Chapter 6

Biomass Handling and Feeding

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Additional information is available at the end of the chapter

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Abstract

Handling and feeding of materials represent a substantial challenge in biomass feedstock supply systems and have been primary factors causing pioneer industrial biorefineries to struggle to achieve their production targets. The focus of this chapter is handling and feeding within the plant prior to conversion. The dominant material properties that impact biorefinery operations are presented, and biomass flow patterns and behavior in silos, bins and hoppers are briefly explained. Methods to measure key properties are reviewed, including the Jenike method as well as the efficacy of newer ring shear methods. Finally, areas are identified in which future effort should focus to have the greatest impact to alleviate the challenges that currently plague the emerging biomass industry.

Keywords: biomass, feedstock, handling, feeding, flowability

1. Introduction

Feeding and handling of materials represent a substantial challenge in biomass feedstock supply systems. Conventional feeding, conveying, and storage systems for dry bulk solids are generally not suitable for lignocellulosic feedstocks because of their low densities and elastic nature. Reports indicate that industrial plants that handle bulk solids operate on an average at 77% of their design capacity, which is considerably lower than that of plants that handle liquids or gases [1]. Importantly, however, many of the surveyed plants handled simple powders for which there are decades of handling experience in multiple industries, including food, pharmaceutical, powder metallurgy, ceramics and plastics. Such powders often have favorable properties, such as low cohesion, small particle sizes and distributions, high densities and low compressibilities that facilitate feeding and handling. In contrast, feedstocks for lignocellulosic biofuels production tend to be cohesive, have large particle size variations, low densities and are highly elastic, leading to greater challenges. It has been estimated that in 2016, the biofuels production achieved only 7% of the total active 58 million gallons per year of nameplate capacity [2]. Delayed startup times and operation below the designed capacity can have serious consequences in terms of the cost of the final product and missed business opportunities. As indicated in **Figure 1**, an increase in plant down time by 10% (decrease in the minimum on-stream factor) can increase the minimum fuel selling price by nearly a USD per gallon. Achieving 80% time on-stream compared to design capacity, even for a short time period of 2 weeks, is still considered a cellulosic biofuel breakthrough as evidenced by a recent press release by POET-DSM [3].

Several factors underlie the difficulty of feeding and handling biomass. Particulate solid materials belong to the family of yield stress materials that have flow behavior that is intermediate between those of solids and liquids [4]. These materials can support imposed stresses without significant deformation until the stress attains a threshold value. At that threshold value, permanent deformation occurs that can include complex localized elastic and plastic behavior due to discrete particle effects that are not present in liquids, creams, or gels. The threshold stress value is closely related to inter-particle friction, which depends strongly upon stress and deformation histories. The complexities associated with the flow of bulk solids make them much more challenging to handle than traditional solids, liquids, or gases. Common problems include uncontrollable flow that takes the form of plugging, obstructed or limited discharge, and erratic flow, as well as particle segregation and loss of live storage due to material adhering to container walls. Under extreme cases, flow problems can even cause high transient stresses that result in structural failure.

In addition to numerous research articles, several books and book chapters have been written on the topic of biomass handling and feeding [5, 6]. As explained by Bell [7], there have been significant, though relatively few, contributions from various researchers in powder mechanics, solids flow, and related topics over the last 100 years. This chapter is divided into three sections. The first section briefly summarizes the primary topics of biomass handling

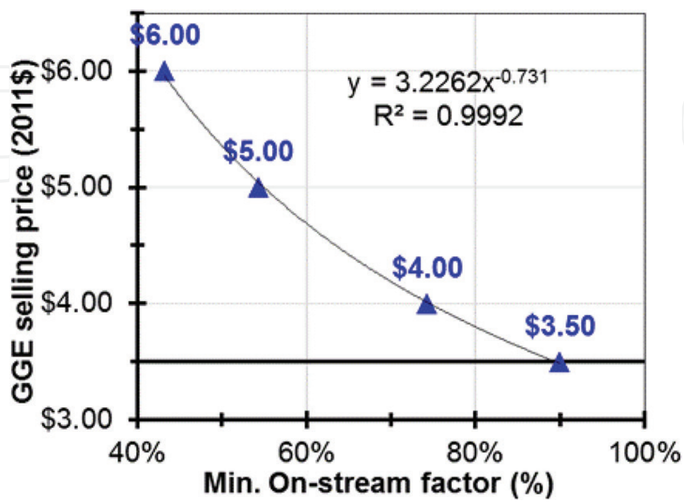

Figure 1. Gallon of gasoline equivalent (GGE) selling price as a function of minimum on-stream factor. Adapted from [2].

and primary impacts of dominant material properties. The second section presents a brief explanation of biomass flow in silos, bins and hoppers and includes key analyses needed to understand biomass flowability in the context of shear deformation, which is how bulk solids flow. The third section focuses on recent advances that have been made in biomass handling and briefly points to areas in which future effort should focus to have the greatest impact to alleviate the challenges that currently plague the emerging biofuels industry.

Biomass energy systems are typically considered to consist of several processes, including resource production, collection, transportation, storage, feeding, conversion and transmission of biofuel or energy to end users. Production and collection include farming and forestry activities, as well as collection of waste materials that are suitable for bioenergy production. Transportation of biomass to conversion plants is usually performed by truck, barge or rail car. Short-term and long-term storage at the plant is necessary to ensure that sufficient material is on-hand to keep the plant operating through small disturbances in supply or to mitigate exceedance, in which spikes in biomass supply exceeds conversion capacity, such as could occur in the fall for agricultural residues. The topics associated with research production through storage are wide-ranging and too voluminous to be considered in this chapter. Basu [5] has provided a brief summary of those activities and their implications. The primary concern of this chapter is biomass handling at the plant prior to conversion.

The ability of a real feedstock material to flow through a particular assembly system is a function of the design of the structure and the rheological properties of the biomass material. These properties include bulk density, moisture content, compressibility, elasticity or spring back, particle size and shape distributions, cohesive strength, unconfined yield strength, adhesive strength (shear stress required to initiate motion on a surface), angle of internal friction (theoretical angle describing stress at failure), wall friction angle (shallowest angle at which a material slides on a surface), and permeability (ability of a material to allow gas or liquid to pass through it). These physical properties are important for both biochemical and thermochemical conversion processes [8, 9]. Thermochemical reactions are known to be sensitive to particle geometry, especially for fast reaction rates and short particle residence times. Biochemical conversion processes are generally more tolerant of variations in particle sizes and shapes, such that constraints on physical properties are primarily imposed by requirements of the feeding and handling systems [10, 11].

