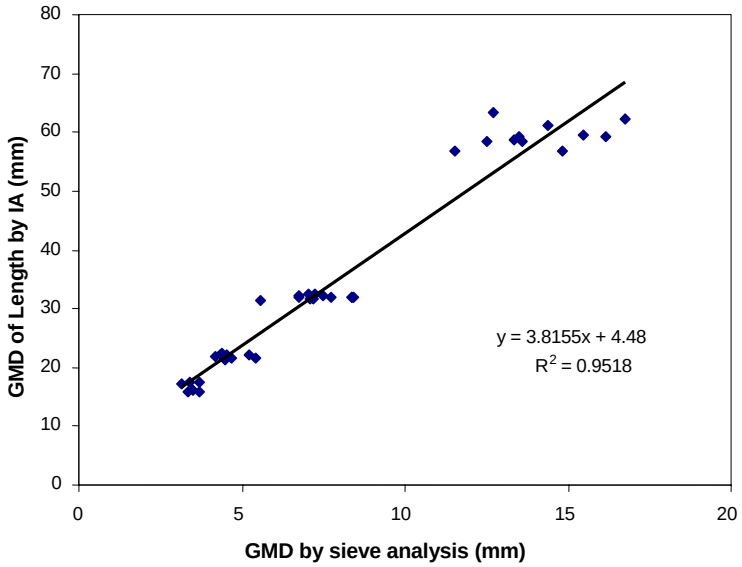



***Figure 4.15.*** Plot of GMD length by IA as a function of GMD by sieve analysis for wheat straw (x=GMD by sieve analysis; y=GMD length by IA).

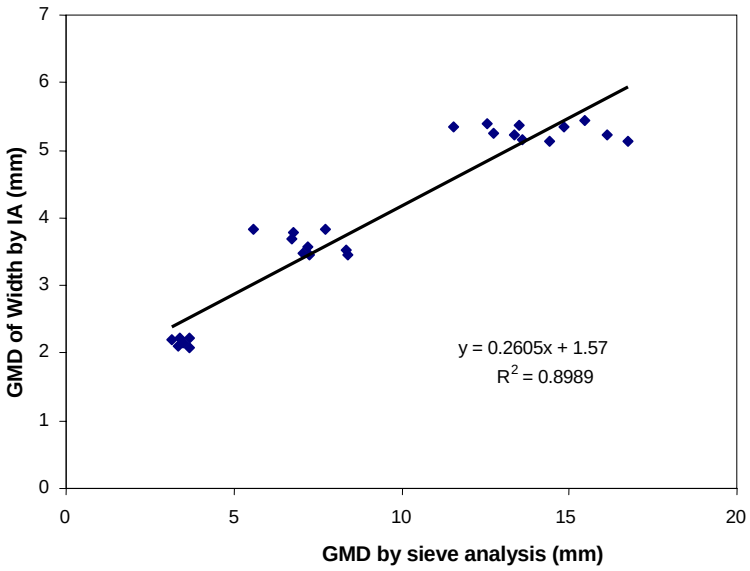



***Figure 4.16.*** Plot of GMD width by IA as a function of GMD by sieve analysis for wheat straw (x=GMD by sieve analysis; y=GMD width by IA).

As indicated in the review (Maerz and Lusher, 2001; McCabe et. al., 1985; ASAE standards, 2003), most sieve analysis for regular or irregular particles use sieve aperture sizes as the size parameter basis for calculating GMD. It makes sense if the particles are spherical, such as to powder, rock, etc. However, for chopped biomass particles that are mostly rectangular or cylindrical in shape, that the same GMD calculation using sieves has weakness in representing actual particle sizes in the standard particle size analysis. Based on the tests, a factor of 4~5 can be applied to the sieve-determined GMD based on this study for those chopped biomass particles to represent the true particle length for grass-like biomass materials.

Table 4.9 summarizes the overall results of both ASABE sieve mass analysis and IA GMD analysis. A given knife mill screen produces particles with different sizes, based on both ASABE sieve analysis and IA ($P<0.05$). ASABE sieve analysis GMD calculated for the 50.8, 25.4, and 12.7 mm screens used in the knife mill were 12.48 to 16.00 mm, 6.59 to 10.31 mm, and 2.66 to 3.56 mm, with the standard deviation of 2.68 to 4.47 mm, 2.67 to 3.94 mm, and 2.40 to 2.79 mm, respectively. Compared with ASABE sieve analysis, IA by particle length gave particle GMDs about 5 times greater to all screens, yielding values of 75.00 to 78.76 mm, 38.61 to 49.01 mm, 16.05 to 17.78 mm, respectively. Also, IA by particle width predicted GMDs about 1/5 as large to all screens, yielding values of 4.10 to 4.20 mm, 2.68 to 2.78 mm, 1.40 to 1.74 mm, respectively.

The IA analyses were focused on the switchgrass and wheat straw since these two biomass materials following the assumptions used in the IA: flat, rectangular shaped. However, the corn stover particles were more close to spherical based on manual

***Table 4.9.*** Comparison of KM configuration, ASABE sieve mass percent, GMD by mass, and GMD by IA.

| ID | KM screen size (mm) | Feed rate (Kg/min) | Knife mill speed (rpm) | Mass percent by screen size | | | | | | Cumulative undersize by screen size, % | | | | | GMD calculation by ASABE (mm) | | GMD by IA (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 19 mm | 12.7 mm | 6.3mm | 3.96 mm | 1.17 mm | Pan | 19 mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm | GMD | Std. Dev. | L | W |
| KMSG-4 | 50.8 | 9 | 320 | 18.0 | 27.0 | 24.1 | 17.9 | 10.0 | 2.9 | 82.0 | 55.0 | 30.9 | 12.9 | 2.9 | 15.26 | 3.07 | 77.85 | 4.18 |
| KMSG-5 | 50.8 | 7 | 322 | 20.8 | 23.0 | 25.9 | 15.2 | 10.4 | 4.7 | 79.2 | 56.2 | 30.3 | 15.1 | 4.7 | 15.00 | 4.47 | 76.98 | 4.12 |
| KMSG-6 | 50.8 | 5 | 322 | 18.1 | 27.4 | 23.9 | 17.8 | 10.0 | 2.8 | 81.9 | 54.5 | 30.6 | 12.8 | 2.8 | 16.00 | 4.41 | 75.00 | 4.22 |
| KMSG-7 | 50.8 | 5 | 502 | 17.3 | 21.1 | 30.3 | 17.7 | 10.5 | 3.1 | 82.7 | 61.7 | 31.3 | 13.6 | 3.1 | 13.30 | 2.70 | 74.93 | 4.10 |
| KMSG-8 | 50.8 | 7 | 502 | 14.5 | 23.8 | 28.9 | 18.3 | 11.5 | 2.9 | 85.5 | 61.6 | 32.7 | 14.4 | 2.9 | 12.79 | 2.63 | 78.76 | 4.15 |
| KMSG-9 | 50.8 | 9 | 502 | 22.0 | 22.9 | 26.3 | 16.3 | 9.2 | 3.3 | 78.0 | 55.1 | 28.8 | 12.5 | 3.3 | 14.77 | 2.81 | 76.54 | 4.11 |
| KMSG-10 | 50.8 | 11 | 502 | 13.0 | 24.2 | 29.6 | 19.5 | 10.2 | 3.4 | 87.0 | 62.7 | 33.1 | 13.6 | 3.4 | 12.48 | 2.61 | 77.30 | 4.16 |
| KMSG-11 | 50.8 | 7 | 507 | 17.7 | 22.3 | 26.4 | 18.3 | 11.2 | 4.2 | 82.3 | 60.1 | 33.7 | 15.4 | 4.2 | 12.90 | 2.85 | 75.90 | 4.17 |
| KMSG-12 | 50.8 | 11 | 508 | 16.2 | 28.1 | 26.3 | 16.8 | 9.2 | 3.5 | 83.8 | 55.7 | 29.4 | 12.6 | 3.5 | 13.81 | 2.68 | 76.45 | 4.20 |
| KMSG-13 | 12.7 | 5 | 508 | 0.4 | 1.3 | 4.6 | 21.0 | 40.8 | 31.9 | 99.6 | 98.4 | 93.7 | 72.7 | 31.9 | 2.66 | 2.53 | 16.05 | 1.74 |
| KMSG-14 | 12.7 | 7 | 508 | 1.1 | 0.9 | 4.3 | 24.5 | 43.6 | 25.6 | 98.9 | 98.0 | 93.7 | 69.2 | 25.6 | 3.01 | 2.52 | 17.78 | 1.70 |
| KMSG-15 | 12.7 | 5 | 332 | 2.1 | 1.7 | 7.5 | 29.8 | 34.8 | 24.0 | 97.9 | 96.2 | 88.7 | 58.9 | 24.0 | 3.56 | 2.85 | 16.55 | 1.73 |
| KMSG-16 | 12.7 | 5 | 255 | 0.1 | 0.6 | 4.2 | 29.1 | 40.2 | 25.8 | 99.9 | 99.3 | 95.1 | 66.0 | 25.8 | 3.00 | 2.40 | 17.11 | 1.40 |
| KMSG-17 | 12.7 | 5 | 400 | 2.0 | 1.0 | 5.6 | 27.4 | 37.5 | 26.5 | 98.0 | 97.0 | 91.4 | 64.0 | 26.5 | 3.22 | 2.79 | 16.45 | 1.74 |
| KMSG-18 | 12.7 | 5 | 462 | 1.4 | 1.6 | 5.2 | 27.6 | 41.5 | 22.7 | 98.6 | 97.0 | 91.8 | 64.2 | 22.7 | 3.33 | 2.60 | 17.20 | 1.74 |
| KMSG-20 | 12.7 | 2.9 | 504 | 0.2 | 0.6 | 3.7 | 23.5 | 44.2 | 27.8 | 99.8 | 99.2 | 95.5 | 72.0 | 27.8 | 2.77 | 2.38 | 16.70 | 1.72 |
| KMSG-21 | 25.4 | 7 | 261 | 7.1 | 11.3 | 27.8 | 25.0 | 19.6 | 9.2 | 92.9 | 81.6 | 53.8 | 28.8 | 9.2 | 7.67 | 2.88 | 49.01 | 2.70 |
| KMSG-23 | 25.4 | 5 | 262 | 8.8 | 16.5 | 28.0 | 25.8 | 15.8 | 5.1 | 91.2 | 74.7 | 46.7 | 20.9 | 5.1 | 9.53 | 2.67 | 43.33 | 2.68 |
| KMSG-24 | 25.4 | 9 | 262 | 8.1 | 18.0 | 31.3 | 22.3 | 14.0 | 6.4 | 91.9 | 74.0 | 42.7 | 20.3 | 6.4 | 10.31 | 3.16 | 48.97 | 2.69 |
| KMSG-25 | 25.4 | 5 | 323 | 5.7 | 11.7 | 29.0 | 27.0 | 18.2 | 8.5 | 94.3 | 82.7 | 53.7 | 26.7 | 8.5 | 8.12 | 3.08 | 45.67 | 2.73 |
| KMSG-26 | 25.4 | 7 | 318 | 10.2 | 12.5 | 30.9 | 20.6 | 16.6 | 9.1 | 89.8 | 77.2 | 46.4 | 25.8 | 9.1 | 9.90 | 3.94 | 48.54 | 2.76 |
| KMSG-27 | 25.4 | 5 | 399 | 9.0 | 12.6 | 32.2 | 24.5 | 15.2 | 6.5 | 91.0 | 78.4 | 46.2 | 21.7 | 6.5 | 10.04 | 3.35 | 47.40 | 2.70 |
| KMSG-28 | 25.4 | 7 | 400 | 3.6 | 11.7 | 24.7 | 26.3 | 21.8 | 11.9 | 96.4 | 84.7 | 60.0 | 33.7 | 11.9 | 6.59 | 2.94 | 38.61 | 2.78 |
| KMSG-29 | 25.4 | 5 | 468 | 7.3 | 12.7 | 27.6 | 23.9 | 20.3 | 8.2 | 92.7 | 80.0 | 52.4 | 28.5 | 8.2 | 8.37 | 3.19 | - | - |
| KMSG-30 | 25.4 | 7 | 470 | 9.1 | 16.2 | 27.7 | 25.4 | 15.7 | 5.9 | 90.9 | 74.7 | 47.0 | 21.6 | 5.9 | 10.00 | 3.12 | - | - |
| KMSG-32 | 25.4 | 5 | 504 | 8.1 | 11.9 | 33.0 | 25.3 | 15.0 | 6.7 | 91.9 | 79.9 | 47.0 | 21.7 | 6.7 | 9.87 | 3.39 | - | - |

