Size Reduction and Densification of Lignocellulosic Biomass Feedstock for Biopower, Bioproducts, and Liquid Biofuel Production

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Abstract
Size reduction and densification of lignocellulosic biomass feedstock play a crucial role in the preprocessing and supply of biomass. Size reduction is an operation where the size distribution of biomass particles is adapted to a level determined by its final use. The purpose of densification is to increase the bulk and inherent energy density of the biomass feedstock, allowing optimization of transportation, storage, and potentially bioconversion. The equipment for biomass size reduction and densification must be robust with respect to the purpose of use, biomass property variability, and be highly efficient in terms of energy use and operating costs. Although the existing agricultural and forage equipment could be employed for size reduction and densification, specific equipment needs to be developed that can efficiently perform size reduction and densification of huge volumes of biomass for commercial bioenergy and bioproduct sectors. An empirical exponential or power equation could be used to describe the relationship between specific energy consumption and particle sizes for size reduction and between specific energy consumption and bulk density for compression of biomass.

INTRODUCTION

Global interest in bioenergy has dramatically increased over the past decade, owing to concerns regarding energy security, oil price spikes, and climate change.[1,2] 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, whereas the United States Department of Energy is targeting the replacement of 30% of the U.S. petroleum consumption with biofuels by 2030.[1–3] In addition, in 2007, the Chinese central government committed $5 billion over 10 years to ethanol development with a focus on lignocellulosic technologies.

Size reduction (often referred to as "comminution") and densification of biomass play a crucial role in the preprocessing of biomass. Size reduction is an operation where the size distribution of biomass particles is adapted to a level determined by its final use. For instance, if biomass is targeted at direct combustion, the material may be cut, baled, transported, and directly fed into a combustion unit. Here, mere rudimentary size reduction takes place in the baler. On the other hand, if the purpose is conversion into liquid biofuel, the average particle size is ideally in the micrometer range, allowing enzymes to readily access lignocellulosic constituents; however, grinding biomass into these extremely small particles requires excessive time and energy. Where biomass is aimed at use in biomaterials, the required particle size ranges from full stems, for instance, for the use of *Miscanthus* as a roofing material, to medium size for use as bedding for animals, and to a small size for use in engineered wood products.

Biomass feedstock, especially prairie grass energy crops and agricultural residues, have a low material and energy density. Densification can be used to optimize transportation by compressing the biomass material to a bulk density that is closely matched to the maximum density determined by load and weight limits. It is evident that densification increases the efficiency of storage and transportation, but also, handling can be improved by transforming the material into a flowable granular form through pelletization. Even size reduction after densification can be improved since the compressed material form allows for a consistent feeding rate. Finally, the achievable densification level is limited by cost and compression equipment scale, since biomass compression to an extreme density while retaining a high throughput requires equipment that is arguably expensive.

SIZE REDUCTION

The purpose of size reduction of biomass is to transform the material into a form that optimizes handling, storage, transportation, and conversion (or direct combustion). In addition, the process produces small particles that are conducive to pelletization, increases the bulk density of the material, and enhances the conversion process.[4] Size

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reduction processes can be categorized as 1) single-fracturing mechanisms such as cutting, shredding, and/or shearing mechanisms as found in forage choppers, rotary veneer choppers, shredders, roller grinders, and crushers; and 2) multiple-fracturing milling mechanisms such as knife mills, hammer mills, ball/rod mills, disk (attrition) mills, and ultrafine mills. Fig. 1 shows an example of a large tub grinder that is used to grind hay bales into animal feed.

The first category, which does not employ particle "classifiers" such as screens and diaphragms, is more suitable for coarse size reduction than for fine size reduction. For example, forage choppers and shredders are suitable for coarse size reduction of stem-based biomass, such as wood logs, cotton stalks, sugarcane, energy cane, sorghum, switchgrass, and *Miscanthus*. The main reason for the limitations of forage choppers or shredders in producing fine particles lies in the required precisely controlled feeding of the biomass into the machine. The size of particles produced by forage choppers and shredders typically ranges from 10 to 38 mm, which is suitable for direct combustion in biopower as well as municipal heating applications. In addition, the coarsely chopped biomass particles may serve as a source material for a pre-treatment process in biorefineries, or as an input for finer size reduction. The second category of size reduction machinery employs screens, diaphragms, or cyclones, and is most commonly found in larger-scale size-reduction practice. Although screen-type mills employ what is essentially a stochastic fracturing mechanism, the machine has the advantage that only particles are produced that have passed through a screen with a desired aperture size. The most common size reduction machines are hammer and knife mills, whereas disk and ball mills can be used to produce very fine particles. Overall, screen-type mills work well for dry biomass, but when its moisture content is larger than 25–30%, the milling screens tend to clog, especially for screens with an aperture size of less than 6.35 mm.