A wide range of feedstock particle-size requirements have been reported for supplying feedstocks for biofuels conversion applications [12]. Feedstocks for fast pyrolysis are approximately 2 mm in size [13, 14], while those for biochemical conversion processes are much larger, varying from 6 to 75 mm. Excessive quantities of fine particles contribute to nuisance dust, clogged filters, and reduced permeability of the bulk solid to gases and liquids. Oversized particles create a different set of problems, such as incomplete conversion as well as plugging of air locks and pneumatic transfer lines. Particle grinding and other preprocessing steps have a strong impact on feeding behavior. For example, Idaho National Laboratory reported that replacing a hammer mill with a knife mill with the same nominal screen size solved a blowout problem with a pressure seal [12]. The level of fines can also increase as particles pass through consecutive unit operations and can cause negative impacts on the

Performance aspect	Governing parameters/mechanisms	Impacts
"Bulk flowability"	Particle-particle interactions, bulk density, chemical composition, moisture, temperature, and trapped gases	Easily flowing materials • facilitate emptying and cleaning equipment to prevent spoilage • readily fill containers to minimize storage and transportation volumes • feed uniformly for processes that requires consistent flow • tend to be easier to mix and blend • if overly aerated, may flow too freely and flood equipment
Time consolidation or caking (increase in strength after prolonged storage times)	Can be due to many different effects, such as crystallization, material creep, capillary condensation, and fungal growth	• Loss of live storage space because material adheres to storage container walls • Risk of loss of perishable material • Erratic flow with large dynamic forces on containing structures • Material bridges over outlet preventing flow
Handling properties in a slurry for enzymatic conversion	Particle-particle and particle-slurry interactions through particle shape, size, and ploy-dispersity	• Lower volatility resulting in increased conversion efficiency • Acidity of product bio-oil may be reduced
Reactivity for thermochemical and biochemical conversion processes	Particle sizes and shapes affect surface area to volume ratios	• Small particles have much faster thermochemical reaction kinetics as compared to large particles • More reactive particles can be substantially larger than less reactive particles. For example, biomass particles can be larger than coal particles in co-fired gasifiers
Permeability of bulk solid to flow of gases or liquids	Pore spaces between particles that allow gases and liquids to flow through bulk solid	• Low permeability restricts chemical access to material's interior, slowing reactions • Low permeability can limit discharge rates from outlets

Table 1. Noninclusive summary of feedstock performance related to particle physical and mechanical properties (adapted from [15]).

feeding and conversion performance [7]. Thus, even if ideal specifications are achieved, care must be taken so that the subsequent unit operations do not unintentionally modify material properties.

The behavior of biomass feedstocks in handling and feeding equipment is affected by many factors beyond traditional rheological properties. These factors include chemical composition of particles, temperature, presence of trapped gases and the unique stress and deformation histories of the bulk solid. The impacts of specific parameters are summarized in **Table 1**. Particle size and moisture content often receive the most attention, and it is important to recognize that in some cases the particle size "specification" is based on the screen size of a laboratory mill, rather than a thorough classification of particle-size distribution. Such a screen size specification is often misleading because in most cases the mean product particle size is

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significantly smaller than the screen size. Many parameters actually affect the particle size distribution and its mean. For example, the mill type strongly affects particle size and shape. Typically, hammer mills produce more fine particle sizes than knife mills using the same screen size and also result in wider particle size distributions. This is particularly important because knife mills are typically used to prepare samples for laboratory tests, while hammer mills are often used in high-throughput industrial-scale applications. The impacts of moisture content, incoming particle size, and tool speed also vary for different mill types [12].

2. Silos, bins and hoppers for storing and discharging

2.1. Flow obstructions and patterns

Proper storage and retrieval of biomass is critical to maintain quality in terms of both chemical properties for conversion and physical properties for feeding and handling. Retrieval or reclamation of biomass from storage is one of the most trouble-prone processes of biomass plant operation [5]. Silos are common in the agricultural and grain industries to store large quantities of material in a protective environment and can be large in diameter (4–15 m) and quite tall. Material is usually augured into the top of the silo and removed at the bottom. Very cohesive materials require specialized and expensive sweeping reclaimers to extract material from the entire bottom cross-section of the silo, where compressive pressures and material strengths can be very high. These systems require extensive engineering and are not discussed further here; however, additional information can be found at http://www.laidig.com/reclaimers.

Less cohesive materials and shorter storage systems in which compressive forces are lower often use less expensive hoppers or chutes to funnel biomass to a small feed discharge mechanism. In the 1960s, Andrew Jenike developed the first complete methodology for the flow of bulk solids within the framework of hoppers, bins, and feeders. His work included test equipment and procedures for measuring the necessary material properties, a theory of bulk solids flow within hoppers and bins, and a procedure to determine the hopper slope and outlet dimensions required for unobstructed gravity flow [6, 16]. The development presented here closely follows the formalism that Jenike advanced.