***Table 4.9.*** Comparison of KM configuration, ASABE sieve mass percent, GMD by mass, and GMD by IA. (Continued)

| ID | KM screen size (mm) | Feed rate (Kg/min) | Knife mill speed (rpm) | Mass percent by screen size | | | | | | Cumulative undersize by screen size, % | | | | | GMD calculation by ASABE (mm) | | GMD by IA (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 19 mm | 12.7 mm | 6.3mm | 3.96 mm | 1.17 mm | Pan | 19 mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm | GMD | Std. Dev. | L | W |
| KMSG-33 | 25.4 | 7 | 504 | 11.9 | 16.6 | 29.0 | 22.4 | 13.3 | 6.8 | 88.1 | 71.5 | 42.5 | 20.1 | 6.8 | 11.30 | 3.59 | - | - |
| KMSG-34 | 25.4 | 8 | 498 | 5.2 | 13.9 | 29.7 | 29.4 | 15.3 | 6.6 | 94.8 | 80.9 | 51.2 | 21.9 | 6.6 | 8.76 | 2.84 | - | - |
| KMSG-35 | 25.4 | 6 | 501 | 18.3 | 18.2 | 26.2 | 19.2 | 12.0 | 6.2 | 81.7 | 63.5 | 37.3 | 18.2 | 6.2 | 14.40 | 4.19 | - | - |
| KMSG-36 | 25.4 | 4 | 502 | 10.7 | 15.2 | 28.1 | 25.5 | 14.2 | 6.3 | 89.3 | 74.1 | 46.0 | 20.5 | 6.3 | 10.85 | 3.57 | - | - |
| KMSG-37 | 25.4 | 2 | 502 | 10.1 | 11.8 | 27.0 | 26.4 | 16.3 | 8.4 | 89.9 | 78.0 | 51.0 | 24.7 | 8.4 | 9.53 | 3.66 | - | - |
| KMSG-38 | 25.4 | 8 | 321 | 11.4 | 15.1 | 31.5 | 22.0 | 13.2 | 6.9 | 88.6 | 73.5 | 42.0 | 20.0 | 6.9 | 11.20 | 3.62 | - | - |
| KMSG-39 | 25.4 | 6 | 321 | 6.8 | 14.8 | 31.1 | 26.5 | 14.4 | 6.4 | 93.2 | 78.3 | 47.3 | 20.8 | 6.4 | 9.59 | 3.06 | - | - |
| KMSG-40 | 25.4 | 4 | 321 | 24.2 | 21.8 | 27.1 | 15.4 | 8.4 | 3.1 | 75.8 | 54.0 | 26.9 | 11.6 | 3.1 | 20.09 | 4.08 | - | - |
| KMSG-41 | 25.4 | 2 | 323 | 14.7 | 21.6 | 29.4 | 19.1 | 10.9 | 4.3 | 85.3 | 63.7 | 34.3 | 15.1 | 4.3 | 14.28 | 3.61 | - | - |
| KMSG-42 | 19 | 8 | 501 | 2.8 | 5.9 | 24.1 | 30.7 | 24.5 | 12.1 | 97.2 | 91.3 | 67.3 | 36.5 | 12.1 | 5.91 | 2.82 | - | - |
| KMSG-43 | 19 | 7 | 501 | 1.8 | 3.9 | 21.5 | 32.0 | 27.9 | 12.9 | 98.2 | 94.3 | 72.8 | 40.8 | 12.9 | 5.31 | 2.71 | - | - |
| KMSG-44 | 19 | 6 | 501 | 1.8 | 3.1 | 17.4 | 26.5 | 31.3 | 19.9 | 98.2 | 95.1 | 77.7 | 51.2 | 19.9 | 4.31 | 2.98 | - | - |
| KMSG-45 | 19 | 5 | 502 | 1.9 | 3.3 | 16.8 | 26.8 | 31.2 | 20.1 | 98.1 | 94.9 | 78.1 | 51.3 | 20.1 | 4.26 | 2.90 | - | - |
| KMSG-46 | 19 | 4 | 502 | 2.7 | 6.7 | 21.1 | 29.5 | 27.8 | 12.2 | 97.3 | 90.5 | 69.5 | 40.0 | 12.2 | 5.69 | 2.84 | - | - |
| KMSG-47 | 19 | 3 | 502 | 3.5 | 4.2 | 21.1 | 29.4 | 28.8 | 13.0 | 96.5 | 92.3 | 71.2 | 41.8 | 13.0 | 5.52 | 2.94 | - | - |
| KMSG-48 | 19 | 2 | 502 | 5.7 | 7.0 | 23.2 | 28.3 | 24.9 | 10.9 | 94.3 | 87.3 | 64.0 | 35.8 | 10.9 | 6.73 | 3.26 | - | - |
| KMSG-49 | 19 | 5 | 454 | 0.6 | 2.3 | 18.9 | 33.3 | 31.2 | 13.7 | 99.4 | 97.1 | 78.2 | 44.9 | 13.7 | 4.72 | 2.49 | - | - |
| KMSG-50 | 19 | 5 | 403 | 2.4 | 4.8 | 21.1 | 31.7 | 27.1 | 12.9 | 97.6 | 92.8 | 71.8 | 40.1 | 12.9 | 5.45 | 2.77 | - | - |
| KMSG-51 | 19 | 8 | 319 | 1.2 | 2.8 | 18.3 | 32.7 | 30.4 | 14.7 | 98.8 | 96.0 | 77.7 | 45.1 | 14.7 | 4.73 | 2.59 | - | - |
| KMSG-52 | 19 | 7 | 319 | 1.2 | 2.3 | 16.8 | 32.8 | 30.4 | 16.5 | 98.8 | 96.6 | 79.7 | 46.9 | 16.5 | 4.49 | 2.65 | - | - |
| KMSG-53 | 19 | 6 | 319 | 0.5 | 1.5 | 18.0 | 33.9 | 30.2 | 16.0 | 99.5 | 98.0 | 80.0 | 46.1 | 16.0 | 4.47 | 2.53 | - | - |
| KMSG-54 | 19 | 5 | 319 | 2.2 | 4.6 | 20.1 | 30.9 | 26.9 | 15.2 | 97.8 | 93.1 | 73.0 | 42.1 | 15.2 | 5.17 | 2.90 | - | - |
| KMSG-55 | 19 | 4 | 319 | 3.8 | 4.2 | 19.2 | 32.6 | 27.7 | 12.5 | 96.2 | 92.0 | 72.8 | 40.2 | 12.5 | 5.65 | 2.98 | - | - |
| KMSG-56 | 19 | 3 | 319 | 2.4 | 4.3 | 19.5 | 27.3 | 29.9 | 16.4 | 97.6 | 93.2 | 73.7 | 46.4 | 16.4 | 4.89 | 2.95 | - | - |
| KMSG-57 | 19 | 2 | 319 | 4.7 | 6.7 | 24.2 | 29.8 | 23.6 | 11.0 | 95.3 | 88.6 | 64.4 | 34.6 | 11.0 | 6.55 | 3.05 | - | - |

