Powder Technology 267 (2014) 354–361

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Flow performance of ground biomass in a commercial auger

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ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 21 July 2014
Accepted 24 July 2014
Available online 2 August 2014

Keywords:
Energy efficiency
Miscanthus and switchgrass
Volumetric flow rate and efficiency
Mass flow rate
Feedstock handling
Internal and external friction

ABSTRACT

The flow performance of preprocessed biomass plays an important role in biomass transportation and handling. The research as presented here investigated how the Angle of Repose (AOR) of miscanthus and switchgrass is related to flow performance of biomass particles in an auger that was originally designed to convey corn and soybeans. The flow performance metrics were the specific energy consumption (SEC), energy efficiency (EE), volumetric efficiency (VE), volumetric flow rate (VFR) and mass flow rate (MFR).

The results showed that the EE and MFR while conveying miscanthus and switchgrass particles ground through 6.35-, 9.53-, 12.7- and 25.4-mm milling screens were much lower than those of corn. However, the differences in VFR between corn and biomass were much smaller than that in SEC and mass flow rate (MFR). This result implies that the low bulk density of biomass feedstock is a more pronounced limiting factor in biomass handling than the conveying mechanism used.

The AOR of miscanthus and switchgrass particles was found proportional to particle size and moisture content. While AOR is an indicator of the material's internal friction, in this study, the AOR of miscanthus and switchgrass was not significantly related to the energy/volumetric efficiency of the auger. By comparing the measured auger power consumption to predictions from empirical equations developed for corn and soybean, it became evident that these equations do not perform well for biomass feedstock.

1. Introduction

The Biomass R&D Technical Advisory Committee of the United States Congress envisioned a 30% replacement of the current U.S. petroleum consumption with biofuels by 2030. The European Commission Directive 2009/28/EC has set the goal of using a minimum of 10% sustainable biofuels within the transportation sector of every member state by 2020 [1]. China, Brazil, India, Canada and Japan have also invested significant resources to facilitate biofuel technology and commercialization. It is evident that worldwide, there is an ever increasing interest in biomass feedstock as a source for sustainable energy.

The handling of feedstock plays a crucial role in biomass logistics. The majority of end-users of bioconversion, gasification and combustion require a form of biomass that is flowable, to enable handling using proven existing equipment such as augers, pneumatic conveyors and conveyor belts [2–5]. The selection of biomass handling methods and equipment depends on the purpose of use and on the type, form and properties of the feedstock [6–9]. For instance, biomass bales are typically handled using bale forklifts [10,11], whereas feedstocks in particulate form mainly utilize augers, belt or pneumatic conveyors.

The flow characteristics of biomass feedstock particles depend upon biomass type, form and physical properties, which differ significantly from those of grain. Theoretical and empirical flow analysis of grain, wood and forage chips, pellets and DDGS (dried distillers grains with solubles) conveyed with augers, belts, and forage blowers have been well documented [8,9,12–15]. In addition, comprehensive experiments regarding grain auger performance were conducted as early as the 1950s and 1960s [12].

Grain particles are fairly elastic and morphologically uniform in comparison with feedstock particles that are ground through a mill. Although the shape of the auger's feed opening is not critical for free-flowing materials such as barley grain and sawdust, the shape does affect the flow performance of fibrous materials such as wheat straw and hay [16]. For instance, if a casing inlet angle is equal to 90°, i.e., the edge of the rectangular opening is perpendicular to the axis of the screw, the auger works well while feeding free-flowing materials into an enclosed horizontal auger, but it is likely to cause blockages for long-fibrous materials [16]. If the casing inlet angle is equal to the sum of the auger's flight angle and the friction angle between material and flight, the auger efficiency is improved even for fibrous materials [16].

Although manufacturers typically provide performance parameters for augers while horizontally conveying grain or sand at low speeds, data for augering lignocellulosic feedstock particles are not available [2,8,9,17]. Various flow characteristics of biomass particles have been determined off-line, such as Angle of Repose (AOR), shear strength

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http://dx.doi.org/10.1016/j.powtec.2014.07.038
0032-5910/

and friction coefficients of chopped corn stover, wheat straw and switchgrass [2,17–19]. For example, a commonly used apparatus for off-line determination of flow characteristics of granular materials is Jenike's shear cell [15,19,20]. However, few studies directly measure the influence of these characteristics on flow performance in existing conveying equipment such as an auger.

Ground herbaceous biomass particles vary in chemical composition, moisture content, size, and shape, each of which affects the elastic and plastic behavior of the particles [21,22]. Biomass physical properties including particle–particle friction (measured by AOR as a proxy), and particle–wall friction have been used in the design of equipment for processing, handling and storage [19,23,24]. High particle–particle and particle–wall friction facilitates storage and belt conveying, but impedes handling through augers and pneumatic conveyors. The majority of relationships among AOR, flowability, compressibility and Hausner ratio have been reported in material/food sciences and engineering with fine powders (Table 1), which differ dramatically from the elongated particles that comprise biomass. For instance, as a ratio of the freely settled bulk density and the tapped bulk density of the material, Hausner's ratio is highly correlated with the flowability of granular materials [15, 23]. Therefore, studying the relationship between biomass physical properties (e.g., AOR) and flowability has to be carried out using targeted conveying equipment so as to improve the overall flow performance and energy consumption of the equipment for a certain material type and form.

The objectives of this study were to (1) investigate the relationship between the material's Angle of Repose (AOR) and flow performance, and (2) evaluate the feasibility of applying existing auger power requirement equations to biomass.

