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Original Article

Preprocessing *Miscanthus sacchariflorus* with Combination System of Cone Grinder and Air Classifier[1]

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ABSTRACT

Considerable differences exist in the characteristics of size reduction and classification because of biomass species. *Miscanthus sacchariflorus* (*M. sacchariflorus*) Goedae-Uksae 1 is not used efficiently because of the imperfections of the processing technology for this biomass. Therefore, for the best use of specific biomass, improvement in the feedstock preparation of the biomass for processing, such as pellet manufacturing, is necessary. In this study, a laboratory-scale cone grinder and air classifier were designed and combined to investigate the performance of the combination system for *M. sacchariflorus*. The average equivalent spherical diameter of particles showed a close relationship with air velocity for air classification. The air velocity range to classify proper particles for pelletization was determined to be 6.0-6.8 m/s. The mass ratios of the collected particles to feed mass for four lengths of chopped *M. sacchariflorus* were 45.1%:46.1%, 39.1%:46.6%, and 44.1%:52.8% at the first, second, and third steps in simulating the multistep combination system, respectively.

Keywords: size reduction, air classification, cone grinder, biomass, *Miscanthus sacchariflorus* Goedae-Uksae 1

1. INTRODUCTION

Size reduction and particle classification are vital pre-processing operations associated with the use of biomass in energy production and as a feed for other industries. The designs and choices of the size reduction and classification processes and the equipments are important in enhancing the efficiency of biomass preparation as raw materials (Naimi *et al*., 2006). The application of pre-processing operations such as size reduction is critical in order to increase the surface area of lignocellulosic biomass prior to various main processes such as chemical reactions, composite material manufacturing, and mechanical densification, Kim *et al*. (2011) developed popping pretreatment method for enzymatic hydrolysis of waste wood. Jang *et al*. (2012) developed the technology to produce cellulose nanofibers from plantation resources by hammer mill type continuous grinding process. Cellulose nanofibers were also prepared for polyurethane nanocomposites (Jang *et al*., 2014) and nanopaper (Park *et al*., 2015) from Korean white pine through wet disk-milling.

The size, shape, and uniformity of the raw material are important quality characteristics especially in the manufacturing of biomass pellets. Besides biomass pellet the biofuel (e.g. bio-ethanol) industry also requires

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a proper size reduction of biomass to improve the efficiency of its conversion to biofuel (Zhang, 2014). Hwang *et al*. (2012) investigated the effect of particle size of woody biomass on the feature of pyrolytic products. Kim and Kim (2019) found that relative crystallinity of the heat treated wood cellulose decreased with decreasing particle size. Lee *et al.* (2020) ground radiata pine bark to a particle size smaller than 1 mm to extract polyphenols for bio-foam preparation.

Biomass size reduction refers to mechanical treatment processes that significantly change the particle size, shape and bulk density of the material. These processes may involve one or a combination of the following types of actions: cutting, shearing, tearing, impact stress, compression and friction (Miu *et al*., 2006).

Devices for physical separation such as vibrating sieves, air-screen cleaners, and classifiers are usually used to classify comminuted biomass based on physical properties. Yang *et al.* (2019) used mechanical sieves to screen proper sized particles from pulverized sawdust to analyze chemical characteristics. Ju *et al.* (2020) also screened ground carbonized materials with a vibratory sieve shaker for manufacturing wood charcoal briquettes. Sieves are generally utilized for large-scale particle separation in the industry and for particle size distribution analysis in laboratories. This separation method is assuming the homogeneous and uniformly-shaped particles on a screen based on the theoretical passage through an aperture. Therefore, the heterogeneous and irregular particles such as biomass should receive significant attention (Yang, 2007). The needle-like shape of particles for some biomass such as Miscanthus renders separation using standard method involving sieves inadequate for particle size classification (Lee, *et al*., 2018).

There are generally big differences in characteristics of size reduction and classification due to biomass species. One of the main reasons why *Miscanthus sacchariflorus* Goedae-Uksae 1 is not utilized efficiently may be the imperfections in processing technologies such as the efficient size reduction and the reliable screening for this biomass. Therefore, for the best use of this biomass, it is necessary to look for ways to improve this biomass feedstock preparation for processing (Kadziuliene *et al*., 2014).

In this work cone-type grinder was combined with air-classifier to enhance the efficiency of raw material preparation process for *Miscanthus sacchariflorus* Goedae-Uksae 1. *Miscanthus sacchariflorus* Goedae-Uksae 1 was comminuted, classified and collected simultaneously. And the performance of this system was evaluated by the yield of proper particles.