As described by Jenike [17], the primary issues in the design of hoppers and chutes are: (1) solid flow pattern, (2) slope angle of discharge, and (3) size of the discharge opening. Although there are a number of flow obstructions that may develop in a bin, two primary types are analyzed here: arching or doming as illustrated in **Figure 2(a)** and ratholing or piping as illustrated in **Figure 2(b)**. Most particulate solids are easily flowable when they are well-aerated but become cohesive and strong when compacted. For example, fluidized bulk solids have very low shear strengths and typically flow with carrier gases; however, the same bulk solids can be made into rigid briquettes or pellets by subjecting them to high compressive stresses, especially in the presence of moisture or binders. The increasing strength of bulk solids with increasing compressive stress allows them to form arches and bridge over openings. In the case of large bins and hoppers, the weight of material in upper layers compresses the lower

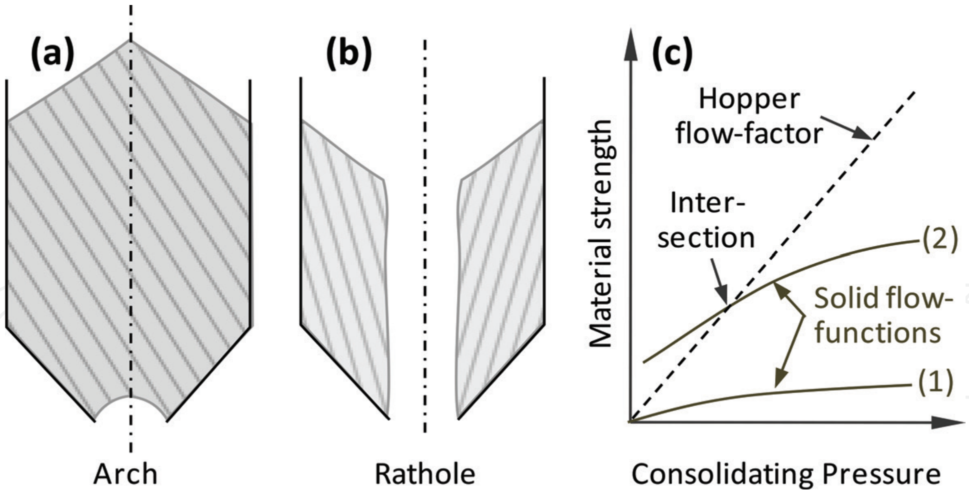

Figure 2. Schematics showing (a) arching, (b) ratholing, and (c) flow functions FF for two materials and a representative hopper flow factor.

material, causing it to gain strength and become cohesive. The cohesive strength, typically referred to as unconfined yield strength f_c, of a solid resulting from its stress history is the cause of the arch shown in **Figure 2(a)**. The strength-pressure curve of a solid is known as its flow-function FF and typically increases rapidly with increased pressure in the low pressure range and then increases more slowly at higher pressures [18]. The strength developed by different bulk solids as a function of consolidation pressure varies from solid to solid as exemplified by the flow-functions of materials (1) and (2) in **Figure 2(c)**. It is evident that material (2) is much stronger and less free flowing than material (1).

Approximating the downward pressure across an arch to be nearly uniform, the total force acting to break the arch scales with the area ($\pi d^2/4$ for a circular outlet, where d = diameter), while the material's ability to maintain the arch only scales with the perimeter (πd for a circular outlet) of the hopper outlet. Thus, if the size of the hopper outlet is steadily increased, eventually the strength of the material becomes insufficient to support the arch and the bulk solid flows. Flow of a bulk solid material can be assured for a hopper with specified geometry and wall material, as long as the strength of the material is maintained below a certain value, giving rise to the concept of a hopper flow-factor, which is also shown in **Figure 2(c)**. The intersection of the material's flow-function with the hopper's specific flow-factor usually determines the minimum outlet size needed to assure consistent gravity flow. Similar reasoning also applies to the formation of ratholes or pipes.

The flow pattern in a hopper affects all aspects of its performance, including not just the outlet size required to assure reliable discharge, but also the order in which the contents are discharged [19] and the loads acting on the structure [20, 21]. Two recent standards identify some flow patterns that have been identified [ISO 11697 (1992) and Eurocode 1 part 4 prEN 1991–4 (2002)]. For most purposes, flow patterns can be classified into two categories, mass flow and funnel or plug flow, as illustrated in **Figure 3(a)** and **(b)**. Perfect mass flow requires that all the material moves downward when material is removed from the outlet. Typically, smooth and steep walls are required to achieve mass flow. In contrast, funnel flow hoppers

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allow some material to remain at rest while only a portion of the material moves through the hopper. In funnel flow, a moving channel of material is formed within the central region of the hopper, while material outside the channel is at rest. A distinguishing feature of funnel flow is that the material flows primarily on itself, such that the walls of the container do not influence the shape of the channel or the velocities of moving particles.

Mass flow hoppers have many advantages over funnel flow hoppers. Mass flow hoppers preserve the first-in-first-out flow sequence, allow powders to deaerate, minimize segregation, and supply uniformly densified material to the feeder (see **Figure 3(a)** and [22]). Funnel flow hoppers have the opposite characteristics: the flow sequence is first-in-last-out, ratholes may form, powders have a strong tendency to flood, segregation problems are exacerbated, and the compaction of material fed to the hopper is nonuniform (see **Figure 3(b)**). Materials that are suitable for mass flow hoppers and not funnel flow hoppers include cohesive solids, fine powders, degradable materials, and solids which segregate [22]. The primary advantage of funnel flow hoppers is that they can have shallow hopper angles and, consequently, require much less headroom. A third common flow pattern, denoted expanded flow, is illustrated in **Figure 3(c)**. In this flow pattern, the lower portion of the hopper is designed to ensure mass flow and prevent arching while the central and top portions are designed solely to prevent ratholing (funnel-type flow is allowed in the central portion of the hopper). Expanded flow designs are practical for hoppers with large diameters filled with solids that exhibit strong tendencies to rathole in funnel flow bins, but flow well in mass flow bins.

2.2. Yield locus and effective yield locus

As a particle moves downward through a bin and hopper, the pressure field around the particle first increases as the height of material above it increases and then in the hopper section, the pressure decreases as the cross-section size decreases toward the outlet. At an open outlet,