2. Materials and methods

Miscanthus (*Miscanthus × giganteus*, Poaceae/Gramineae) and switchgrass (*Panicum virgatum L.* Poacea/Gramineae) were tested in this study. These biomass crops were planted at the Energy Farm of the University of Illinois at Urbana-Champaign (lat. 40.065833, lon. −88.208426). The biomass samples were cut, in-field conditioned for one or two days, and baled with a large square baler (Model: BB940, New Holland Agriculture, New Holland, PA 17557, USA) in March, 2009. Miscanthus and switchgrass bales were chosen at random and broken up for size reduction. Miscanthus bales consisted of approximately 70–80% stem material and 20–30% sheath and leaf material, while switchgrass bales consisted of 55–70% stem material, and 30–45% sheath and leaf material [3]. Corn was harvested from the South Farm of University of Illinois at Urbana-Champaign in the Fall of 2009.

2.1. Material preparation

For coarse size reduction of miscanthus and switchgrass, a tub grinder (Haybuster H-1000 Series II, DuraTech Industries, Jamestown, ND, USA) was utilized, which ground bales through screens with aperture sizes of 6.35, 12.7, 25.4 and 38.1 mm. For fine size reduction, 25.4-mm miscanthus and switchgrass particles were further ground with a Retsch SM2000 knife mill with screens of an aperture size of 1-mm trapezoidal, and 2-, 4-, 6-, 8- and 10-mm square openings [3]. Hereinafter, aperture sizes of milling screens will be used to describe the particle size of the samples. For example, miscanthus particles ground through screens with an aperture size of 1, 2, 4, 6, 8, 10, 12.7 and 25.4 mm are abbreviated to 1-, 2-, 4-, 6-, 8-, 10-, 12.7- and 25.4-mm miscanthus. Before grinding, miscanthus and switchgrass samples were spread out for 72 h in layers with a thickness of less than 15 cm on a laboratory floor and allowed to air-dry, following the NREL (National Renewable Energy Lab) laboratory analytical procedure [25]. Three replicates of 20–25 g biomass for each sample were allowed to dry for 24 h in an oven at 103 ± 3 °C to determine their moisture content, following the ASAE S358.2 DEC1988 (R2008) Standard for forage analysis [25].

Table 1
Relationships among flow property, AOR, compressibility index and Hausner ratio (Carr, 1965; Ganesan et al., 2008).

Flow property description	AOR (degrees)	Compressibility index (%)	Hausner ratio
Excellent	25–30	10	1.00–1.11
Good	31–35	11–15	1.12–1.18
Fair—aid not needed	36–40	16–20	1.19–1.25
Passable—may hang up	41–45	21–25	1.26–1.34
Poor—must agitate, vibrate	46–55	26–31	1.35–1.45
Very poor	56–65	32–37	1.46–1.59
Very, very poor	>66	>38	>1.60

2.1.1. Moisture conditioning

Conditioning the biomass to the required moisture content was achieved by two methods, by spraying water evenly over the particles, and by the isotherm curve procedure of ASAE 245.6 [3]. To condition the material to a desired moisture content of 25%, the amount of water needed was calculated, and applied to batches of 500 g biomass samples by spraying water evenly onto particles. The wetted material was then put into a sealed plastic trash liner, which was placed in a covered garbage bin. This bin was stored at 22–25 °C for 72 h to achieve an equilibrium moisture content [3,22]. The moisture-conditioning error was controlled within ±3%.

To adjust the moisture content of biomass samples to 15%, a mini temperature-humidity chamber MR-148 (TechTools Inc., Brooklyn, NY) was used and the isotherm curve procedure of ASAE 245.6 was also followed. The chamber temperature was set to 13 °C, and the relative humidity was controlled to 89.0 ± 2% with a saturated NaCL solution [26,27]. Samples of 100 g were placed in the chamber for more than three weeks. The samples were weighed daily with an accuracy of ±0.1 mg. An equilibrium state was assumed when three consecutive weight measurements showed a difference of less than 1 mg [26,27].

2.2. Angle of Repose (AOR) measurements

The Angle of Repose of biomass feedstock refers to the maximum angle at which a biomass pile can rest on an inclined plane without

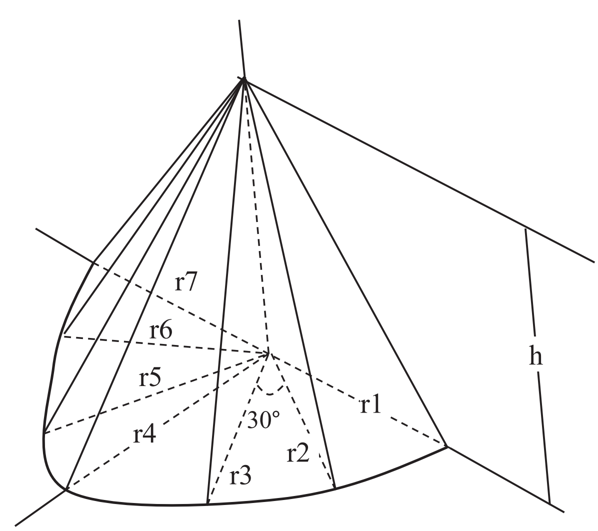

Fig. 1. Biomass Angle of Repose (AOR) calculated from the height (h) and average of radius r of the base of the particle semi-cone at seven positions with an interval angle of 30°.

sliding down. A Mark 5 AOR tester (Powder Research Ltd, Harrogate North Yorkshire, UK) was used to quantify AOR values of feedstock particles as follows (Fig. 1):

(i) Particles were poured into a converging chute over a 20 second period to create a semi-cone with a well-defined sharp apex. For ground feedstock particles, 10–20 g biomass samples were used, while 200 g was used for corn.
(ii) The height h and radius r of the base of the particle semi-cone were measured at seven positions with an interval angle of 30° (Fig. 1); and
(iii) AOR values (α) were determined using the following equation:

$$\alpha = \tan^{-1}\left(\frac{h}{r}\right) \tag{1}$$

where h represents the height in cm and r represents the radius in cm of the semi-cone. AOR measurements of each material form and type were repeated 3–5 times depending on the standard deviations of the measurements.