2. MATERIALS and METHODS

2.1. Material preparation

Bioenergy Crop Research Center in Muan, Korea provided the air-dried samples of *Miscanthus sacchariflorus* Goedae-Uksae 1. The average moisture content of samples measured using the oven-drying method was 9.1% (wet basis). A forage chopper (Model No. SC4500, Hwangso Co., Korea) with a 2.25 kW electric motor was used to chop samples to lengths of 18, 40, 80, and 160 mm.

Some of chopped samples were comminuted using a laboratory-scale knife mill (Model No. LKM2015, Drying Engineering, Inc., Korea) equiped with a 3.75 kW electric motor with a rotation speed of 1720 rpm. The gap between the knives and the cutting bars was set at 3 mm and the aperture size of knife mill screen was 3 mm.

2.2. Air-classification system

Air classification system was composed of cyclone (diameter 300 mm, height 600 mm), turbo blower (motor power 1.5 kW, air flow rate 40 m^3/min, static pressure 285 mmAq), bag filter (diameter 300 mm, length 1600 mm), and ducting systems (diameter 100 ~ 150 mm) (Fig. 1). Magnetic vibrating feeder with maximum vibrations per minute (VPM) of 3600 (Model No. HMF-00B, Hwashin Co., Korea) was installed with chute at the slope angle of 8° in front of suction duct inlet to distribute particles uniformly. Linear relationship between VPM of vibrating feeder and material feeding rate was found through the preliminary test with feed rate per charge of 40 g as shown in Fig. 2. Each test was repeated three times to minimize the experimental error. For example, 40 g of feed could pass through the vibrating feeder in about 13 seconds at VPM of 2520. For this study VPM was set at 2520.

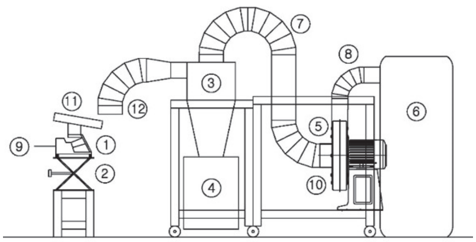

Fig. 1. Schematic diagram of air classification system (① Vibrating feeder, ② Adjustable jack support, ③ Cyclone, ④ Duct storage, ⑤ Turbo blower, ⑥ Bag filter, ⑦ Duct 1, ⑧ Duct 2, ⑨ Vibrating feeder controller, ⑩ Inverter for blower, ⑪ Outlet chute of cone grinder, ⑫ Suction duct).

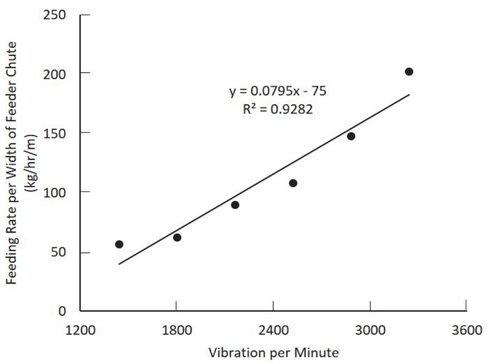

Fig. 2. Relationship between VPM of vibrating feeder and material feeding rate for comminuted particles of *Miscanthus sacchariflorus.*

Air velocity at the inlet of suction duct was measured by vane-type digital anemometer and controlled by frequency control type inverter. Regression equation between frequency set at the inverter and air velocity was predicted as Eq. (1).

$$v_a = 0.3763 \times F_i + 0.08 \ (R^2 = 0.9963) \qquad (1)$$

where v_a is air velocity at the inlet of suction duct and F_i is the frequency set value of inverter.

Particles were pneumatically conveyed into cyclone and most of them were collected in duct storage. Too small particles that could not be collected by cyclone was finally collected in bag filter. Therefore, the yield of this air-classification system was represented as the ratio of mass of collected particles to total mass of particles fed by vibrating feeder.

2.3. Particle shape analysis

A flatbed scanner (Canon-scan 4400F, Canon U.S.A. Inc., Lake Success, NY) provided digital image (4800 dpi × 9600 dpi) that were used to analyze aspect ratios, circularities indices, hydraulic diameters, and equivalent spherical diameters of large particles that were produced by knife mill and could be collected at each air velocity of air classifier. For imaging, 6 ~ 9 larger particles among each collected sample were selected by naked eyes (Fig. 3). All the image processing procedures and analysis conditions were same as the previous study by Lee *et al*. (2018). The acquired image were converted into binary form through a 8-bit gray scale image before analysis using the Image J software (Ferreira and Rasband, 2012). The 8-bit gray scale images were converted to binary images with a threshold of 100. Finally, the dimensional characteristics of the particles on the images such as areas, perimeters, circularities, and aspect ratios were determined.