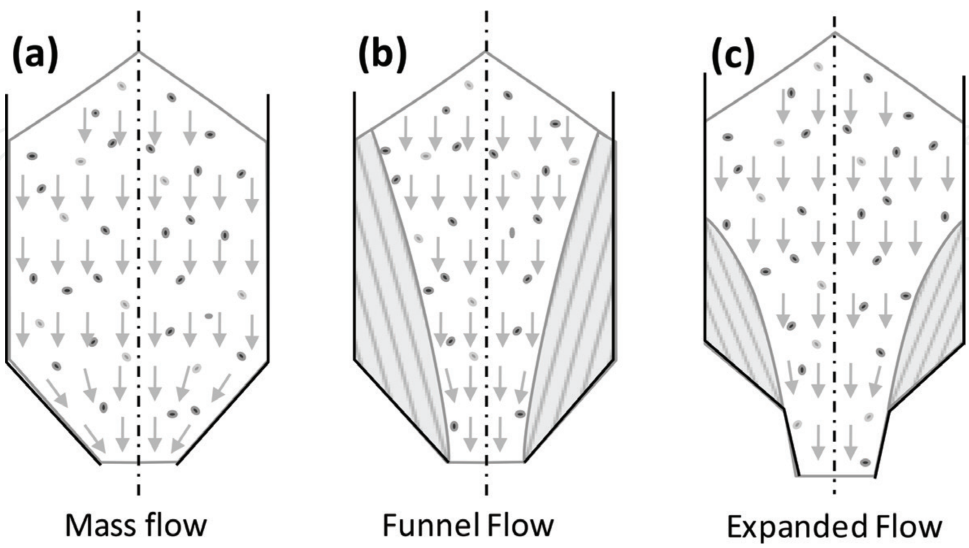

Figure 3. Schematics showing (a) mass flow, (b) funnel flow, and (c) expanded flow. Note that for funnel flow, the shape of the flow channel is independent of the shape of the hopper.

the stresses perpendicular to the material surface are nearly zero (i.e., the material is unconfined). At some point in this process, the major and minor principal stresses (pressures), σ_{major} and σ_{minor}, respectively, experienced by neighboring particles pass through maximum values, labeled as σ_1 and σ_2, respectively. For materials with low spring back or elasticity, the final bulk density ρ_b of the material depends only on σ_1 and σ_2, which are the dominant consolidation pressures.

Importantly, the shear strength of a static mass of material depends not only on the instantaneous principal stresses, σ_{major} and σ_{minor}, but also on their maximum values, σ_1 and σ_2, that are attained within the "memory" of the material (i.e., the shear strength is a function of σ_{major}, σ_{minor}, and ρ_b). This relationship is depicted in **Figure 4** as a yield locus curve, which represents the collection of points in consolidation-shear stress space that results in failure of the material at a specified bulk density $\rho_b(\sigma_1, \sigma_2)$. This follows the well-known flow-no flow criteria, which is that flow in a bulk solid occurs if the applied stress at a location exceeds the material's yield strength. If the stress in the material is below the yield locus (i.e., the stress is less than material shear strength), then flow does not occur. The point marked "0" denotes the end of the yield locus. If a neighborhood of particles is subjected a pressure greater than that at point "0," then the consolidation pressures, σ_1 and σ_2, necessarily increase, which also increases the bulk density, and a new yield locus is formed that is typically higher on the τ axis. Another important point to note in **Figure 4** is that a Mohr stress semi-circle through the point "0" and tangent to the yield locus determines the maximum major and minor consolidation pressures, σ_1 and σ_2, (as described in nearly any strength of materials text book). The unconfined yield stress $f_c(\sigma_1, \sigma_2)$ can also be determined using the yield locus because it is the major consolidation pressure that corresponds to zero minor consolidation pressure (corresponding to an unconfined surface). Thus, the Mohr-stress semi-circle that defines f_c is also tangent to the yield locus but is subject to the additional constraint that it pass through the origin (i.e., the minor stress is zero), as depicted in **Figure 4**.

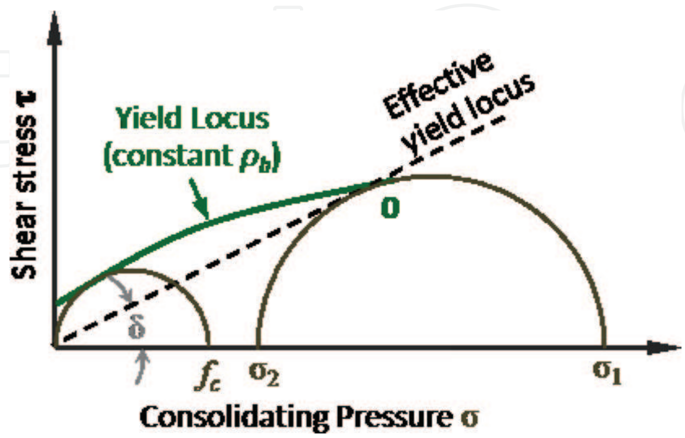

Figure 4. Schematic showing typical yield locus and effective yield locus for a material that has been subjected to maximum consolidation pressures σ_1 and σ_2 (resulting in a steady bulk density ρ_b, assuming that spring back is negligible).

The local cohesion of the material, which is a measure of the inter-particle binding strength in the absence of applied pressure (i.e., the shear strength with zero consolidation pressure) is the intercept of the yield locus with the shear stress axis. A fourth parameter that can be found from the yield locus is the effective angle of internal friction δ, which is the angle between the σ axis and the tangent to the Mohr's circle passing through point "0." δ defines the straight line termed the "effective yield locus" and is a measure of the internal friction at steady flow.

2.3. Jenike shear tester and test method

To measure the yield locus curves of finely divided materials (i.e., powders) at specified values of bulk density ρ_b, Jenike developed a special shear cell test apparatus, shown schematically in **Figure 5**. The shear cell is closely modeled after simple direct shear cells used to measure the shear strength of soils (A direct shear tester is one in which the design of the tester controls the location of the shear zone. In an indirect shear tester, the shear zone is allowed to develop according to the applied state of stress). The primary difference between the Jenike shear cell and simple shear cells used in soil analysis is that Jenike's cell is designed to be much more sensitive to small normal loads N and provision is made to ensure that the sample experiences similar maximum consolidation pressures, σ_1 and σ_2, before different points on the yield locus are measured.