Fig. 1 Size reduction of *Miscanthus* and switchgrass feedstock bales at the Energy Farm of the University of Illinois at Urbana-Champaign.

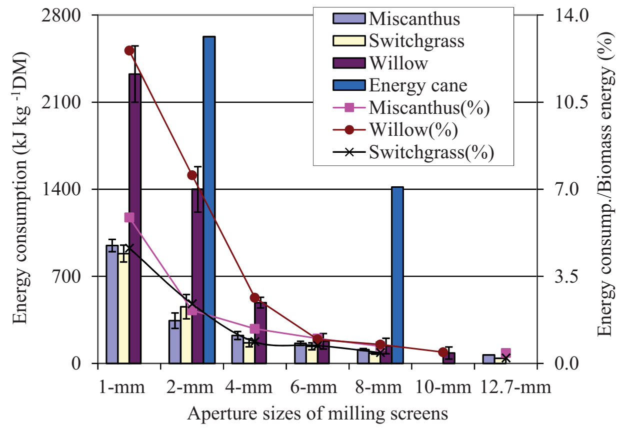

Fig. 2 Specific energy requirement of biomass size reduction. Note: The right *y*-axis refers to the percentage of specific energy consumption of size reduction to biomass inherent heating value (PIHV).
Source: From Miao, Grift, et al.[5]

Size reduction is one of the most energy-consuming operations in biomass preprocessing (Fig. 2). Per unit mass, and single-fracturing mechanisms are typically more energy efficient compared to multiple-fracturing milling mechanisms. Although Von Rittinger's, Kick's, and Bond's laws have been used to express the efficiency of milling machines, an empirical exponential or power equation may be used to describe the relationship between specific energy consumption and the resulting particle size for milling machines.[4–7] Fig. 2 shows the relationship between energy consumption and screen aperture size with a bench-scale knife mill that was captured using power law models for various bioenergy crops.

DENSIFICATION

The purpose of densification is to increase the bulk and inherent energy density of the biomass feedstock, allowing optimization of transportation, storage, and potentially bioconversion. Ideally, the densification process should retain the biomass' inherent energy content, require low-energy input, and not significantly increase the cost of feedstock production. Biomass densification refers to baling, bundling, module building, boxing, silo-bagging, packing, and pelletizing (briquetting or cubing). Baling is one of the elementary steps in the one- or two-pass biomass harvest process, especially for agricultural residues, dedicated prairie grass energy crops, and/or short-rotation woody coppice.[8–10] Round and square bales are the most common forms used in lignocellulosic transportation and storage. In North America and Europe, bale shape, size, and bulk density vary with baling machine, feedstock type and

Fig. 3 Baling *Miscanthus* and switchgrass at the Energy Farm of the University of Illinois at Urbana-Champaign.

properties, and farmers' practices. Square bales usually have a higher bulk density than round bales, and are simpler to handle during transportation and storage (Fig. 3). A drawback of square bales is that when uncovered outside, storage rain does not readily flow off the bales, possibly causing them to degrade rapidly. In the United States, based on specifications of most handling and baling equipment, the ideal square bale mass and size are 450 kg and $1.22 \times 0.76 \times 1.52$ m.[8–10] In contrast, in practice, the bale mass and size varies from 300 to 1500 kg and from $1.14 \times 0.76 \times 1.14$ to $1.32 \times 0.81 \times 1.93$ m,[8–11] respectively. The bulk density of agricultural residues and prairie grass bales produced in the field typically ranges from 110 to 170 kg DM m^{-3}, although high-compression balers can produce densities of up to 210 kg DM m^{-3}. An extreme bale density of 350–400 kg DM m^{-3} is achievable using specialized stationary equipment at biomass-processing centers.

In the United States, on-road vehicle size and weight limits constrain the bulk density of the material being transported to a range from 220 to 250 kg DM m^{-3}. For rail transportation, a much higher material density is allowed, ranging from 850 to 900 kg DM m^{-3}. Ideally, the biomass feedstock should have a density in the respective ranges mentioned to optimize the transportation efficiency.

Because of conceivable long-term storage of biomass for bioenergy and value-added bioproducts, bales can only be produced from the material with a moisture content lower than 15%; in-field windrowing is an option to bring the material to the required moisture content before baling. Bundling is mainly applicable to stalk-type biomass feedstock, such as *Miscanthus*, energy cane, sugarcane, sorghum, and short-rotation woody coppice. Module building, silo-bagging, boxing, and packing are mainly applied to biomass in bulk form.