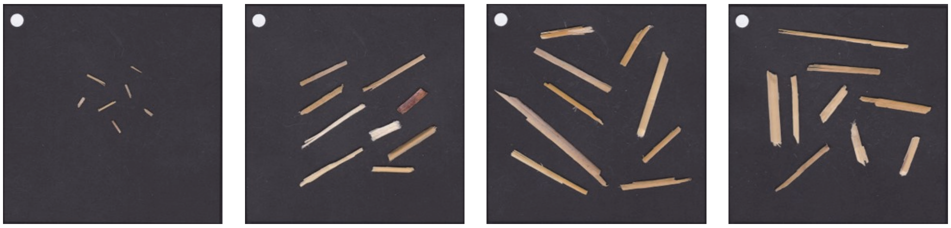

Fig. 3. Images of large particles of *Miscanthus sacchariflorus* at air velocity of 6.0, 7.0, 8.0, and 9.0 m/sec from left to right, respectively.

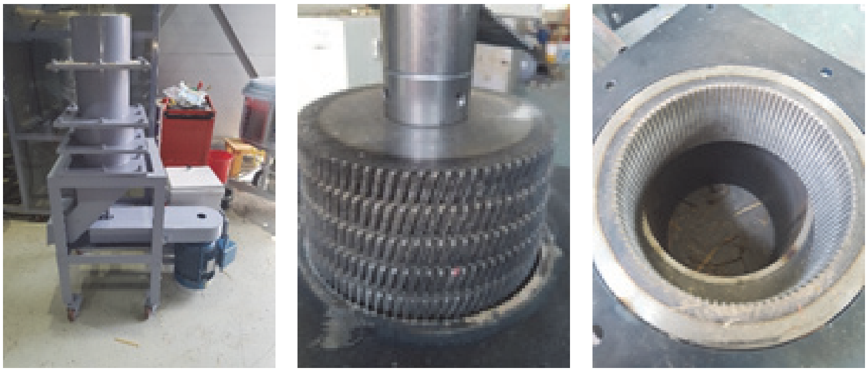

Fig. 4. Laboratory scale cone grinder, grinding wheels, and grinder inner wall from left to right, respectively.

Seo *et al.* (2018) also measured sizes of particles for particleboard and oriented strandboard with image processing technique.

2.4. Combination of air classifier with cone-grinder

Lee *et al*. (2018) found that most particles of *Miscanthus sacchariflorus* comminuted by knife mill had needle-like shape even after screening by sieve shaker. This means that pre-processing of *Miscanthus sacchariflorus* with knife milling and sieve-screening is expected to produce proper particles for pelletization at extremely low yield rate.

Cone grinder is generally applied to crush and comminute stones or mineral materials by combined actions of shearing, tearing, compression, and friction. In this study a laboratory scale cone grinder with inner diameter of 200 mm was designed and built (Fig. 4). This cone grinder had five wheels with teeth around the circumference. Five grinding wheels were piled up to form a trapezoid and the inner wall of grinder was grooved like teeth. either. Diameter of the smallest and the largest grinding wheel was 154 mm at the top and 194mm at th bottom of this trapezoid in grinding chamber, respectively. With this design the gap between grinding wheel and inner wall decreased gradually from inlet to outlet of cone grinder. Therefore, large particles could be comminuted to smaller ones stepwise. Inlet duct of air classifier was installed at the outlet of cone grinder to collect particles with proper size and the oversized particles were discharged through the cone grinder chute.

The oversized particles were fed again into cone grinder to simulate multi-step process of cone-grinding and air-classifying as Fig. 5. Three steps were simulated and mass of collected particles was measure at

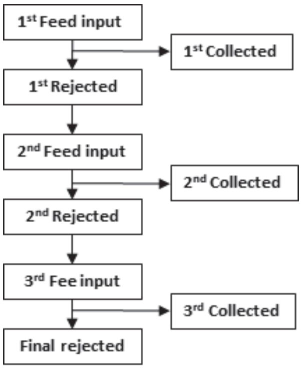

Fig. 5. Simulation of multi-step process of cone-grinding and air-classifying.