2.3. Specific energy consumption (SEC) measurement

A lab-scale grain auger (Model 4C8, S. Howe's Inc., Silver Greek, New York, USA) was used in the feedstock handling experiments (Fig. 2). Table 2 shows the specifications of the auger.

The SEC of the auger was measured using a Yokogawa clamp-on power meter (Model CW121-D-2/C2, Yokogawa M&C Corporation, JMI Instrument Company, Highland, Indiana, USA) [3]. The total energy consumption was calculated according to Eq. 2:

$$E_T = \frac{\int_0^T (P_t - \overline{P}_0)\,dt}{m_{DM}} = \frac{\int_0^T \Delta P_t\,dt}{m_{DM}} \tag{2}$$

Table 2
Parameters of the lab-scaled auger used in the research.

Parameters	Values
Pitch (mm)	95.41
Radial clearance between screw and casing (mm)	6.35
Screw flight diameter (mm)	95.41
Core shaft diameter (mm)	41.14
Casing thickness (auger tube) (mm)	3.02
Thickness of flight (mm)	8.27
Casing diameter (outside) (mm)	112.33
Choke length (m) (i.e., intake length)	0.254
Auger length (m)	2.286
Speed of screw rotation (rpm)	85
Angle of auger elevation (deg, adjustable)	30
μ_1, material–metal friction†	0.15
μ_2, material–material friction†	0.78
F_d (dimensionless)‡, empirical factor related to screw weight per unit length	12
F_m (dimensionless)‡, empirical factor related to sizing small conveyor motors adequately to avoid overloading.	0.6

† μ_1 and μ_2 excerpted from Afzalinia and Roberge (2007) and Pettengill and Millier (1968) for barley straw friction and wet Alfalfa with moisture content of 68.0–74.8%, respectively; ‡Excerpted for Alfalfa meal and pellets from CEMA (1980) (Williams et al., 2008).

(a)

(b)

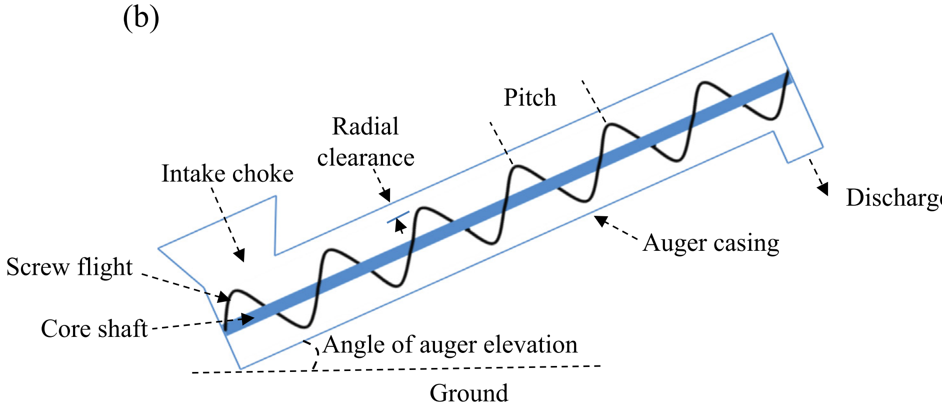

Fig. 2. Lab-scale auger (a) and terminology used (b) in the study.

where E_T is the SEC for conveying a unit of dry matter (kJ kg^{-1} DM), P_t is the instantaneous power in W consumed by the auger, $\overline{P}_0$ is the average power consumption in W of the auger under idle conditions, ΔP_t is the instantaneous net power in W consumed, and m_{DM} is dry matter mass in kg of biomass feedstock being conveyed over the time period T.

2.4. Volumetric efficiency measurement

The volumetric efficiency η_V is a dimensionless parameter equal to the ratio between the material's volumetric flow rate in m^3 s^{-1} and the auger's theoretical volumetric flow rate in m^3 s^{-1}. In equation form:

$$\eta_V = \frac{Q_a}{Q_t} \tag{3}$$

In the study, Q_a was derived from the measured mass flow rate (MFR, kg DM s^{-1}) of the amount of material delivered by the auger per unit of time divided by bulk density (kg DM m^{-3}).

Q_t is the theoretical volumetric flow rate (m^3 s^{-1}), which can be derived from the dimensions and running speed of the auger as follows:

$$Q_t = \frac{\pi}{4}\left(d_{sf}^2 - d_{ss}^2\right) l_p n \tag{4}$$

where d_{sf} is the screw flight diameter (m), d_{ss} is the screw shaft diameter (m), l_p is the pitch length (m), and n is the speed of rotation (rev s^{-1}) [8,9,12].

2.5. Power equation validation

According to Srivastava et al. (2006) [8] and Williams et al. (2008) [9], the power requirement of auger was widely estimated as follows;

$$P' = \frac{P/L}{Q_a \rho} \tag{5}$$

$$\eta_v = f\left(\frac{d_t}{d_p}, \frac{d_{sf}}{l_p}, \frac{d_{ss}}{l_p}, \frac{l_i}{l_p}, n\sqrt{\frac{l_p}{g}}, f(\theta), \mu_1, \mu_2\right) \tag{6}$$

where $\eta_v = \frac{Q_a}{\frac{\pi}{4}\left(d_{sf}^2 - d_{ss}^2\right) l_p n}$ or $\frac{P/L}{Q_a \rho g}$

$$P = \left[\left(\frac{12L \cdot 60n \cdot F_d}{500,000}\right) + \left(\frac{127132.8 \cdot Q_t \cdot (12 \cdot L) \cdot (\rho \cdot 0.06242796) \cdot F_m}{1,000,000}\right)\right] \cdot F_o \cdot 745.70 \tag{7}$$