***Table 4.9.*** Comparison of KM configuration, ASABE sieve mass percent, GMD by mass, and GMD by IA. (Continued)

| ID | KM Screen Size (mm) | Feed Rate (Kg/ min) | KM Speed (RPM) | Mass percent by screen size | | | | | | Cumulative undersize by screen size, % | | | | | GMD calculation by ASABE, mm | | GMD by IA (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 19 mm | 12.7 mm | 6.3mm | 3.96 mm | 1.17 mm | Pan | 19 mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm | GMD | STD | L | W |
| KMWS-1 | 50.8 | 5 | 508 | 15.8 | 16.6 | 25.5 | 21.9 | 16.1 | 4.0 | 84.2 | 67.5 | 42.0 | 20.1 | 4.0 | 14.40 | 4.59 | 2.41 | 61.24 |
| KMWS-2 | 50.8 | 7 | 508 | 12.1 | 14.1 | 23.6 | 26.2 | 19.4 | 4.6 | 87.9 | 73.8 | 50.2 | 24.0 | 4.6 | 11.55 | 4.22 | 2.24 | 56.77 |
| KMWS-3 | 50.8 | 9 | 508 | 12.9 | 16.8 | 25.2 | 28.3 | 14.4 | 2.5 | 87.1 | 70.3 | 45.1 | 16.8 | 2.5 | 13.52 | 3.98 | 2.33 | 59.18 |
| KMWS-4 | 50.8 | 5 | 328 | 14.4 | 15.3 | 22.6 | 27.3 | 17.2 | 3.1 | 85.6 | 70.2 | 47.6 | 20.4 | 3.1 | 13.36 | 4.36 | 2.32 | 58.80 |
| KMWS-5 | 50.8 | 7 | 330 | 12.6 | 13.1 | 27.4 | 27.8 | 16.4 | 2.7 | 87.4 | 74.3 | 46.9 | 19.1 | 2.7 | 12.73 | 4.02 | 2.50 | 63.37 |
| KMWS-6 | 50.8 | 5 | 248 | 14.7 | 21.7 | 24.9 | 23.1 | 13.5 | 2.2 | 85.3 | 63.6 | 38.7 | 15.7 | 2.2 | 15.47 | 4.13 | 2.34 | 59.44 |
| KMWS-7 | 50.8 | 7 | 245 | 13.5 | 20.2 | 26.1 | 25.1 | 13.2 | 1.8 | 86.5 | 66.2 | 40.1 | 15.0 | 1.8 | 14.83 | 3.94 | 2.24 | 56.92 |
| KMWS-8 | 50.8 | 5 | 403 | 13.4 | 16.5 | 27.5 | 24.3 | 15.0 | 3.3 | 86.6 | 70.1 | 42.6 | 18.2 | 3.3 | 13.61 | 4.13 | 2.30 | 58.45 |
| KMWS-9 | 50.8 | 7 | 403 | 17.0 | 20.2 | 25.2 | 22.4 | 13.0 | 2.1 | 83.0 | 62.7 | 37.5 | 15.0 | 2.1 | 16.76 | 4.38 | 2.45 | 62.28 |
| KMWS-10 | 50.8 | 5 | 458 | 17.0 | 17.3 | 26.9 | 22.3 | 14.4 | 2.1 | 83.0 | 65.7 | 38.8 | 16.5 | 2.1 | 16.15 | 4.44 | 2.33 | 59.21 |
| KMWS-11 | 50.8 | 7 | 458 | 10.2 | 17.5 | 27.2 | 28.3 | 14.5 | 2.2 | 89.8 | 72.3 | 45.1 | 16.7 | 2.2 | 12.53 | 3.59 | 2.30 | 58.52 |
| KMWS-12 | 12.7 | 3 | 463 | 0.0 | 0.4 | 2.9 | 29.6 | 52.1 | 14.9 | 100.0 | 99.6 | 96.7 | 67.1 | 14.9 | 3.38 | 2.08 | 0.69 | 17.45 |
| KMWS-13 | 12.7 | 3 | 463 | 0.4 | 0.6 | 5.3 | 32.8 | 46.5 | 14.4 | 99.6 | 99.1 | 93.8 | 60.9 | 14.4 | 3.69 | 2.24 | 0.69 | 17.53 |
| KMWS-14 | 12.7 | 3 | 502 | 0.0 | 0.3 | 1.7 | 27.3 | 53.9 | 16.8 | 100.0 | 99.7 | 98.1 | 70.8 | 16.8 | 3.17 | 2.06 | 0.67 | 17.09 |
| KMWS-15 | 12.7 | 3 | 401 | 0.0 | 0.3 | 4.2 | 34.1 | 48.9 | 12.5 | 100.0 | 99.7 | 95.5 | 61.4 | 12.5 | 3.69 | 2.05 | 0.62 | 15.85 |
| KMWS-16 | 12.7 | 3 | 323 | 0.0 | 0.3 | 3.1 | 30.3 | 49.9 | 16.3 | 100.0 | 99.7 | 96.6 | 66.2 | 16.3 | 3.35 | 2.13 | 0.62 | 15.80 |
| KMWS-17 | 12.7 | 3 | 264 | 0.1 | 0.1 | 3.2 | 32.9 | 49.4 | 14.4 | 99.9 | 99.8 | 96.6 | 63.7 | 14.4 | 3.51 | 2.09 | 0.63 | 16.05 |
| KMWS-18 | 25.4 | 5 | 504 | 1.5 | 3.9 | 17.4 | 36.3 | 33.4 | 7.4 | 98.5 | 94.6 | 77.2 | 40.9 | 7.4 | 5.58 | 2.51 | 1.24 | 31.52 |
| KMWS-19 | 25.4 | 7 | 504 | 3.7 | 5.2 | 23.0 | 33.2 | 28.3 | 6.6 | 96.3 | 91.1 | 68.1 | 34.9 | 6.6 | 6.74 | 2.94 | 1.27 | 32.33 |
| KMWS-20 | 25.4 | 5 | 467 | 4.6 | 5.0 | 25.7 | 36.5 | 23.8 | 4.4 | 95.4 | 90.3 | 64.7 | 28.2 | 4.4 | 7.71 | 2.94 | 1.26 | 32.05 |
| KMWS-21 | 25.4 | 5 | 402 | 3.5 | 7.5 | 25.8 | 32.8 | 24.2 | 6.1 | 96.5 | 89.0 | 63.1 | 30.4 | 6.1 | 7.22 | 2.77 | 1.24 | 31.57 |
| KMWS-22 | 25.4 | 5 | 339 | 3.0 | 4.8 | 23.8 | 37.7 | 25.1 | 5.6 | 97.0 | 92.2 | 68.4 | 30.7 | 5.6 | 6.76 | 2.52 | 1.26 | 31.88 |
| KMWS-23 | 25.4 | 4 | 339 | 5.7 | 9.4 | 27.7 | 32.2 | 20.7 | 4.3 | 94.3 | 84.9 | 57.2 | 25.0 | 4.3 | 8.39 | 2.76 | 1.26 | 32.00 |
| KMWS-24 | 25.4 | 3 | 339 | 4.6 | 7.4 | 21.7 | 32.4 | 28.3 | 5.6 | 95.4 | 88.0 | 66.3 | 33.9 | 5.6 | 7.09 | 2.88 | 1.25 | 31.62 |
| KMWS-25 | 25.4 | 2 | 339 | 7.0 | 9.8 | 24.2 | 31.1 | 23.3 | 4.6 | 93.0 | 83.2 | 58.9 | 27.9 | 4.6 | 8.35 | 2.95 | 1.26 | 31.88 |
| KMWS-26 | 25.4 | 5 | 253 | 2.6 | 4.6 | 28.7 | 37.2 | 23.3 | 3.6 | 97.4 | 92.8 | 64.1 | 26.9 | 3.6 | 7.25 | 2.32 | 1.27 | 32.36 |
| KMWS-27 | 25.4 | 4 | 499 | 4.5 | 6.3 | 25.4 | 35.8 | 22.7 | 5.3 | 95.5 | 89.2 | 63.8 | 28.1 | 5.3 | 7.47 | 2.72 | 1.27 | 32.21 |