The process to measure a point on a yield locus actually consists of two steps, referred to as (1) "preconsolidation" or "preshear" and (2) "shear." The objective of the first step is to preconsolidate the sample to the point "0" in **Figure 4**. The exact procedure to fill the ring and preconsolidate the sample is described in an ASTM and other standards [ASTM D-6128-06; Institution of Chemical Engineering, UK, 1989]. After uniformly filling the cell with material, a vertical force N_0 is applied to preconsolidate the sample. A horizontal shear force S is then applied to the bracket to move the lid and ring at a slow constant velocity relative to the base. The sample is slowly sheared in this manner until a steady state flow with constant force S is observed, indicating that the sample is preconsolidated to point "0" in **Figure 4**. This short preshearing step helps establish a uniform stress state throughout the sample. The force S is then removed, and the normal load N_0 is replaced with a smaller load N_1. The second step of

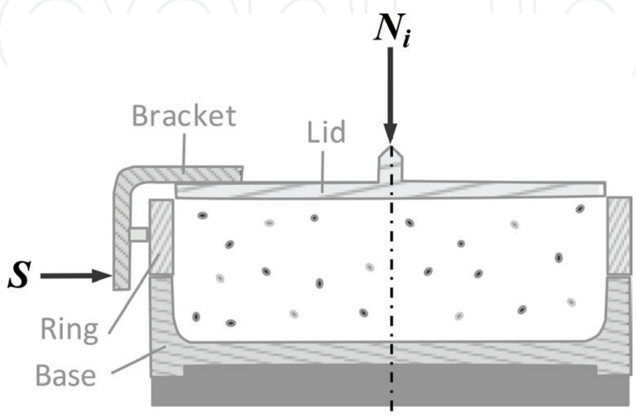

Figure 5. Schematic of Jenike's shear cell showing base, ring, lid and bracket.

the shear process, referred to as "shear," is accomplished by again applying a force S on the bracket and recording the maximum force required to shear the sample. The normal load N_1 and the maximum recorded shear force S are then converted to a consolidating pressure and yield shear stress, respectively by dividing each value by the horizontal area of the shear cell. The two values obtained in this manner define a single point on the desired yield locus. To obtain additional points on the yield locus, the two steps "preshear" and "shear" are repeated with different normal loads N_2, N_3, etc. The entire process is shown schematically in **Figure 6**.

It is critical that the first step ("preshear") be performed in as nearly as identical a manner as possible before each point on the yield locus is measured to ensure that the preconsolidation stresses are the same for each measurement (i.e., each measurement shares the same maximum principal stresses σ_1 and σ_2). After a sufficient number of points are obtained to define a yield locus, the unconfined yield stress f_c for the specific maximum principal stress σ_1 is found as described above. A plot of several values of f_c versus corresponding values of σ_1 yields the material flow function featured in **Figure 2(c)**. The measured flow-function FF is used with design charts developed by Jenike to quantitatively design systems to handle flowing bulk solids, such as determining the minimum outlet of a hopper that is required to ensure that an arch or rathole cannot form.

The flow-function is also used to classify the flowability of bulk solids. Jenike warns that several numbers and curves are required to precisely define the flowability of a bulk solid [20]; yet, for the sake of convenience, Jenike offered a simple flowability scale based on the flow function. The classification is accomplished by picking a point on the flow-function and determining the ratio of the major principal stress σ_1 to the unconfined yield strength f_c, denoted as $ff_c = \sigma_1/f_c$. The flowability of the material is then defined by the following scale:

$0 < ff_c < 2$—Very cohesive and non-flowing

$2 < ff_c < 4$—Cohesive

$4 <$ f $ff_c < 10$—Easy-flowing

$10 < ff_c$—Free-flowing

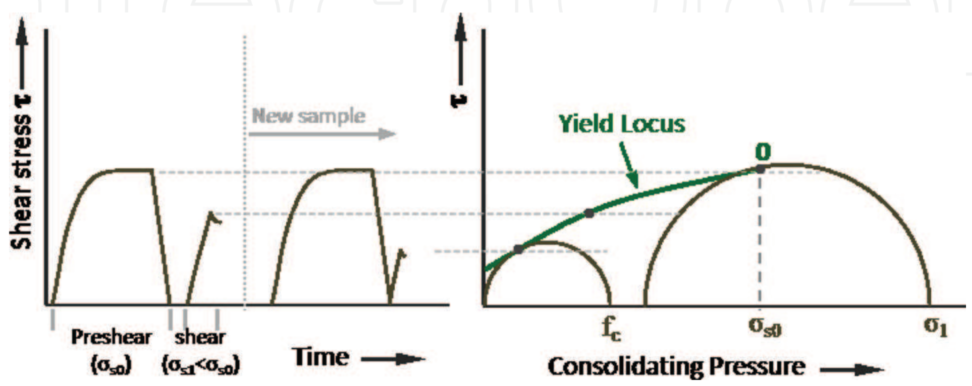

Figure 6. Procedure to measure three points on a yield locus using the Jenike shear tester.

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This classification scheme is most useful for materials for which the flow-function is approximately a straight line. If the slope of the flow function of a material is not approximately constant, then the ratio σ_1/f_c is not constant and the material can exhibit behavior ranging from very cohesive to free-flowing depending on the consolidation pressure it is exposed to. Classification of such a material requires choosing a point on the flow function that is representative of conditions that exist when the material is required to flow.

Although Jenike's approach offers proven principles for designing systems to handle bulk solids, it also has drawbacks, which have greatly hindered its widespread adoption by industry [20, 23]. First, ensuring that the preconsolidation stresses at the point "0" in **Figure 4** are consistently and properly attained before measuring each point on the yield locus is not trivial and requires a high level of skill and training. Second, the tests are very time-consuming and expensive. It has been estimated that obtaining a flow-function curve for a material requires approximately 15 h for a skilled technician. The time cost is further exacerbated if multiple flow functions are required to understand a material's flow behavior at different moisture contents, temperatures, or after prolonged periods of consolidation (the shear strength of many materials increases with temperature, moisture, and after prolonged consolidation times). A third drawback is that measurements are not possible at small normal stresses, so that it is necessary to extrapolate the yield locus to find its intersection with the τ axis (cohesion). A fourth drawback is that the Jenike tester has very limited travel (approximately 7 mm) to minimize the reduction of the shear cross-sectional area during the test. The small amount of travel is sometimes insufficient to ensure that a consistent stress state is attained during the preshear step. Materials that are particularly problematic are those with large particles, high moisture content, and/or a high elastic limit (large spring back). The final drawback to the Jenike tester is that substantial variability often exists in the measured values, increasing the error in the extrapolation of the yield locus to find its intersection with the τ axis (cohesion) and making it necessary to employ conservative designs for hoppers to promote flow.