where P' = specific power (W s kg^{-1} m^{-1}), P = power requirement (W), d_t = auger tube inside diameter (m), L = auger screw length (m), l_i = exposed screw intake length (m), θ = angle of conveyor inclination (°), ρ = material bulk density (kg m^{-3}), μ_1 = material–wall friction (dimensionless), μ_2 = material–material friction (dimensionless), g = gravitational acceleration (m s^{-2}), the definitions of Q_a, Q_t, d_{sf}, d_{ss}, l_p, and n are the same as above, F_d = an empirical diameter factor that accounts for screw weight per unit length, F_m = an empirical material factor related to the physical properties of the material being conveyed, and F_o = an empirical factor that accounts for sizing small conveyor motors adequately to avoid overloading, and can be determined according to CEMA (1980) [9]:

$$F_o = 1.9142 \cdot HP_t^{-0.3368} \tag{8}$$

where HP_t is the total calculated power in horsepower for the auger prior to applying the F_o motor factor, i.e., the quantity inside the brackets of Eq. 7 [9]. As commonly-used equations, Eqs. 3–8 were employed to calculate the volumetric efficiency and specific energy consumption of the auger [8,9,12], respectively.

3. Results and discussion

Fig. 3(a) shows the specific energy consumption (SEC) in kJ kg^{-1} DM of augering corn, as well as miscanthus and switchgrass, both comminuted into 6.35, 9.53, 12.7 and 25.4 mm particles respectively. Firstly, it is clear that the SEC for conveying miscanthus and switchgrass particles was far higher than that for conveying corn.

Secondly, the SEC for conveying biomass particles by the auger was proportional to particle size. The SEC was captured in a power function related to the aperture size (x in mm) of a milling screen as follows:

$$SEC = 0.1373x^{1.397}\left(\text{Adj. } R^2 = 0.97,\ \text{RMSE} = 0.88\right) \text{ for miscanthus}$$

and

$$SEC = 0.9671x^{0.8787}\left(\text{Adj. } R^2 = 0.87,\ \text{RMSE} = 1.98\right) \text{ for switchgrass}$$

The regressions were significant at the 95% confidence level.

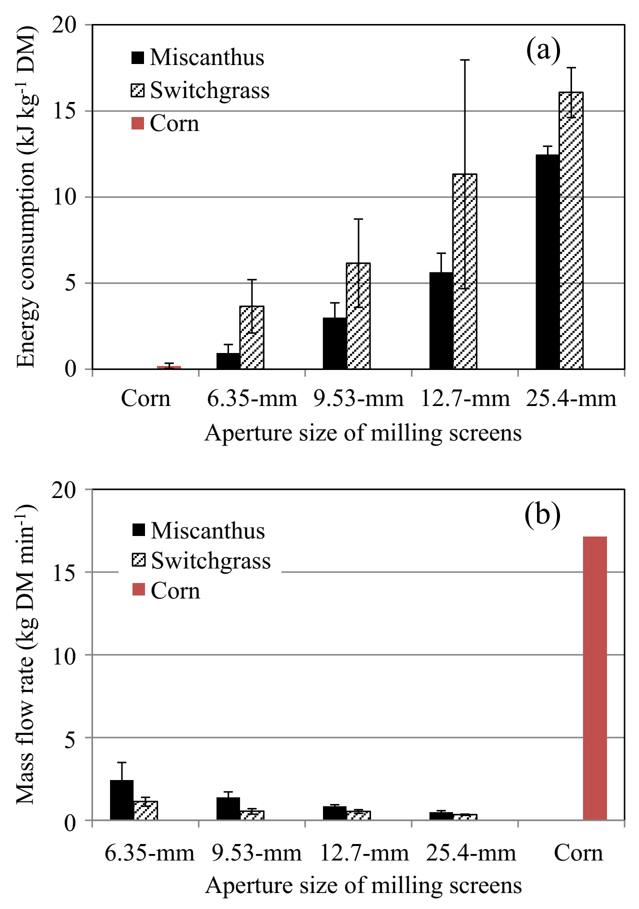

Fig. 3. Specific energy consumption (SEC, in kJ kg^{-1} DM) (a) and mass flow rate (kg DM min^{-1}) (b) for conveying corn, miscanthus and switchgrass particles.

Thirdly, the SEC for conveying miscanthus particles was consistently lower than that for conveying switchgrass particles. The differences in specific energy consumption between miscanthus and switchgrass ranged from 22.4% to 74%, significant at the 95% confidence level based on Student's *t*-test. For example, the SEC for conveying 6.35-mm miscanthus was 0.95 kJ kg^{-1} DM, while it was 3.65 kJ kg^{-1} DM for conveying 6.35-mm switchgrass.

The mass flow rates for miscanthus and switchgrass were inversely proportional to particle size. For example, the mass flow rates of 6.35-mm miscanthus and switchgrass particles were 2.42 and 1.12 kg DM min^{-1} (Fig. 3b), respectively. These values were 5 and 3 times higher than those for 25.4-mm miscanthus and switchgrass conveyance, respectively. Given a specific particle size, the mass flow rates of miscanthus conveyance were higher than those for switchgrass. The relationship between mass flow rate (kg DM min^{-1}) and aperture size (x in mm) of milling screens was captured as follows:

$$MF = 29.41x^{-1.355}\left(\text{Adj. R}^2 = 0.98,\ \text{RMSE} = 0.1082\right)\ \text{for miscanthus}$$

and

$$MF = 7.81x^{-1.081}\left(\text{Adj. R}^2 = 0.85,\ \text{RMSE} = 0.1333\right)\ \text{for switchgrass.}$$

The regressions were significant at the 95% confidence level.

