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Flow performance of ground biomass in a commercial auger

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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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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

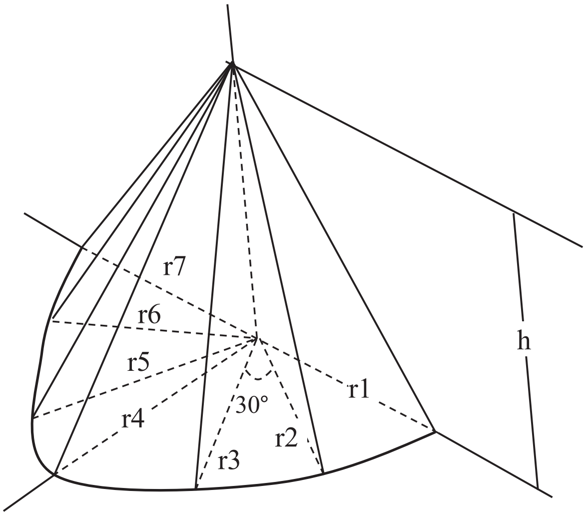

Fig. 1. Biomass Angle of Repose (AOR) calculated from the height (h) and average of radius r of the base of the particle semi-cone at seven positions with an interval angle of 30°.