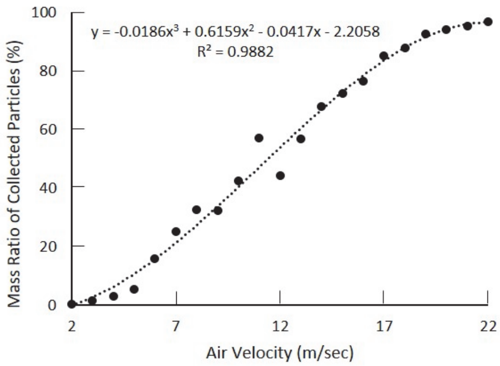

Fig. 6. Relationship between air velocity and mass ratio of collected particles of *Miscanthus sacchariflorus.*

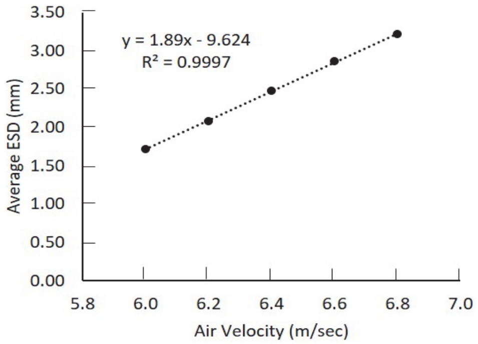

Fig. 7. Relationship between air velocity and average ESD of collected large particles of *Miscanthus sacchariflorus* within the air velocity range of 6.0 ~ 6.8 m/sec.

each step. Finally, the ratio of sum of total mass of collected particles through these three steps to input mass was represented as the yield of this combination system.

Miscanthus sacchariflorus chopped to lengths of 18, 40, 80, and 160 mm were prepared as feeds for cone grinder. Feed rate was set at 30 g per charge for stable and continuous feeding and each test was repeated three times to minimize the experimental error.

3. RESULTS and DISCUSSION

3.1. Determination of air velocity for air-classification

Fig. 6 shows the mass ratio of collected particles to input mass of *Miscanthus sacchariflorus* comminuted by knife mill. This mass ratio increased as air velocity increased as expected. Preliminary test results for average aspect ratio and circularity index from particle shape image analysis did not show significant relationships with air velocity. Meanwhile, average equivalent spherical diameter (ESD) of particles showed highly significant relationship with air velocity as Fig. 7.

Pelletizing process requires particle size smaller than 4 mm for pellet diameter of 8 mm in general. ESD of large particles collected at air velocity of 7 m/sec was estimated as 3.61 mm. Therefore, the air velocity range to classify particles proper for pellet manufacturing was determined as 6.0 ~ 6.8 m/sec.

$$D_{es} = 2 \times \left(\frac{3 \times V}{4 \times \pi}\right)^{1/3} \quad (2)$$

where D_{es} is ESD of particle (mm) and V is volume of particle (mm^3).

Based on the law of pneumatic conveying for solid particles the lowest air velocity required to convey solid particles pneumatically is equal to the terminal velocity. When sum of drag force and buoyancy force is equal to gravity acceleration of gravity is 0 and a solid particle descends at uniform velocity. This uniform descending velocity is called as terminal velocity (Mills, 2004).

$$v_t = \sqrt{\frac{4 \times g \times d}{3 \times C_d} \times (\frac{\rho_s - \rho}{\rho})} \quad (3)$$

where v_t is terminal velocity (m/sec), g is acceleration of gravity (= 9.81 m/sec^2), d is diameter of particle (m), C_d is drag coefficient, ρ_s is density of solid particle (kg/m^3), and ρ is density of air (= 1.16 kg/m^3 at 30℃).

Reynolds numbers for the air velocity range of 6.0 ~ 6.8 m/sec were calculated as Table 1.

$$R_e = \frac{\rho \times v_a \times D_H}{\mu} \quad (4)$$

where R_e is Reynolds number, D_H is inner diameter of pipe (= 0.1 m), and μ is dynamic viscosity of air (= 1.860 x 10^{-5} kg/m/sec at 30℃).