The estimations of specific energy requirement with Eqs. 5–8 for the auger did not match the measurements for conveying miscanthus and switchgrass (Fig. 4), though the predictions of SEC from Eqs. 7 and 8 were similar to the measured values while conveying corn. The predictions for miscanthus and switchgrass conveying power requirement from Eqs. 5–8 were lower than the measurements, especially when conveying large particles. The predictions from Eqs. 7 and 8 were relatively close to the measurements for conveying small particles.

The physical properties of the material significantly affected the flow rate and specific energy consumptions of an auger, especially for biomass particles with a large size distribution and aspect ratios far greater than one. For example, the mass flow rate of corn conveying was 7 and 16 times higher than those of 6.35-mm miscanthus and switchgrass particles (Fig. 3b), respectively. Moisture content can greatly increase internal and adhesion friction [28,29]. Wet biomass, such as sugarcane bagasse with a moisture content ranging from 50 to 60%, no longer constitute discrete particles when flowing [8,9]. In contrast, they may form clumps, causing clogging if the flow rate continues to increase. Those phenomena were observed frequently while conveying particles ground through a screen with an aperture size of 25.4 mm, especially for biomass with a moisture content higher than 30%.

At present, most specifications of handling equipment such as power requirement and volumetric efficiency are provided by the manufacturers for granular materials such as sand or grain. Estimations of auger power requirement do not include any direct variables of biomass flowability properties except for material internal and external friction [8,9,12,13]. For example, the majority of power requirement equations, such as the ones given in Eqs. 3–8, do not include particle size and/or shape as a variable. Those variables may be unnecessary for grain or pellets handling due to their similar morphology, size distribution, hard surfaces, and low particle–particle and particle–wall friction. For herbaceous particles, however, more variables of the physical properties of feedstock particles should be taken into account in the theoretical calculations of energy consumption.

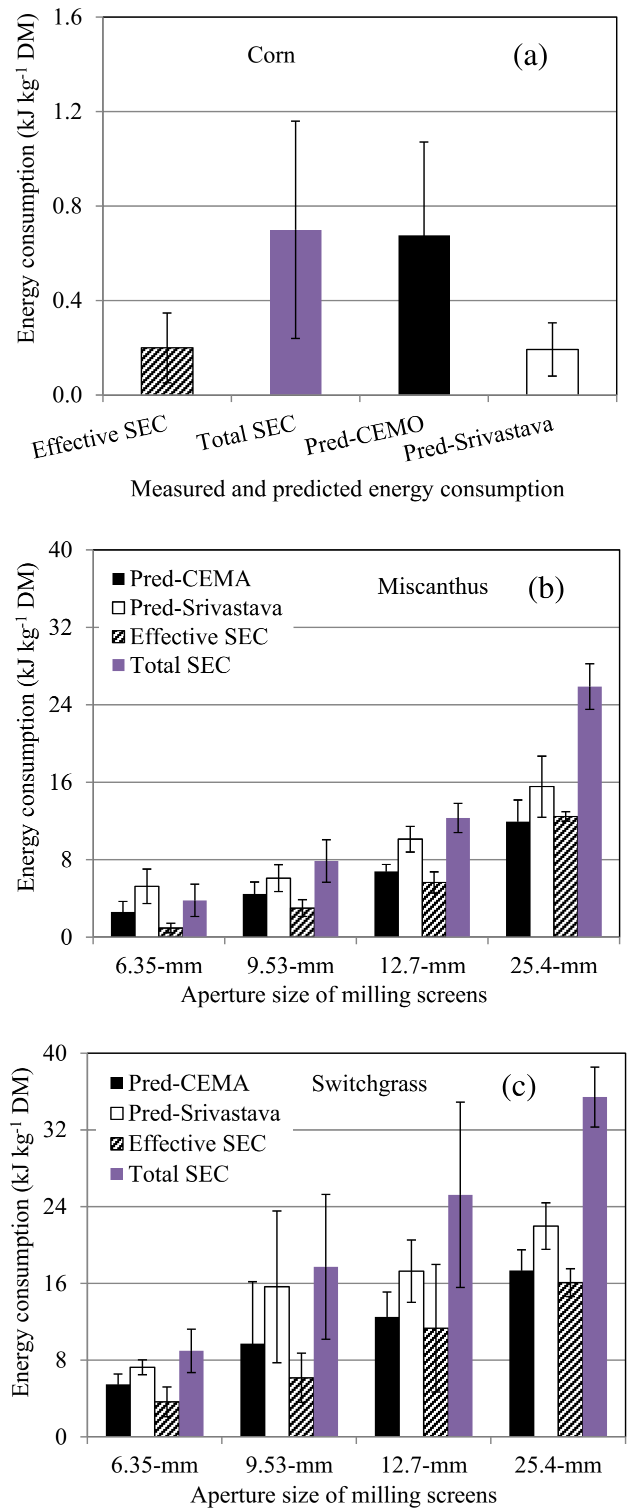

Fig. 4. Measured and predicted specific energy consumption (SEC, in kJ kg^{-1} DM) for conveying corn (a), miscanthus (b) and switchgrass (c) particles. Note: Pred-Srivastiva and Pred-CEMA—SEC predicted from Eqs. 5 and 6 (Srivastava et al., 2006) and Eqs. 7 and 8 (CEMO, 1980; Williams et al., 2008), respectively; total SEC—total specific energy consumption; Net SEC, i.e., effective SEC—total SEC subtracting idle energy consumption. SEC predicted from Eqs. 5–8 should be close to total SEC.