***Table 4.9.*** Comparison of KM configuration, ASABE sieve mass percent, GMD by mass, and GMD by IA. (Continued)

| ID | KM Screen Size (mm) | Feed Rate (Kg/ min) | KM Speed (RPM) | Mass percent by screen size | | | | | | Cumulative undersize by screen size, % | | | | | GMD calculation by ASABE, mm | | GMD by IA (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 19 mm | 12.7 mm | 6.3mm | 3.96 mm | 1.17 mm | Pan | 19 mm | 12.7mm | 6.3mm | 3.96mm | 1.17mm | GMD | STD | L | W |
| KMWS-28 | 25.4 | 3 | 501 | 7.3 | 9.0 | 20.1 | 34.4 | 24.8 | 4.4 | 92.7 | 83.7 | 63.6 | 29.2 | 4.4 | 8.41 | 3.31 | 1.26 | 31.98 |
| KMWS-30 | 19 | 5 | 501 | 0.8 | 1.6 | 10.2 | 40.3 | 37.5 | 9.6 | 99.2 | 97.6 | 87.4 | 47.1 | 9.6 | 4.66 | 2.26 | 0.85 | 21.46 |
| KMWS-31 | 19 | 4 | 501 | 0.3 | 1.5 | 9.4 | 37.3 | 41.3 | 10.3 | 99.7 | 98.2 | 88.8 | 51.5 | 10.3 | 4.34 | 2.17 | 0.87 | 22.02 |
| KMWS-32 | 19 | 3 | 501 | 0.1 | 1.0 | 9.2 | 37.0 | 41.5 | 11.1 | 99.9 | 98.9 | 89.7 | 52.6 | 11.1 | 4.21 | 2.16 | 0.86 | 21.72 |
| KMWS-33 | 19 | 2 | 501 | 1.7 | 2.5 | 16.7 | 37.4 | 34.7 | 7.0 | 98.3 | 95.8 | 79.1 | 41.7 | 7.0 | 5.42 | 2.34 | 0.85 | 21.49 |
| KMWS-34 | 19 | 4 | 453 | 0.0 | 0.7 | 10.0 | 39.4 | 40.4 | 9.4 | 100.0 | 99.2 | 89.3 | 49.8 | 9.4 | 4.41 | 2.09 | 0.86 | 21.84 |
| KMWS-35 | 19 | 4 | 397 | 0.4 | 1.3 | 10.0 | 39.2 | 40.4 | 8.7 | 99.6 | 98.4 | 88.4 | 49.1 | 8.7 | 4.54 | 2.13 | 0.88 | 22.25 |
| KMWS-36 | 19 | 4 | 323 | 0.1 | 0.8 | 9.4 | 40.8 | 38.5 | 10.5 | 99.9 | 99.1 | 89.7 | 48.9 | 10.5 | 4.37 | 2.14 | 0.87 | 22.00 |
| KMWS-37 | 19 | 3 | 323 | 0.3 | 0.8 | 11.2 | 40.7 | 36.3 | 10.9 | 99.7 | 98.9 | 87.8 | 47.1 | 10.9 | 4.49 | 2.21 | 0.84 | 21.41 |
| KMWS-38 | 19 | 2 | 323 | 0.3 | 1.0 | 10.7 | 37.8 | 39.0 | 11.1 | 99.7 | 98.6 | 87.9 | 50.1 | 11.1 | 4.37 | 2.21 | 0.88 | 22.35 |
| KMWS-39 | 19 | 4 | 258 | 0.9 | 1.9 | 15.9 | 42.7 | 29.6 | 9.0 | 99.1 | 97.2 | 81.3 | 38.6 | 9.0 | 5.22 | 2.27 | 0.87 | 22.17 |

observations, the GMD calculation used in the IA could not be applied to the corn stover. Also, corn stover particles collected form the lower two sieves and dust pan contained significant amount of fine dusty particles compared with switchgrass and wheat straw based on observation.

*Chapter 5*

# CONCLUSIONS

Traditional sieving test provides fast analysis of particle size and size distributions. In this study, ASTM standard sieve test performed poorly in the test due to woven screen and vertical sieve motion. On the other hand, ASABE separator with relatively thick sieve construction and horizontal sieve motion performed superiorly than the ASTM standard separator. It suggested that construction of sieve analysis for biomass materials should be similar to the ASABE standard separator.

Switchgrass nodes particles could be separated after size reduction. Our test suggested that potential separation of biomass material, such as nodes, could be achieved based on slight differences in the physical properties. Switchgrass nodes could be separated from the particles during sieving by using knife mill equipped with larger screens, e.g. 50.8 mm or 25.4 mm screen used in knife mill. The results show that there are about 25 to 30 % mass with nodes presented on the 19.0 mm sieve as apposed to 17.5 % of average nodes population in the sample. On the contrary, switchgrass prepared by 12.7 mm knife mill yields less than 5 % of the mass with nodes on the same sieve.

IA shows great potential in the analysis of biomass particle. The size and size distribution of switchgrass, wheat straw, and corn stover can be analyzed by IA. This method is fast, easy, and low cost. Analysis by IA takes about 10 minutes per 50 samples compared with 1 to 2 hours by manual measuring individual particle dimensions depending

on the condition of the samples. The results show that the standard deviation of GMD calculated from IA ranges from 0.04 to 0.31 mm for switchgrass particles with GMD length from 24.93 to 95.64 mm. This IA method yields much better accuracy than the traditional sieving analysis. The IA provides far more detailed information about individual particle physical dimensions than traditional sieving test, which only yields the cumulative mass curve and an overall GMD. From the IA data, particle projected area, length, width, and perimeter could be obtained. Such detailed information could be used to calculate the volume, surface area, length/width ratio, etc. This would greatly facilitate the design of biomass particle handling equipments, fermentation units, and biofuel production units.

GMD calculated from the ASABE standard S424.1 may not be able to represent the actual particle size, due to the calculations using the sieve aperture dimensions instead of particle sizes. It is suggested that the standard summary statistics calculated by various consensus standards may not provide the greatest accuracy for the biomass. IA results suggested that a factor of 4 ~ 5 could be applied to the GMD calculated by sieving test to show the true particle GMD sizes for the grass-like biomass materials.

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# APPENDIX

MACRO CODE

```
macro "Size Distribution Image Processing Tool 1" {
	requires("1.30k");
	run("Open...");
	conversionTo8bit();
      response();
	processCal();
	final();
}


function conversionTo8bit() {
	run("8-bit");
}


function response () {
	requires("1.34m");
	flag = 0;
	title = "Confirm";
	lowT = 10;
	highT = 254;
	setThreshold(lowT, highT);
	while (flag!=1) {
		Dialog.create("Adjust Threshold Limits");
		Dialog.addMessage("Adjust Threshold Limits and press OK");
		Dialog.addMessage("When done check the Exit box and press OK");
		Dialog.addNumber("Low:", lowT);
		Dialog.addNumber("High:", highT);
		Dialog.addCheckbox("Exit:", false);
		Dialog.show();
		lowT = Dialog.getNumber();
		highT = Dialog.getNumber();
		out = Dialog.getCheckbox();
		if (out==true) flag = 1;
		setThreshold(lowT, highT);
	};
	setThreshold(lowT, highT);
}


function processCal() {
	run("Apply LUT");
```

```
	run("Analyze Particles...", "minimum=100 show=Outlines display clear summarize
size");
}

function final() {
	requires("1.34m");
	Dialog.create("Process Status");
	Dialog.addMessage("Image Processing Completed");
	Dialog.addMessage("Press OK and save the required files");
	Dialog.show();
}
```

# ANSI/ASAE S424.1 DEC01
# Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening



**American Society of Agricultural Engineers**

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**2950 Niles Rd., St. Joseph, MI 49085-9659, USA ph. 269-429-0300, fax 269-429-3852, hq@asae.org**

ANSI/ASAE S424.1 DEC01
Approved JUN 1988; revision approved SEP 1992; reaffirmed MAR 1998 by American National Standards Institute

# Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening

*Developed by the ASAE Forage Harvesting and Utilization Committee; approved by the ASAE Power and Machinery Division Standards Committee; adopted by ASAE April 1986; revised editorially March 1988; approved as an American National Standard June 1988; revised March 1992; revision approved by ANSI September 1992; reaffirmed by ASAE December 1996; reaffirmed by ANSI March 1998; reaffirmed by ASAE for five years December 2001.*

## 1 Purpose and scope

**1.1** The purpose of this Standard is to define a test procedure to determine the particle size distribution of chopped forage materials and to define a method of expressing the particle length of the material. The determined particle size distribution can be used to evaluate forage harvesting machine and handling equipment variables and to define forage physical length in animal feeding trials.