2.4. Other shear testers capable of determining the flow function

Despite the drawbacks of the Jenike shear tester, it remains one of the very few testers that is capable of measuring the unconfined yield stress f_c (and hence the flow function) of a material without additional uncertain assumptions. Other instruments that can also measure f_c include biaxial shear testers, uniaxial shear testers, and ring shear testers. Biaxial shear testers are uncommon due to their complexity, and are not practical for the measurement of flow properties for routine design of bulk solids handling systems. So-called "uniaxial" testers are very simple, and underestimate f_c because the consolidation pressure is applied in the same direction as the shear stress [23]. A further disadvantage of uniaxial testers is that they can only be used to test bulk solids that are sufficiently cohesive that they retain their consolidated shape when lateral support is removed. A result of the last observation is that uniaxial testers cannot perform tests at low consolidation pressures. The primary advantage of uniaxial testers is their simplicity-tests can be performed quickly. It is worth noting that a simpler and quicker procedure can be followed with the Jenike shear tester to obtain approximate results for quality control or product development. This method employs only a single test (preshear and shear) and a repetition test to determine an estimate for the yield locus and a single point on the flow-function [20].

The last type of instrument capable of measuring unconfined yield stress f_c is a rotational ring shear tester. Early ring tester models were only partly successful in accurately measuring the unconfined yield stress f_c of materials, and it was not until an improved unit was developed by Schulze in 1994 that the superiority of ring testers over the Jenike shear tester became apparent [23]. The test procedure with a ring shear tester is equivalent to that described above—the sample is still sheared in two steps including "preshear" and "shear." The primary advantage of ring shear testers is the unlimited rotary travel that they offer, making it possible to measure a complete yield locus without changing the sample or refilling the shear cell. Unfortunately, however, ring shear testers do not overcome all of the limitations of linear shear testers. In particular, ring shear testers have difficulty evaluating the flow performance of compressible materials because the stress fields of those materials are highly non-uniform during the test [24, 25]. An automated commercial version of the Schulze ring shear tester is now available that increases the speed of the test process and reduces the dependence of measured flowability properties on the skill level of the operator [6]. Of course, these improvements come at a substantial cost: the base price of a commercial Schulze ring tester is greater than $70,000 USD. However, even with these features, ring shear tests are not always reliable for biomass as shown in **Figure 7**, which compares predicted minimum hopper opening sizes to ensure consistent flow based on shear test results of various ground pine materials to experimentally measured values [26].

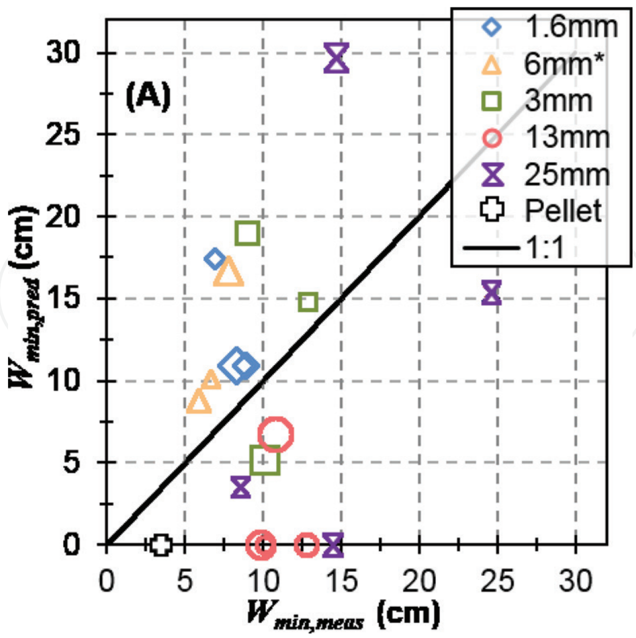

Figure 7. Predicted minimum hopper outlet widths versus the values measured using the hopper tests. Symbol size indicates moisture content with larger symbols representing higher moisture content (10–40% wet basis).

2.5. Conveying and feeding

Silos and bins serve to store material, which is then discharged through reclaimers or hoppers as explained above. After material is reclaimed from storage, it is subjected to final evaluation for suitability, including excessive moisture or unacceptable sizes of particles. Foreign materials, such as rocks and metals are also removed. The material is then conveyed using belt, chain, or pneumatic conveyors to the conversion reactor and is fed into the reactor. There are six primary types of biomass feeders: (1) gravity chute, (2) screw conveyor, (3) pneumatic injection, (4) rotary spreader, (5) moving-hole feeder, and (6) belt feeder. Proper design of the reclaiming, conveying, and feeding equipment is essential to ensure uninterrupted flow from storage to feeder. The design principles are based upon the material properties discussed above and, overall, share similar considerations with the design of silos, bins and hoppers summarized above. For detailed analyses of the various options, the reader is referred to specialized texts, such as those by [5–7, 23]. One topic that is of note here is the cost of biomass handling systems. Material handling represents a significant portion of the capital and operating costs of a biomass conversion facility even if all of the components operate exactly as intended. **Table 2** shows an example of relative costs of handling equipment for two biomass pelleting facilities, one for herbaceous feedstocks and one for woody feedstocks. The herbaceous facility is designed to handle baled material while the woody facility is designed to handle wood chips. For both feedstocks, the drying operation is the single largest cost with grinding and densification being the next most expensive. Overall, handling and processing bales incurs approximately $1.2 million more in total direct costs than handling and processing wood chips.

System type	Herb.	Woody
Material receiving	5%	4%
Separator/screener	2%	1%
Primary grinder	16%	—
Dryer	31%	41%
Secondary grinder	10%	13%
Densification	13%	16%
Dust collection	6%	7%
Buffer storage	2%	2%
Controls	2%	2%
Equipment installation and electrical	4%	4%
Civil/structural work	9%	9%
Total direct cost	$5.4 M	$4.2 M

Table 2. Relative estimated costs in 2011 USD ($) of herbaceous and woody biomass handling and preprocessing systems, each operating at 9 tons/h (adapted from [27]).