3.1. Volumetric efficiency (VE) and volumetric flow rates (VFR) of corn, miscanthus and switchgrass conveying

The volumetric efficiencies of miscanthus and switchgrass particles were inversely proportional to particle size (Fig. 5a). The relationship between volumetric efficiency (VE) and aperture size (x in mm) of milling screens was captured in power functions:

$$VE = 3.216x^{-0.9207}\left(\text{Adj. R}^2 = 0.95,\ \text{RMSE} = 0.0396\right)\ \text{for miscanthus}$$

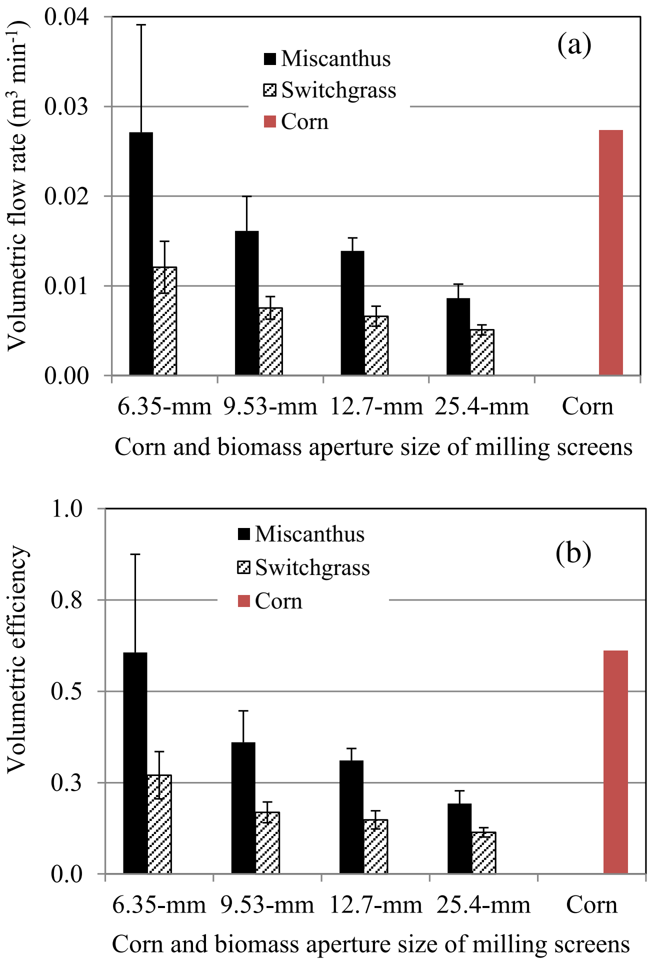

Fig. 5. Volumetric flow rate (VFR) in $m^3\ min^{-1}$ (a) and volumetric efficiency (VE, dimensionless) (b) for conveying corn, miscanthus and switchgrass particles.

and

$$VE = 0.9693x^{-0.72}\left(\text{Adj. } R^2 = 0.87,\ \text{RMSE} = 0.024\right) \text{ for switchgrass}$$

The regressions were significant at the 95% confidence level.

The volumetric efficiencies for conveying miscanthus were significantly higher than those of switchgrass for a given particle size (Fig. 5a). Student's *t*-test for means of paired samples showed that the differences in volumetric efficiencies between miscanthus and switchgrass were significant at the 95% confidence level. For example, the volumetric efficiency of 6.35-mm miscanthus was 0.61, which was considerably higher than that of 6.35-mm switchgrass with a value of 0.27.

The volumetric efficiency for conveying corn was similar to the conveying of 6.35-mm miscanthus, but much higher than the results for conveying switchgrass and larger miscanthus particles (Fig. 5). In comparison to 6.35-mm miscanthus particles, the higher energy efficiency and mass flow rate for conveying corn were mainly attributed to a higher bulk density, and lower particle–particle and particle–wall friction of corn. This result implied that to convey miscanthus fine particles, the current grain auger structure may not be a major problem. Further investigation of material flow with possibly discrete element simulation (DEM) and material tracking with high-throughput real-time imaging technology are needed to investigate the flow mechanism of biomass particles in an auger.

The trends of volumetric flow rates of miscanthus and switchgrass particles were similar to those of volumetric efficiencies (Fig. 5b). As shown in Eq. 3, a linear relationship exists between volumetric flow