**1.2** This Standard shall be used to determine the particle size of chopped forage materials where the reduction process yields particles such as that material produced by shear-bar type forage harvesters. It is not intended for use on material produced by flail-type harvesters where substantial fractions of the material may be extremely long.

**1.3** This Standard is intended for use in the field as well as in the laboratory. It is intended to separate chopped forage samples without drying them first.

## 2 Test equipment

**2.1** For particle measuring purposes, a set of square-hole screens having widths of 406 mm (16.0 in.) lengths of 565 mm (22.25 in.) and specifications shown in Table 1 shall be used. The screens shall be supported in frames with depths of 63.5 mm (2.50 in.) and arranged horizontally in a stack such that the screen with the largest opening size is at the top. Those with smaller openings shall be arranged with progressively smaller hole sizes below each other. If screens with different size openings from those listed in Table 1 are used, the actual dimensions for the openings shall be used in the data analysis and shall be reported. Pertinent screening dimensions should be in geometric progression with the smallest selected to be appropriate to the particle size spectrum of the sample.

**2.2** A suitable screen shaker is required. The shaker shall oscillate the screen stack in a horizontal plane. The center of one end of the screen stack shall oscillate in a straight horizontal line on a slider block. The opposite end of the screen stack shall be supported on horizontal crank arms, the crank end centers of which are located 765.2 mm (30.12 in.) from the center of the slider block pivot located on the other end of the screen stack. The centers of the arms shall travel in a horizontal circle with a diameter of 117 mm (4.62 in.) (see Figs. 1 and 2).

NOTE: Information on plans for constructing such a screen shaker may be obtained from the American Society of Agricultural Engineers.

**2.3** The screen shaker shall drive the screen stack at a frequency of 2.4 $\pm$ 0.08 $H_z$(144$\pm$5/cycles/min).

**2.4** The shaker should be operated with the screens level.

**2.5** A weighing balance having an accuracy of at least $\pm$ 0.5 g shall be used for weighing the fractions.

**Table 1 – Dimensions of square-hole screens for testing purposes**

| Screen no. | Nominal size opening | | Square hole diagonal | | Screen thickness | | Open area |
|---|---|---|---|---|---|---|---|
| | mm | in. | mm | in. | mm | in. | % |
| 1 | 19.0 | 0.75 | 26.9 | 1.06 | 12.7 | 0.50 | 45 |
| 2 | 12.7 | 0.50 | 18.0 | 0.71 | 9.6 | 0.38 | 33 |
| 3 | 6.3 | 0.25 | 8.98 | 0.35 | 4.8 | 0.19 | 33 |
| 4 | 3.96 | 0.156 | 5.61 | 0.22 | 3.1 | 0.12 | 39 |
| 5* | 1.17 | 0.046 | 1.65 | 0.065 | 0.64 | 0.025 | 41.5 |
| Pan | — | — | — | — | — | — | — |

*14 mesh woven wire cloth with 0.64 mm (0.025 in.) diameter wires. All others are aluminum sheets or plates.

## 3 Method of screening

**3.1** Uncompressed samples of 9 to 10 L of forage should be used. Samples of 2 to 3 L of material may be used if extra care is taken to recover the material from each screen. For field work, the larger samples are usually preferred. The sample volume size should be reported with the data.

**3.2** Place the sample on the top of the sample feeder (near the closed end) above the top screen of the screen set and operate the shaker for 120 s.

**3.3** The tapered louvers on the feeder should be preset to feed the sample to the top screen in 20 to 30 s. The louvers may be inclined to change the feeding time. This adjustment is made using successive trials with practice samples similar to the crop material to be evaluated for particle size distribution.

**3.4** Material on each screen and bottom pan shall be weighed and recorded.

**3.5** If the amount retained on the top screen exceeds 1% of the total sample mass, representative subsamples should be obtained from this screen and measured manually. The average length may then be used in the data analysis as geometric mean length, $\bar{X}_1$.

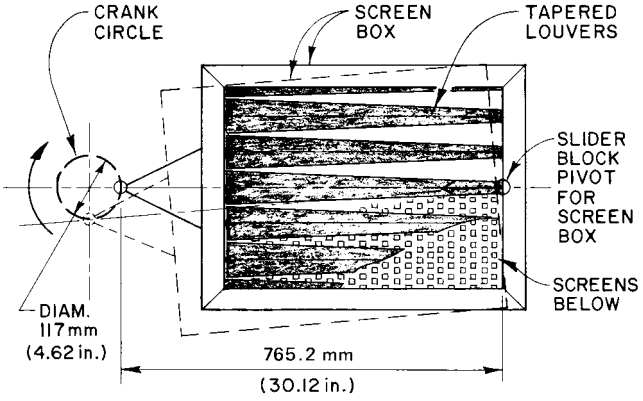



**Figure 1 – Top view of forage particle separator showing screen motion land and feeder position**

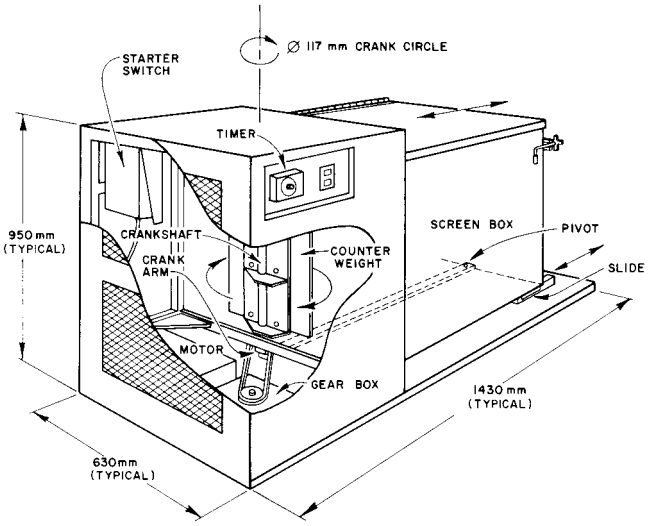



**Figure 2 – Schematic diagram of forage particle separator**

**3.6** The screening process should be repeated to produce 3 sets of data. These data sets may be averaged or analyzed separately with the procedure specified in the report.

**3.7** A representative sample of the unscreened material shall be used for moisture content determination. Moisture content (wet basis) shall be reported along with particle size data.

**3.8** Screen openings must be kept free of forage particles so that effective screening can be accomplished. A stiff bristle cleaning brush, or compressed air, is useful for cleaning screens which have become clogged with forage particles. Screens may need to be cleaned periodically to remove plant residue materials. Plant residues may be removed by washing with water containing a detergent. Screens and the particle separator must be air dried before use.

**3.9** If static electricity becomes a problem when separating dry forage materials, liquid laundry static control may lightly be sprayed onto the sample before separating.

**3.10** If separation problems occur due to high crop moisture levels, samples can be dried in a low temperature oven (65 °C) to a target moisture of approximately 50% moisture wet basis before separating.

## 4 Data analysis

**4.1** Analysis of mass distribution of all chopped forage materials is based on the assumption that these distributions are logarithmic normally distributed.

### 4.2 Calculation of particle size

**4.2.1** The size of particles shall be reported in terms of geometric mean length, $X_{gm}$, and standard deviation, $S_{gm}$, by mass.

**4.2.2** Calculated values are obtained as follows:

$$X_{gm} = \log^{-1} \frac{\Sigma(M_i \log \bar{x}_i)}{\Sigma M_i} \quad (1)$$

$$S_{gm} = \log^{-1}\left[\frac{\Sigma M_i(\log \bar{X}_i - \log X_{gm})^2}{\Sigma M_i}\right]^{1/2} \quad (2)$$

where

$X_i$ = diagonal of screen openings of the $i^{th}$ screen
$X_{(i-1)}$ = diagonal of screen openings in next larger than the $i^{th}$ screen (just above in a set)
$X_{gm}$ = geometric mean length
$\bar{X}_i$ = geometric mean length of particles on $i^{th}$ screen $= [X_i \times X_{i-1}]^{1/2}$
$M_i$ = mass on $i^{th}$ screen (actual mass at the conditions of screening or percent of total; decimal or percent form)
$S_{gm}$ = standard deviation

NOTE: $\bar{X}_i$ is measured manually as described in paragraph 3.5. If it is less than 1% of the total, it is treated as zero.

**4.2.3** Material passing through screen No. 5 and collected in the pan shall be considered to have a geometric mean length of 0.82 mm (0.0325 in.). This becomes $\bar{X}_6$ in equations [1] and [2].