3. Solutions to biomass handling challenges

3.1. Co-optimization of feeding equipment and material properties

Failure to recognize the extent of material variability during equipment and process design is a common cause of feeding and handling problems. Systems can be designed to accommodate the full range of material variability; however, costs often increase as systems are made more robust. In the end, the selected design becomes a trade-off between increased capital costs for more robust systems (which is a near term, well-defined expense) and increased operating expenses due to additional down time if less expensive equipment fails. Importantly, the impact of increased operating costs is farther in the future and is rarely well defined. Relying on uniform bulk densities for gravity feed, low moisture and consistent particle-size distributions allows equipment designs to be simple and low cost. As long as the material meets the desired specifications, no problems are anticipated, but when material properties deviate outside narrow design specifications, equipment efficiency and reliability suffer, often dramatically.

There are two primary approaches to addressing material handling problems. First, the equipment systems may be engineered to anticipated material properties, or second, the feed material may be engineered to perform properly in the equipment systems. The first approach follows traditional engineering design concepts and tends to gain the most attention. In truth, a balanced approach that carefully considers both methods is usually best, especially for processes that are intended to handle different feedstock materials or materials that do not have well-defined and controlled properties.

Figure 8 depicts how this dual approach of more robust equipment design and better control of feedstock material properties can improve the reliability of a hypothetical operation,

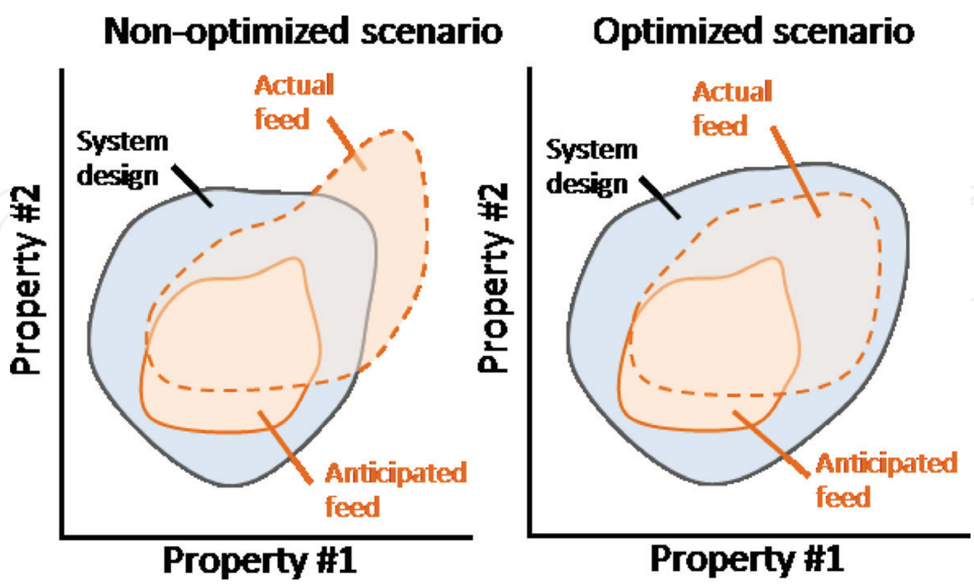

Figure 8. The combined approach for solving biomass handling and feeding problems through improved system design and improved preprocessing operations that control feedstock properties to meet to specifications. The scenario on the right in which the equipment systems and feedstocks have been optimized will likely exhibit superior and more reliable performance.

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such as a bin/auger feeder. The range of anticipated material properties and the corresponding design specifications of the hypothetical equipment are illustrated in the regions labeled "anticipated feed" and "system design," respectively. Variation of material properties, due to unavoidable diversity of sources and supply conditions, including seasonal and weather effects, over the course of operation, often breaches equipment design specifications as depicted by the region labeled "actual feed." Ensuring that the reliable operational envelope of the process completely encompasses the actual operating conditions requires consideration and control of both the equipment design and material properties, such as bulk density and moisture content, as well as particle size/shape distributions and roughness. The combination of improved equipment design and better control of material properties is illustrated at the right side of **Figure 8** by the expanded system design envelope and the reduced envelope of actual feed properties that is achieved by actively managing the variation of raw material properties. The objective of this holistic approach is the simultaneous optimization of both cost and performance.

Achieving an optimal balance between minimizing the cost and complexity of equipment and managing the variation of feedstock properties requires a comprehensive understanding of the material properties and the factors that impact those properties. A common mistake identified by Bell [7] is believing that feeding and handling problems can be readily solved during start up. In truth, retrofitting equipment and processes can be very expensive and drawn-out because problems are often discovered one at a time as successive pieces of equipment come online. Actions that are taken to solve one problem may have unintended consequences that ripple through downstream operations and can add to the confusion between causes and effects. Fully characterizing all potential feedstocks and carefully managing material properties to match handling and conversion equipment is crucial to minimizing the probability of unexpected operating inefficiencies and failures.

3.2. Recommended future research directions

Solving biomass feeding and handling challenges will require a combination of techniques and capabilities, including numerical simulation, comprehensive material characterization, and mechanical tests. Numerical simulations to date have not had great impact in evaluating the flowability of biomass in handling equipment because of the extreme complexity of the flow problem. It is recognized that Cauchy equations of force and momentum conservation are insufficient to simulate solids flow because of the interactions of the various forces, including wet and dry friction, capillary, gravity, Coulomb, and elastic windup [28]. However, attempting to empirically solve solids flow problems through a series of tests to classify or rank biomass materials in all possible flow situations is not practical. Tests would have to be conducted for each equipment geometry at all scales using all types of biomass materials and all types of biomass preprocessing options that impact the dominant flow properties of bulk density, particle size and shape distributions, particle surface friction, particle rigidity, and moisture content. The number of tests that would be required is prohibitive, and correctly interpreting the large database of properties and test results would be daunting if not infeasible.