Model for determining proper air velocity to classify particles smaller than target size was developed assuming that the terminal velocity required to collect the particle with the certain maximum size is equal to that proper air velocity. Futhermore, diameter of particle is assumed to be ESD because the shapes of particles is too irregular to determine the particle diameters. Comminuted particles of *Miscanthus sacchariflorus* showed pin-type shape as Fig. 3. Drag coefficient C_d can be derived from Eq. (3). Therefore, drag coefficients were determined using Eq. (5) and the relationship between C_d and D_{es} was estimated as Eq. (6) from the experimental data.

$$C_d = \frac{4 \times g \times D_{es} \times (\rho_s - \rho)}{3 \times v_t^2 \times \rho} \quad (5)$$

$$C_d = 0.0777 \times D_{es} + 0.1364 \quad (R^2 = 0.8478) \quad (6)$$

where D_{es} is ESD (m). Finally, the model for determining proper air velocity was developed as Eq. (7).

$$v_t = \sqrt{\frac{0.01308 \times D_{es}}{0.0777 \times D_{es} + 0.1364} \times (\frac{\rho_s - \rho}{\rho})} \quad (7)$$

Table 2 shows the predicted proper air velocity for the maximum ESD that could be collected. For example, the proper air velocity to collect particles with sizes smaller than ESD of 4 mm for pellet manufacturing was predicted as 6.9 m/sec for *Miscanthus sacchariflorus.* ESD of the largest particle collected at air velocity of 6.8 m/sec was estimated as 3.67 mm according to this experimental data.

Table 1. Reynolds numbers calculated for air velocity range of 6.0 ~ 6.8 m/sec

Air velocity (m/sec)	6.0	6.2	6.4	6.6	6.8
R_e	37419	38667	39914	41161	42409

Table 2. Predicted proper air velocities for the maximum ESDs of *Miscanthus sacchariflorus* particles that could be collected

Max. ESD to be collected (mm)	1.0	2.0	3.0	4.0	5.0
Proper air velocity (m/sec)	5.0	6.0	6.6	6.9	7.1

3.2. Performance of combination system of cone-grinder and air-classifier

Table 3 shows the results of the simulation tests for the combination system of cone grinder and air classifier. Air velocity at the inlet duct of air classifier was set at 6.8 m/sec that could guarantee the collection of particles with average ESD smaller than 4.0 mm.

The ratios of mass of collected particles to mass of feed for four lengths of chopped *Miscanthus sacchariflorus* were 45.1 ~ 46.1%, 39.1 ~ 46.6%, and 44.1 ~ 52.8% at the first, second, and third step, respectively.

Table 3. The mass ratios of collected particles of *Miscanthus sacchariflorus* to input according to chopped length and number of steps

Step	Chopped length (mm)			
	160	80	40	18
After 1st step	45.1%	47.7%	47.4%	46.1%
After 2nd step	39.1%	46.6%	41.4%	44.2%
After 3rd step	52.8%	46.8%	49.6%	44.1%
Total mass ratio (%)	84.2%	85.1%	84.5%	83.2%

Fig. 8. Images of *Miscanthus sacchariflorus* particles collected at the air velocity of 6.0, 6.4, and 6.8 m/sec after comminuting with cone grinder from left to right, respectively.

Total mass ratios of collected particles to feed were 83.2 ~ 84.2% with an average of 83.7%. No significant difference due to chopped length or number of steps could be found.

The mass ratio of collected particles to mass of knife-milled feed was below 20% at air velocity of 7 m/sec for air classifier in Fig. 6. Therefore, it was revealed that cone grinder could comminute *Miscanthus sacchariflorus* with higher performance than knife mill.

Womac *et al*. (2007) recommended a multiple-stage grinding process for proper size reduction of biomass. Lee *et al*. (2018) found that knife milling with vibrating sieve screening method could not prepare appropriately sized particles from *Miscanthus sacchariflorus*. Fig. 8 shows the images of *Miscanthus sacchariflorus* particles collected at various air velocities after comminuting by cone grinder. Most particles prepared with this combination system had small size and fibrous shape that could be helpful for pelletizing process. This fibrous shape of particles seems to be mainly due to the actions of cone grinder, especially shearing, tearing, and friction, while the main actions in knife milling or hammer milling are cutting and impacting.

4. CONCLUSION

A laboratory scale combination system of cone grinder and air classifier were designed and built to improve the performance for pre-processing of *Miscanthus sacchariflorus* Goedae-Uksae 1. Air velocity of 6.8 m/sec at the inlet duct of air classifier was determined for the collection of particles with average equivalent spherical diameter smaller than 4.0 mm. At this air velocity for air classification total mass ratios of collected particles to inputs were 83.2 ~ 84.2% with an average of 83.7% when simulating three-step cone-grinding and air-classifying system. This high yield and fibrous shape of particles with proper size are expected to enhance the efficiency of following-up processes, such as pelletization.

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