**4.2.4** An example of how the equations may be used to find geometric mean particle length and standard deviation for a sample data set follows:

**Percent mass distribution of a chopped alfalfa sample**

| Screen no. | Screen diagonal, mm | Percent total mass on screens, % | Cumulative undersize, % |
|---|---|---|---|
| 1 | 26.9 | 3.8 | 96.2 |
| 2 | 18.0 | 8.1 | 88.1 |
| 3 | 8.98 | 25.1 | 63.0 |
| 4 | 5.61 | 26.9 | 36.1 |
| 5 | 1.65 | 34.2 | 1.9 |
| Pan | ___ | 1.9 | ___ |
| | | 100.0 | |

The average measured length of the particles on the top screen (No. 1) was 48 mm. This becomes $\bar{X}_1$ in equations [1] and [2]. Equation [3] and the above information are used to obtain the following mean lengths for particles in each fraction:

$\bar{X}_1 = 48$
$\bar{X}_2 = (18.0 \times 26.9)^{1/2} = 22.0$
$\bar{X}_3 = (8.98 \times 18.0)^{1/2} = 12.7$
$\bar{X}_4 = (5.61 \times 8.98)^{1/2} = 7.10$
$\bar{X}_5 = (1.65 \times 5.61)^{1/2} = 3.04$
$\bar{X}_6 = 0.82$

Equations [1] and [2] are used to obtain

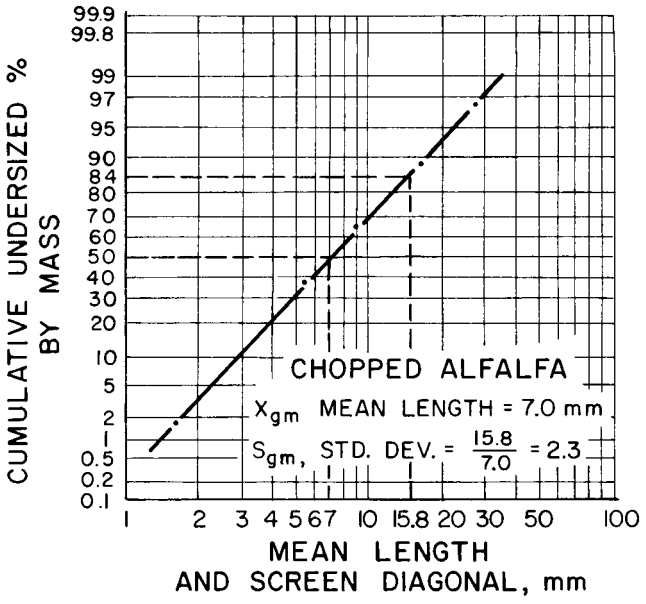



**Figure 3 – Cumulative percent undersized particles versus screen diagonal opening size for alfalfa for graphic determination of mean length and standard deviation**

$$X_{gm} = \log^{-1}\left[\frac{0.038\ \log(48) + 0.081\ \log(22) + 0.251\ \log(12.7) + 0.269\ \log(7.1) + 0.342\ \log(3.04) + 0.019\ \log(0.82)}{0.038 + 0.081 + 0.251 + 0.269 + 0.342 + 0.019}\right] = 6.95 \text{ mm}$$

$$S_{gm} = \log^{-1}\left[\frac{0.038\left[\log\left(\frac{48}{6.95}\right)\right]^2 + 0.081\left[\log\left(\frac{22}{6.95}\right)\right]^2 + 0.251\left[\log\left(\frac{12.7}{6.95}\right)\right]^2 + 0.269\left[\log\left(\frac{7.1}{6.95}\right)\right]^2 + 0.342\left[\log\left(\frac{3.04}{6.95}\right)\right]^2 + 0.019\left[\log\left(\frac{0.82}{6.95}\right)\right]^2}{0.038 + 0.081 + 0.251 + 0.269 + 0.342 + 0.019}\right]^{1/2}$$

$$= 2.26$$

**4.2.5** Graphical solutions for geometric mean length and standard deviation may be obtained by plotting the results on logarithmic normal probability graph paper. Fig. 3 shows an example of a plot of the data from paragraph 4.2.4

where

$X_{gm}$ = $X_{50}$ = particle length at 50% probability
$S_{gm}$ = $X_{84}/X_{50}$ = standard deviation
$X_{84}$ = particle length at 84% cumulative probability

## References


1. Finner, M. F., J. E. Hardzinski and L. L. Pagel, 1978. Evaluating particle length of chopped forages. ASAE Paper No. 78-1047. St. Joseph. MI: ASAE.
2. Stockham, J. D. and E. G. Fochtman. 1977. Particle size analysis. Ann Arbor Science Pub., Inc.

Designation: E 11 – 95

# Standard Specification for Wire Cloth and Sieves for Testing Purposes[1]

This standard is issued under the fixed designation E 11; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This specification covers the requirements for design and construction of testing sieves using a medium of woven wire cloth mounted in a frame for use in testing for the classification of materials according to designated particle size (See Notes 1 and 2), and wire cloth, meeting the specifications of Table 1, to be designated test grade wire cloth. All subsequent references to wire cloth shall mean test grade wire cloth. Methods for checking testing sieves and wire cloth for conformance to this specification are included in the annex.

NOTE 1—Complete instructions and procedures on the use and calibration of testing sieves are contained in *ASTM STP447B*.[2] Note that sieve analysis results from two testing sieves of the same sieve designation may not be the same because of the variances in sieve opening permitted by this specification. To minimize the differences in sieve analysis results, the use of testing sieves matched on a performance basis is suggested. *ASTM STP447B*[2] also contains a list of all published ASTM standards on sieve analysis procedures for specific materials or industries. This list may be referenced to obtain statements of precision and bias for sieve analysis of specific materials.

NOTE 2—For other types of sieves, see Specification E 323 and Specification E 161.

1.2 The values stated in SI units shall be considered standard for the dimensions of the wire cloth openings and the diameter of the wires used in the wire cloth. The values stated in inch-pound units shall be considered standard with regard to the sieve frames.

1.3 The following precautionary statement refers only to the test method portion, Annex A1, of this specification: *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*

C 430 Test Method for Fineness of Hydraulic Cement by the 45-μm No. 325 Sieve[3]

E 161 Specification for Precision Electroformed Sieves (Square-Opening Series)[4]

E 323 Specification for Perforated-Plate Sieves for Testing Purposes[4]

E 437 Specifications for Industrial Wire Cloth and Screens (Square Opening Series)[4]

2.2 *Federal Standard:*

Fed. Std. No. 123 Marking for Shipment (Civil Agencies)[5]

2.3 *Military Standard:*

MIL-STD-129 Marking for Shipment and Storage[5]

## 3. Ordering Information

3.1 Orders for items under this specification include the following information as necessary:

3.1.1 Name of material (U.S.A. Standard Testing Sieves or U.S.A. Standard sieve cloth),

3.1.2 ASTM designation and year of issue (ASTM E 11 – 95),

3.1.3 Quantity of each item,

3.1.4 Standard sieve designation (see Table 1, Column 1),

3.1.5 Alternative sieve designation if needed (see Table 1, Column 2),

3.1.6 For testing sieves in standard circular frames:

3.1.6.1 Nominal sieve frame diameter (see 5.2 and 5.3),

3.1.6.2 Nominal sieve frame height (see Table 2),

3.1.7 For sieve cloth not in frames or in nonstandard frames:

3.1.7.1 Lateral dimensions of sieve cloth,

3.1.7.2 Description of nonstandard frame,

3.1.8 For U.S. Government purchases, if supplementary requirements apply,

3.1.9 Compatible sieve pans and covers, and

3.1.10 Special requirements (specific type of metal for sieve cloth and frames, matched sieves, for example).

## 4. Sieve Cloth Requirements

4.1 Wire cloth used in U.S.A. standard testing sieves meeting the specifications shown in Table 1 shall be designated "test grade". Test grade sieve cloth shall be woven from stainless steel, brass, bronze, or other suitable wire with a plain weave, except that cloth with openings of 63 μm (No. 230) and finer may be woven with a twill weave. For definitions of "plain" and "twill" weave, refer to Specification E 437. The wire shall not be coated or plated.

4.2 The openings of the sieve cloth of successive sieves progress from a base of 1 mm in the ratio of approximately $4\sqrt{2}:1$.

4.3 All measurements of openings and wire diameters

[1] This specification is under the jurisdiction of ASTM Committee E-29 on Particle Size Measurement and is the direct responsibility of Subcommittee E29.01 on Sieves, Sieving Methods, and Screening Media.

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[2] *Manual on Testing Sieving Methods, ASTM STP 447B.* Available from ASTM Headquarters.

[3] *Annual Book of ASTM Standards,* Vol 04.01.

[4] *Annual Book of ASTM Standards,* Vol 14.02.