In contrast, a close coupling between instrumented lab and pilot scale tests and multiscale modeling may be able to elucidate the appropriate constitutive relations that are needed to augment the Cauchy equations of force and momentum conservation for successful continuum modeling. The powerful outcome of empirically-based numerical simulations is that the results would be scalable within any reasonable equipment size and the impact of specific material properties, such as those described above, could be determined to understand the operational envelope of specific processes. The multiscale models would operate as a direct transfer function to translate microscopic and macroscopic material properties that can be measured in the laboratory to material flow performance in biomass feeding and handling systems. The flow simulations could be used to identify cost effective approaches to modify the biomass materials and/or the transportation and handling equipment to reduce supply chain costs and also to minimize the equipment down-time due to material feeding problems. Continuum models may also be augmented by discrete element method (DEM) modeling that can simulate the motion and even the deformation of each particle in a flow field. **Figure 9** show an example of DEM model of a material that consists of particles with different shapes flowing in a wedge-shaped hopper. Simulating each individual particle in the flow offers the possibility of realistically capturing particle size and shape effects that cannot be directly incorporated into continuum models; however, such models have very high computational costs, so they are typically limited to simulations that involve not more than a few million particles with relatively simple shapes.

A final need that should be addressed is real-time, inline feeding and handling quality assurance (QA) and quality control (QC). Even with near perfect understanding of how material

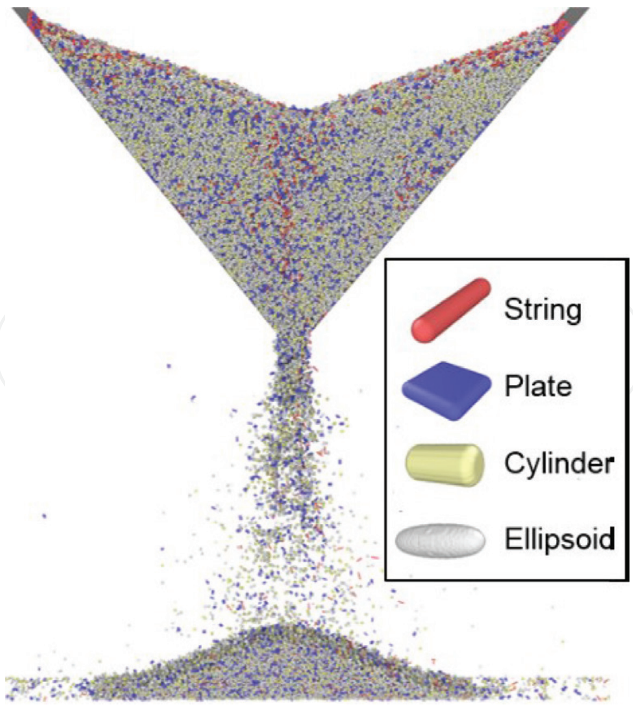

Figure 9. DEM model of flow in a wedge-shaped hopper. The material consists of particles with different shapes as indicated by particle color. Image courtesy of Hai Huang and Yidong Xia at Idaho National Laboratory.

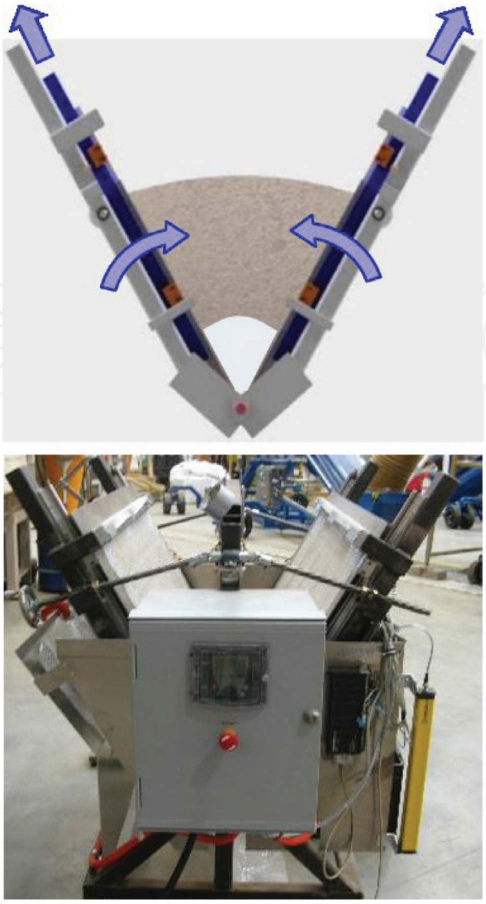

Figure 10. Wedge-shaped flow hopper with rotating and sliding walls for monitoring flow properties in real-time.

attributes impact flowability performance, feeding and handling problems can still arise if variation in harvest, storage, or preprocessing results in localized material that does not meet the specifications. Data recently obtained at Idaho National Laboratory, Idaho in which the author participated indicates a manner in which an in-line test can be rapidly performed [29] using a custom V-shaped hopper with sliding walls as shown in **Figure 10**. The proposed apparatus offers real-time, inline measurement of material flow performance. Installing this or similar QA/QC equipment in biomass feeding and handling systems can prevent out-of-spec material from causing expensive down-time and potential damage to processing equipment.

4. Conclusions

Feeding and handling of biomass has been a primary factor causing pioneer industrial biorefineries to struggle to achieve production targets. The primary biomass properties that impact feeding behavior include bulk density, moisture content, compressibility, elasticity or spring back, particle size and shape distributions, cohesive strength, unconfined yield strength, internal friction angle, and wall friction angle (a property shared with the container surface). The primary issues in the design of hoppers and chutes are: (1) solid flow pattern, (2) slope angle of discharge, and (3) size of the discharge opening. Comprehensive methodologies have been developed to test material properties and design equipment systems for well-behaved particulate materials, such as the Jenike method and tester. However, these methods are not always reliable for compressible, elastic, and anisotropic materials, such as biomass. Solving biomass feeding and handling challenges will require a combination of techniques and capabilities including numerical simulation, comprehensive material characterization, and mechanical tests. Numerical simulations to date have not had great impact in evaluating the flowability of biomass in handling equipment because of the extreme complexity of the flow problem. However, a close coupling between instrumented lab tests and multiscale modeling may be able to elucidate the appropriate constitutive relations that are needed for successful continuum modeling. These models could operate as a transfer function to translate microscopic and macroscopic material properties that can be measured in the laboratory to material flow performance in biomass feeding and handling systems at lab, pilot, and industry scale to understand the impact of variation in key flow properties on process reliability. This combination of experiments and flow simulations could be used to identify cost effective approaches to modify the biomass materials and/or the transportation and handling equipment to reduce supply chain costs and also to minimize equipment down-time due to material feeding problems.

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