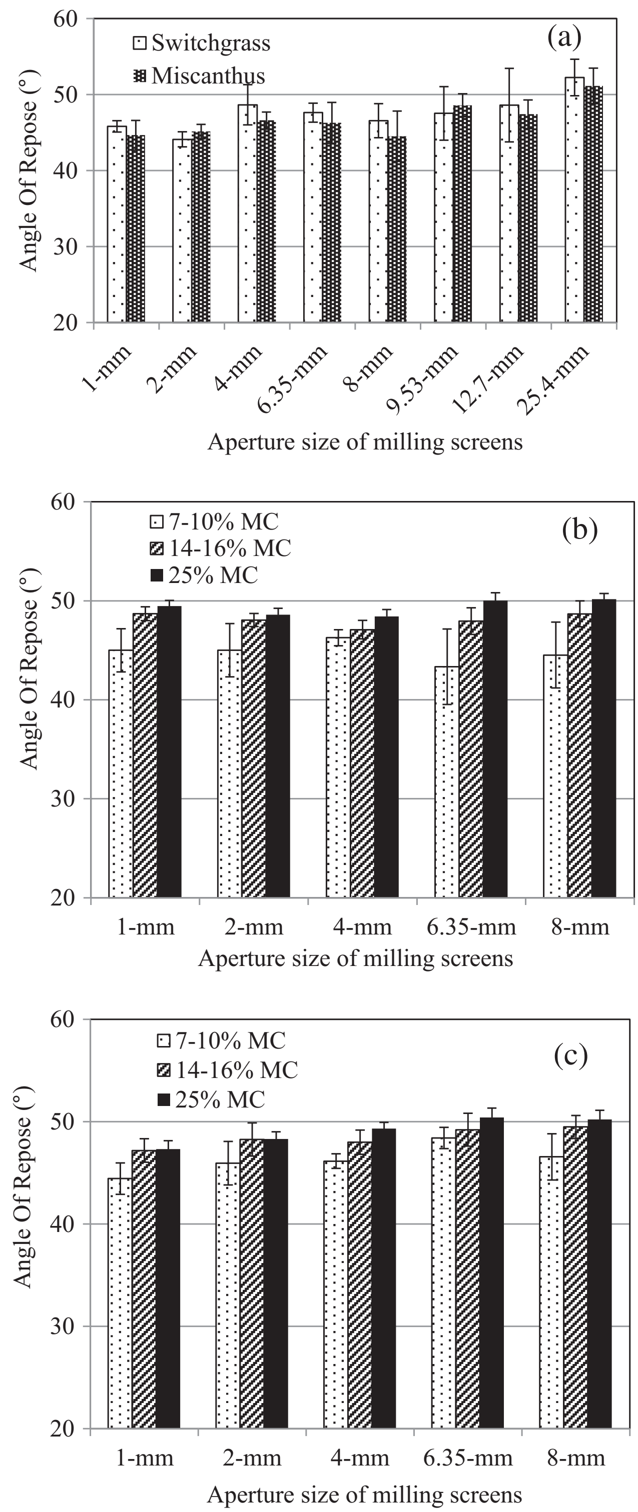

Fig. 6. Comparison in Angle Of Repose (AOR) between air-dried Miscanthus and switchgrass particles (a) and effects of moisture content on AOR of Miscanthus (b) and switchgrass (c) particles. Note: MC – moisture content (%). The moisture content of room air-dried biomass particles was about 7-10%. Data in Figure 6a was used to fit the relationships between AORs and aperture sizes (mm) (x) of milling screens for Miscanthus and switchgrass.

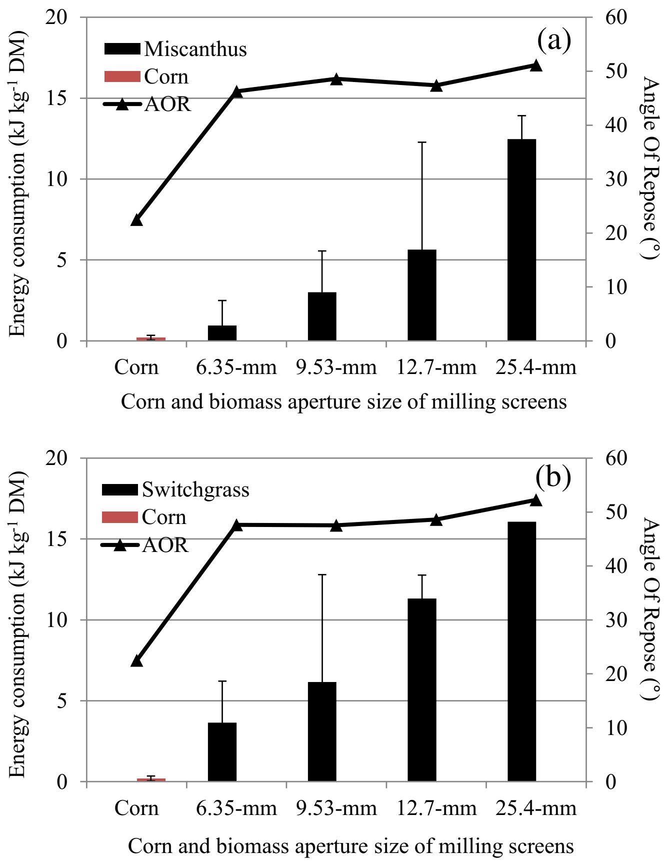

Fig. 7. Specific energy consumption (SEC) (kJ kg^{-1} DM) of corn and biomass conveying in an enclosed auger vs. Angle Of Repose (AORs) of miscanthus (a) and switchgrass (b) particles.

rate and volumetric efficiency. The regressions between the actual volumetric flow rate (VF in m^3 min^{-1}) and aperture size (x in mm) of milling screens were captured in power functions:

$$VF = 0.1458x^{-0.9273}\left(\text{Adj. } R^2 = 0.95,\ \text{RMSE} = 0.0018\right) \text{ for miscanthus}$$

and

$$VF = 0.04463x^{-0.7334}\left(\text{Adj. } R^2 = 0.87,\ \text{RMSE} = 0.0011\right) \text{ for switchgrass.}$$

The regressions were significant at the 95% confidence level.

3.2. Angle Of Repose (AOR) of biomass particles and corn

The AOR of miscanthus and switchgrass particles was proportional to particle size. For miscanthus and switchgrass, for example, with 1-mm to 25.4-mm particles, the AORs increased from 44.7 ± 1.9° and 45.8 ± 0.7° to 51.1 ± 2.3° and 52.2 ± 2.4° (Fig. 6a), respectively. The correlation coefficients between AOR and the aperture size of milling screens were 0.8784 ($p < 0.0041$) and 0.8728 ($p < 0.0047$) for miscanthus and switchgrass, respectively. The correlations between AOR and aperture sizes of milling screens were all significant at the 95% confidence level. The relationship between AOR and aperture sizes (mm) (x) of milling machine screens was expressed as:

$$AOR = 0.2526x + 44.61\ \left(\text{Adj. } R^2 = 0.7335,\ \text{RMSE} = 1.16,\ p < 0.0041\right) \text{ for Miscanthus}$$

$$AOR = 0.2671x + 45.34\ \left(\text{Adj. } R^2 = 0.722,\ \text{RMSE} = 1.261,\ p < 0.0047\right) \text{ for switchgrass}$$

For reference, the AOR of corn was measured as 22.5°. Given a specific particle size, the AOR values of miscanthus particles were slightly lower than those of switchgrass particles (Fig. 6a).