[5] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

**TABLE 1 Nominal Dimensions, Permissible Variations for Wire Cloth of Standard Test Sieves (U.S.A.) Standard Series**

| Sieve Designation | | Nominal Sieve Opening, in.[B] | Permissible Variation of Average Opening from the Standard Sieve Designation | Opening Dimension Exceeded By Not More Than 5 % of the Openings | Maximum Individual Opening | Nominal Wire Diameter, mm[C] |
|---|---|---|---|---|---|---|
| Standard[A] | Alternative | | | | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| 125 mm | 5 in. | 5 | ±3.70 mm | 130.0 mm | 130.9 mm | 8.00 |
| 106 mm | 4.24 in. | 4.24 | ±3.20 mm | 110.2 mm | 111.1 mm | 6.30 |
| 100 mm[D] | 4 in.[D] | 4 | ±3.00 mm | 104.0 mm | 104.8 mm | 6.30 |
| 90 mm | 3½ in. | 3.5 | ±2.70 mm | 93.6 mm | 94.4 mm | 6.30 |
| 75 mm | 3 in. | 3 | ±2.20 mm | 78.1 mm | 78.7 mm | 6.30 |
| 63 mm | 2½ in. | 2.5 | ±1.90 mm | 65.6 mm | 66.2 mm | 5.60 |
| 53 mm | 2.12 in. | 2.12 | ±1.60 mm | 55.2 mm | 55.7 mm | 5.00 |
| 50 mm[D] | 2 in.[D] | 2 | ±1.50 mm | 52.1 mm | 52.6 mm | 5.00 |
| 45 mm | 1¾ in. | 1.75 | ±1.40 mm | 46.9 mm | 47.4 mm | 4.50 |
| 37.5 mm | 1½ in. | 1.5 | ±1.10 mm | 39.1 mm | 39.5 mm | 4.50 |
| 31.5 mm | 1¼ in. | 1.25 | ±1.00 mm | 32.9 mm | 33.2 mm | 4.00 |
| 26.5 mm | 1.06 in. | 1.06 | ±.800 mm | 27.7 mm | 28.0 mm | 3.55 |
| 25.0 mm[D] | 1.00 in.[D] | 1 | ±.800 mm | 26.1 mm | 26.4 mm | 3.55 |
| 22.4 mm | ⅞ in. | 0.875 | ±.700 mm | 23.4 mm | 23.7 mm | 3.55 |
| 19.0 mm | ¾ in. | 0.750 | ±.600 mm | 19.9 mm | 20.1 mm | 3.15 |
| 16.0 mm | ⅝ in. | 0.625 | ±.500 mm | 16.7 mm | 17.0 mm | 3.15 |
| 13.2 mm | 0.530 in. | 0.530 | ±.410 mm | 13.83 mm | 14.05 mm | 2.80 |
| 12.5 mm[D] | ½ in.[D] | 0.500 | ±.390 mm | 13.10 mm | 13.31 mm | 2.50 |
| 11.2 mm | 7/16 in. | 0.438 | ±.350 mm | 11.75 mm | 11.94 mm | 2.50 |
| 9.5 mm | ⅜ in. | 0.375 | ±.300 mm | 9.97 mm | 10.16 mm | 2.24 |
| 8.0 mm | 5/16 in. | 0.312 | ±.250 mm | 8.41 mm | 8.58 mm | 2.00 |
| 6.7 mm | 0.265 in. | 0.265 | ±.210 mm | 7.05 mm | 7.20 mm | 1.80 |
| 6.3 mm[D] | ¼ in.[D] | 0.250 | ±.200 mm | 6.64 mm | 6.78 mm | 1.80 |
| 5.6 mm | No. 3½[E] | 0.223 | ±.180 mm | 5.90 mm | 6.04 mm | 1.60 |
| 4.75 mm | No. 4 | 0.187 | ±.150 mm | 5.02 mm | 5.14 mm | 1.60 |
| 4.00 mm | No. 5 | 0.157 | ±.130 mm | 4.23 mm | 4.35 mm | 1.40 |
| 3.35 mm | No. 6 | 0.132 | ±.110 mm | 3.55 mm | 3.66 mm | 1.25 |
| 2.80 mm | No. 7 | 0.110 | ±.095 mm | 2.975 mm | 3.070 mm | 1.12 |
| 2.36 mm | No. 8 | 0.0937 | ±.080 mm | 2.515 mm | 2.600 mm | 1.00 |
| 2.00 mm | No. 10 | 0.0787 | ±.070 mm | 2.135 mm | 2.215 mm | 0.900 |
| 1.7 mm | No. 12 | 0.0661 | ±.060 mm | 1.820 mm | 1.890 mm | 0.800 |
| 1.4 mm | No. 14 | 0.0555 | ±.050 mm | 1.505 mm | 1.565 mm | 0.710 |
| 1.18 mm | No. 16 | 0.0469 | ±.045 mm | 1.270 mm | 1.330 mm | 0.630 |
| 1.00 mm | No. 18 | 0.0394 | ±.040 mm | 1.080 mm | 1.135 mm | 0.560 |
| 850 µm[F] | No. 20 | 0.0331 | ±35 µm | 925 µm | 970 µm | 0.500 |
| 710 µm | No. 25 | 0.0278 | ±30 µm | 775 µm | 815 µm | 0.450 |
| 600 µm | No. 30 | 0.0234 | ±25 µm | 660 µm | 695 µm | 0.400 |
| 500 µm | No. 35 | 0.0197 | ±20 µm | 550 µm | 585 µm | 0.315 |
| 425 µm | No. 40 | 0.0165 | ±19 µm | 471 µm | 502 µm | 0.280 |
| 355 µm | No. 45 | 0.0139 | ±16 µm | 396 µm | 426 µm | 0.224 |
| 300 µm | No. 50 | 0.0117 | ±14 µm | 337 µm | 363 µm | 0.200 |
| 250 µm | No. 60 | 0.0098 | ±12 µm | 283 µm | 306 µm | 0.160 |
| 212 µm | No. 70 | 0.0083 | ±10 µm | 242 µm | 263 µm | 0.140 |
| 180 µm | No. 80 | 0.0070 | ±9 µm | 207 µm | 227 µm | 0.125 |
| 150 µm | No. 100 | 0.0059 | ±8 µm | 174 µm | 192 µm | 0.100 |
| 125 µm | No. 120 | 0.0049 | ±7 µm | 147 µm | 163 µm | 0.090 |
| 106 µm | No. 140 | 0.0041 | ±6 µm | 126 µm | 141 µm | 0.071 |
| 90 µm | No. 170 | 0.0035 | ±5 µm | 108 µm | 122 µm | 0.063 |
| 75 µm | No. 200 | 0.0029 | ±5 µm | 91 µm | 103 µm | 0.050 |
| 63 µm | No. 230 | 0.0025 | ±4 µm | 77 µm | 89 µm | 0.045 |
| 53 µm | No. 270 | 0.0021 | ±4 µm | 66 µm | 76 µm | 0.036 |
| 45 µm | No. 325 | 0.0017 | ±3 µm | 57 µm | 66 µm | 0.032 |
| 38 µm | No. 400 | 0.0015 | ±3 µm | 48 µm | 57 µm | 0.030 |
| 32 µm | No. 450 | 0.0012 | ±3 µm | 42 µm | 50 µm | 0.028 |
| 25 µm[D] | No. 500 | 0.0010 | ±3 µm | 34 µm | 41 µm | 0.025 |
| 20 µm[D] | No. 635 | 0.0008 | ±3 µm | 29 µm | 35 µm | 0.020 |

[A] These standard designations correspond to the values for test sieve openings recommended by the International Standards Organization, Geneva, Switzerland, except where noted.

[B] Only approximately equivalent to the metric values in Column 1.

[C] The average diameter of the wires in the x and y direction, measured separately, of any wire cloth shall not deviate from the nominal values by more than ±15 %.

[D] These sieves are not in the standard series but they have been included because they are in common usage.

[E] These numbers (3½ to 635) are the approximate number of openings per linear in. but it is preferred that the sieve be identified by the standard designation in millimetres or micrometres.

[F] 1000 µm—1 mm.

shall be made along the midpoints of the opening as shown in Fig. 1.