Pelletization, which includes briquetting and cubing, is one of the most commonly used densification processes. The purpose of pelletization is, apart from increasing the density, to transform the irregularly shaped biomass feedstock into a granular, flowable form. The pelleted form effectively transforms biomass into a commodity that can be blended, transported, handled, and stored using the existing agricultural infrastructure. Commercial pellets have a diameter ranging from 4.5 to 6.5 mm with an aspect ratio ranging from 2 to 6, whereas their bulk density ranges from 450 to 600 kg DM m^{-3}. The bulk density of briquettes and cubes typically ranges from 300 to 450 kg DM m^{-3}.[9,11,12]

The biomass particle size required by most current pellet mills ranges from 3 to 8 mm. Pelletization usually takes place at a satellite-centralized processing center for bulk herbaceous feedstock, agricultural residues, sawdust and wood chips, as well as forest litter and debris. The current pelletization technology is energy intensive and prone to high biomass loss. An empirical exponential or power equation has been used to describe the relationship between specific energy consumption and bulk density for both bale compression and pelletization[11,12] (Fig. 4).

Another more exotic form of densification is torrefaction, which is essentially a mild form of pyrolysis. In this process, under atmospheric pressure and with the absence of oxygen, the biomass is heated to a temperature ranging from 200°C to 320°C, at which point, the biomass releases a fraction of its volatile gases, thereby increasing the bulk/energy density.[8] Torrefied feedstock not only possesses a high bulk density but is also suitable for subsequent size reduction, transportation, and long-term storage.

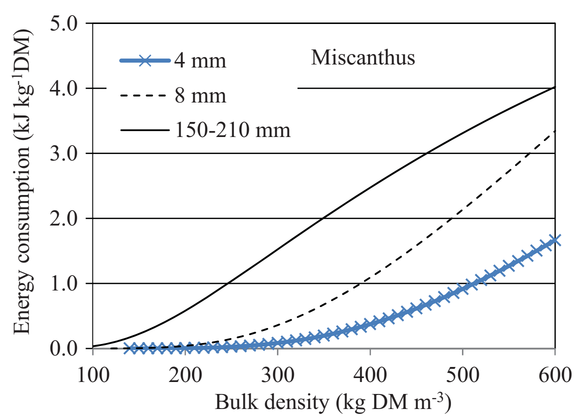

Fig. 4 Specific energy requirement for densification of *Miscanthus* with various particle sizes. Note: DM refers to dry matter. 4 and 8 mm refer to the aperture sizes of milling screens. 150–210 mm is the length range of large *Miscanthus* particles used in the experiments of Miao et al.
Source: From Miao, Grift, et al.[12]

CHALLENGES IN SIZE REDUCTION AND DENSIFICATION

While the levels of size reduction and densification are dictated by the end use of the biomass, they are also limited by feedstock type and inherent material properties, equipment, and facility conditions.[2–4,8] For example, size reduction and densification of wet biomass including energy cane, sweet sorghum, and sugarcane bagasse is more challenging than for dry biomass. In the commercial production of preprocessed feedstock, biomass densification and size reduction face the following challenges: the equipment must be reliable (therefore based on mature technology), and possess sufficient throughput capacity; it must produce biomass forms that allow for optimization of the entire feedstock supply–conversion chain, and it must be easily integrated into the existing feedstock supply–conversion chains.[2,3] Currently, the majority of technologies used for size reduction and densification are based on the existing agricultural or forage equipment. This equipment typically has a relatively low throughput, whereas in a full-scale bioenergy and bioproduct industry, the volume of material that must be processed is larger by several orders of magnitude. For example, to meet the goal of replacing 30% of the current U.S. petroleum consumption with biofuels by 2030, annually, a huge volume of 1 billion dry tons of feedstock will need to be grounded. This is more than 3 times the 2011 U.S. corn production and 7 times the 2011 U.S. dry hay production in weight. It is clear that machinery for size reduction and densification needs to be developed that can process biomass feedstock with very high throughput and efficiency and is robust with respect to variations in biomass properties.

CONCLUSIONS

Biomass densification and size reduction are the essential tasks in the preprocessing of biomass for biopower, bioproduct, and liquid biofuel production. To meet the target biomass production volumes as set forth by various economic powers in the world, equipment needs to be developed that can efficiently perform size reduction and densification of huge volumes of biomass, preferably into a flowable form that can utilize the existing handling, storage, and transportation infrastructure. The equipment must be robust with respect to biomass property, variability, and highly efficient in terms of energy use and operating costs. An empirical exponential or power equation could be used to describe the relationships between specific energy consumption and resulting particle sizes for size reduction and between specific energy consumption and bulk densities for compression of biomass.

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