There were positive relationships found between biomass AOR and moisture content. For all particle sizes, the AOR of miscanthus and switchgrass with a moisture content of 25% was greater than that of samples with a moisture content of 14–16% and air-dried (7–10% of moisture content) (Fig. 6b and 6c). For example, the AORs of miscanthus and switchgrass were 46.1 ± 0.7°, 48.0 ± 1.2° and 49.3 ± 0.6° for biomass with a moisture content of <10% (air-dried), 14–16% and 25%, respectively. The findings of positive relationships between particle size and AOR and between moisture content and AOR for herbaceous biomass particles conform to Illeleji and Zhou (2008) and Chevanan et al. (2009).

3.3. Relationship between biomass AOR and energy consumption for auger conveying

For miscanthus and switchgrass particles, the relationship between AOR and flow specific energy consumptions (SEC) in an auger was not significant at the 95% confidence level (Fig. 7). The relationships between AOR and volumetric efficiency for handling miscanthus and switchgrass were not significant at the 95% confidence level either (Fig. 8). However, there was a weak positive relationship between AOR and SEC and a weak negative relationship between AOR and volumetric efficiency, though the relationships were not significant at the 95% confidence level. For example, the correlation coefficients between AOR and volumetric efficiency were −0.8573 ($p = 0.1427$) and −0.6893 ($p = 0.3107$) for miscanthus and switchgrass conveying, respectively, while the correlation

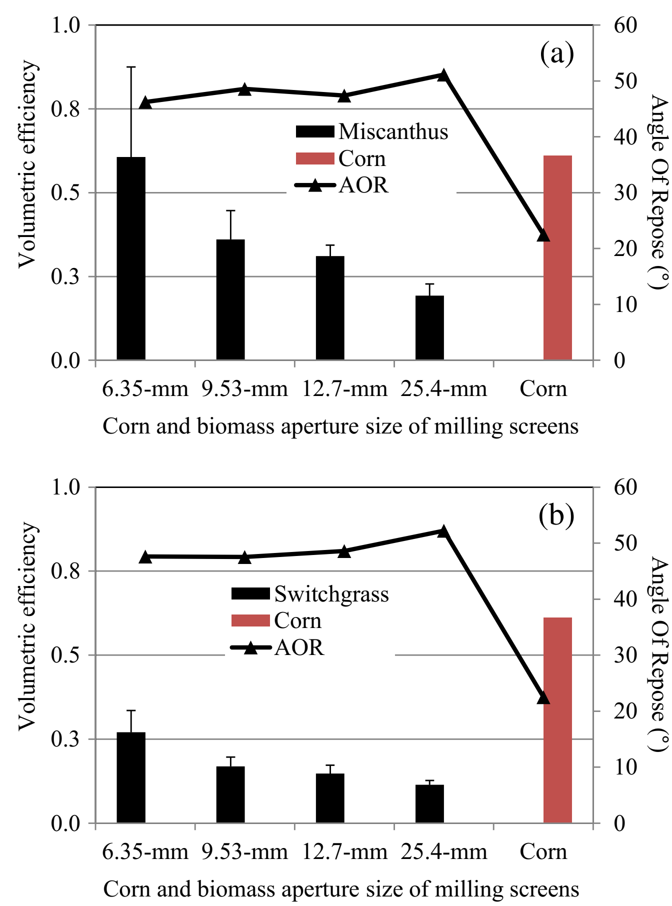

Fig. 8. Volumetric efficiency of corn and biomass conveying in enclosed auger vs. Angle of Reposes (AORs) of miscanthus (a) and switchgrass (b) particles.

coefficients between AOR and SEC were 0.8984 ($p = 0.1016$) and 0.9126 ($p = 0.0874$) for conveying miscanthus and switchgrass particles with the auger, respectively.

The flow regime of biomass particles is affected by more parameters than are present in the traditional equations (e.g., Eqs. 5–8), leading to the conclusion that these equations do not apply here [8,9,29]. Thus, it is difficult to accurately predict the flow energy consumption using traditional Eqs. 5–8 which do not take into consideration the above feedstock properties.

For practical applications, biomass flow performance should be investigated with specific handling equipment, e.g., augers, belt and pneumatic conveyors. Our results showed that there were no significant relationships between AOR values and energy consumption and between AOR and volumetric efficiency. Therefore, published physical properties of biomass such as AOR and coefficients of friction may not be useful in the prediction of flow behavior of biomass particles for given handling equipment. The effects of moisture content on AOR make the relationships between AOR and flow property even more complicated. Further studies regarding the relationship between energy consumption, volumetric efficiency, and physical properties of biomass particles are needed for specific handling equipment.

4. Conclusions

In this paper, Angle of Repose (AOR) and flowability in an auger were investigated for comminuted miscanthus and switchgrass. Conclusions were drawn as follows:

(1) The energy efficiency and mass flow rates for conveying miscanthus and switchgrass particles are far lower than that for conveying corn with an auger. On the other hand, the volumetric flow rate and volumetric efficiency of biomass feedstock conveyance are relatively close to those for conveying corn, especially for small miscanthus particles. This result implies that the low bulk density of biomass feedstock is one of the factors limiting energy efficiency improvement of biomass conveyance.

(2) Biomass AOR varies with biomass type, form, moisture, particle size and shape. The AOR of miscanthus and switchgrass was found proportional to particle size and moisture content.

(3) The relationship between AOR and SEC for handling miscanthus and switchgrass with an auger was not significant at the 95% confidence level.

(4) When applying commonly-used auger power requirement equations, the predictions of SEC for handling biomass particle did not compare well to measurements. Further studies are needed that include more physical properties in the equations for power/volumetric efficiency.

Acknowledgments

Publication contains data produced under an Energy Biosciences Institute-funded award. The authors are grateful to student interns Joshua D. Jochem, Julian C. Bohn, Qiyang (Martin) Huang, Colleen Moloney and lab technician Li Xu for enabling the experiments.

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