4.4 Sieve cloth shall conform to the dimensional requirements of Table 1. The average opening (distance between parallel wires measured at the center of the opening), in the *x* (horizontal) and *y* (vertical) directions measured separately, shall conform to the values in Column 1, within the permissible variation in average opening size shown in Column 4. Not more than 5 % of the openings shall exceed the value shown in Column 5. The maximum individual

**TABLE 2 Dimensions of Standard Frames**

| Nominal Diameter, in. | Mean Diameter, in. (mm) | | Typical Frame[A] |
|---|---|---|---|
| | Inside at Top[B] | Outside on Skirt | Nominal Height[C] in. (mm) |
| 3 | 3.000 + 0.030/−0.000 | 3.000 + 0.000/−0.030 | 1¼ (32) FH[D] |
| | (76 + 0.76/ −0.00) | (76 + 0.00/ −0.76) | ⅝ (16) HH |
| 6 | 6.000 + 0.030/−0.000 | 6.000 + 0.000/−0.030 | 1¾ (45) FH |
| | (152 + 0.76/ −0.00) | (152 + 0.00/ −0.76) | 1 (25) HH |
| 8 | 8.000 + 0.030/−0.000 | 8.000 + 0.000/−0.030) | 2 (50) FH |
| | (203 + 0.76/ −0.00 | (203 + 0.00/ −0.76) | 1 (25) HH |
| 10 | 10.000 + 0.030/−0.000 | 10.000 + 0.000/−0.030 | 3 (76) FH |
| | (254 + 0.76/ −0.00) | (254 + 0.00/ −0.76) | 1½ (38) HH |
| 12 | 12.000 + 0.030/−0.000 | 12.000 + 0.000/−0.030 | 3¼ (83) FH |
| | (305 + 0.76/ −0.00) | (305 + 0.00/ −0.76) | 2 (50) IH |
| | | | 1⅝ (41) HH |

[A] Other frame heights are not precluded.
[B] Measured 0.2 in. (5 mm) below the top of the frame.
[C] Distance from the top of the frame to the sieve cloth surface.
[D] FH = full height; HH = half height; IH = intermediate height.

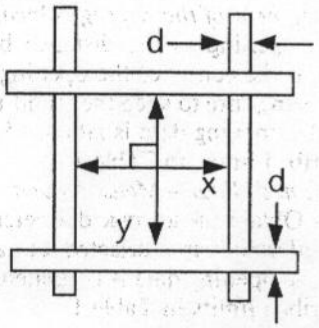



**FIG. 1 Proper Dimensioning of Wire Cloth Mesh**

opening size shall not exceed the value shown in Column 6.

4.4.1 The average diameter of the $x$ (horizontal) and $y$ (vertical) wires, measured separately, shall conform to the diameter in Column 7 within the tolerances in Footnote A of Table 1.

4.5 Wires shall be crimped in such a manner that they will be rigid when in use.

4.6 There shall be no punctures or obvious defects in the cloth.

## 5. Test Sieve Frames

5.1 *General Requirements*—Frames for wire cloth sieves shall be constructed in such a manner as to be rigid. The wire cloth shall be mounted on the frame without distortion, looseness, or waviness. To prevent the material being sieved from catching in the joint between the wire cloth and the frame, the joint shall be filled smoothly or constructed so that the material will not be trapped.

5.2 *Standard Frames*—Sieve frames shall be circular with nominal diameters of 3, 6, 8, 10, or 12 in. (76, 152, 203, 254, or 305 mm) as may be specified. The dimensions shall conform to the requirements in Table 2. Frames shall be made from noncorrosive material such as brass or stainless steel and be of seamless construction.

5.2.1 The bottom of the frame shall be constructed so as to provide an easy sliding fit with any sieve frame of the same nominal diameter conforming to the specified dimensions.

5.2.2 The joint or fillet at the connection of the sieve cloth to the frame will provide a minimum clear sieving surface with a diameter equal to the nominal diameter less 0.5 in. (13 mm).

NOTE 3—Attention is called to Test Method C 430, which contains requirements for 2 in. (51 mm) diameter sieves used in the mineral industry, especially the cement group.

5.3 *Nonstandard Frames*—Other sieve frames may be either square, rectangular, or circular. The frame may have the sieve cloth permanently installed, or may be designed to permit replacement. The provisions of 5.1 apply.

NOTE 4—While there are no requirements for nesting of nonstandard sieve frames, care should be applied in use to prevent loss of material during analysis.

5.4 *Pans and Covers*—Pans and covers for use with sieves shall be made so as to nest with the sieves. Pans with extended rims ("stacking skirts") shall be furnished when specified. The pans and covers shall conform to the dimensions in Table 2.

## 6. Product Marking

6.1 Each test sieve shall bear a label marked with the following information:

6.1.1 U.S.A. standard testing sieve,

6.1.2 This designation (ASTM E-11),

6.1.3 Standard sieve designation (from Table 1, Column 1),

6.1.4 Name of manufacturer or distributor, and

6.1.5 Alternative sieve designation (from Table 1, Column 2) (optional).

## 7. Keywords

7.1 opening; particle size; sieve; sieve analysis; sieve cloth; sieve designation; test grade wire cloth; test sieve

## SUPPLEMENTARY REQUIREMENTS

The following supplementary requirements shall apply only when specified by the purchaser in the contract or order.

## S1. Responsibility for Inspection

S1.1 Unless otherwise specified in the contract or purchase order, the producer is responsible for the performance of all inspection and test requirements specified herein. Except as otherwise specified in the contract or order, the producer may use his own or any other suitable facilities for the performance of the inspection and test requirements specified herein, unless disapproved by the purchaser. The purchaser shall have the right to perform any of the inspections and tests set forth in this specification where such inspections are deemed necessary to ensure that materials meet the specification.

## S2. Government Procurement

S2.1 Unless otherwise specified in the contract, the materials shall be packaged in accordance with the suppliers'

standard practice that will be acceptable to the carrier at lowest rates. Containers and packing shall comply with the Uniform Freight Classification rules or National Motor Freight Classification rules. Marking for shipment of such materials shall be in accordance with Fed. Std. No. 123 for civil agencies, and MIL-STD-129 for military agencies.

## ANNEX

**(Mandatory Information)**

## A1. TEST METHODS FOR CHECKING WIRE CLOTH AND TESTING SIEVES TO DETERMINE WHETHER THEY CONFORM TO SPECIFICATION

A1.1 Every opening in the metal wire cloth in a test sieve shall be eligible for inspection for compliance with the requirements listed in Table 1.

A1.1.1 When a sieve has 30 openings or less, measure all openings. In other cases the examination shall proceed in stages from a survey of general condition, to a methodical scrutiny of individual openings, and finally to measurement of opening size for compliance with the tolerances.

A1.1.2 Measure opening size, as described in Test Methods Two, Three, and Four, on equipment with a precision of at least 2.5 μm or 10 % of the value in Column 4 for the specific mesh designation, whichever is greater.

A1.2 *Test Method One—Examination of General Condition of the Wire Cloth*—For this purpose, view the sieve cloth against a uniformly illuminated background. If obvious deviations, for example, weaving defects, creases, wrinkles, foreign matter in the cloth, are found, the wire cloth is unacceptable.

A1.3 *Test Method Two—Examination for Maximum Individual Opening*—The observer shall carefully and methodically examine the appearance of all the openings, in order to detect oversize openings. Openings whose width deviates by about 10 % of the average value are apparent to the unaided eye of a skilled observer. By this test method, known as the "handicap method", it is probable that all oversize openings exceeding the average value by about 10 % or more will be detected. At the same time it is easily possible to detect sequences of large openings, and local irregularities in the weaving, appearing as distortions in the openings. If an opening is found to be larger than that permissible in accordance with Column 6 of Table 1, the wire cloth is unacceptable.

A1.4 *Test Method Three—Determination of the Size Distribution of Wire Cloth Openings*—To establish the size distribution of sieve openings, determine the frequency of opening size measurements using the following procedures:

A1.4.1 For samples (testing sieves or wire cloth) with 30 or less openings, measure all full openings. For samples with over 30 openings, measure a minimum of 30 full openings.

A1.4.2 Select openings in a line or lines diagonal to the direction of the wires according to Fig. A1.1, and measure ten adjacent openings along each line. When greater numbers of openings are available, choose the fields in such a manner that none of the openings being measured overlap.

A1.4.3 *Measurement of the Average Opening Size*—Measure the average opening as the distance between parallel wires (measured at the center of the opening—see Fig. 1) in both directions, being sure to keep the $x$ and $y$ measurements separate. Once the opening data is tabulated, check the data versus the prescribed limits in Table 1.

A1.5 *Test Method Four—Measurement of the Average Wire Diameter*—Obtain the average diameter of the wires by measuring 30 different wires selected at random in each direction. Once the opening data is tabulated, check the data versus the prescribed limits in Table 1.

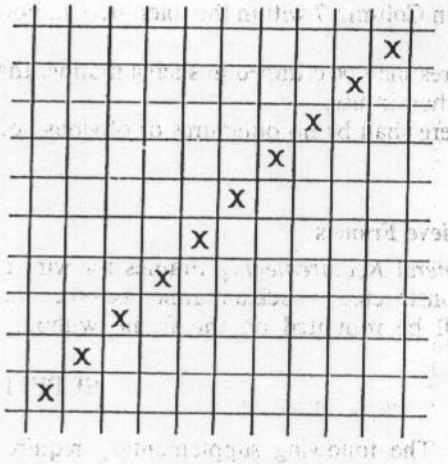


**FIG. A1.1 Orientation of Openings to be Measured in Each Field**

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# VITA

Yuechuan Yang was born on Dec. 2, 1978 in Chengdu, China. He attended No. 7 High School and graduated in June 1997. He then pursued a Bachelor of Science degree in Civil Engineering at Hunan University, China. After completing his degree at Hunan University in July 2001, He joined a working group in Chengdu Municipal Engineering Company and worked there as a project engineer. By July 2002, he attended University of Tennessee for advanced degree.