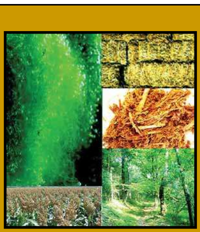
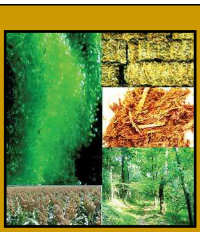


Fiber Focus



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Brought to you by: **Material Flow Solutions, Inc.**

5921 N County Rd 225, Gainesville, FL, 32609 Phone: 352-303-9123 E-mail: kjohanson@matflowsol.com

Designing the Proper Handling System for Biomass Fuel Production

Introduction. Biomass feed stock is made up of particles, albeit often very large particles. As with any system that handles particles, the first step in successful system design is material flow property characterization. The principle flow properties to be measured begin with unconfined yield strength, wall friction angle, density and permeability. Often biomass is used as a precursor to either the formation of a liquid fuel such as ethanol or gaseous fuel such as methane. In either case, the biomass must be handled as a bulk solid material or as a particle mass completely surrounded by liquid. Thus, both the gas and liquid permeability values must be measured. Because of the unique nature of these particles, two additional flow properties should be quantified for successful handling: viscosity (how the material handles in slurry form) and spring-back (strength as it fluctuates with pressure load applied). We will begin this discussion by defining several flow property terms.

Unconfined yield strength as a flow property. Unconfined yield strength is the major principle stress that will cause material in an unconfined state to fail in shear. It is the primary flow property that governs the development of hang-ups in process equipment. It is used to compute critical arching and rathole dimensions for a given material in a hopper or bin – two essential parameters in successful handling system design. All hang-ups in process equipment result in the formation of a free surface. By definition, the stress acting normal to any free surface is zero. However, stresses acting along the free surface may not be zero (Figure 1). In a hang-up condition, the material on a free surface is supported by stresses that act along the free surface and are equal to the unconfined yield strength of the material.

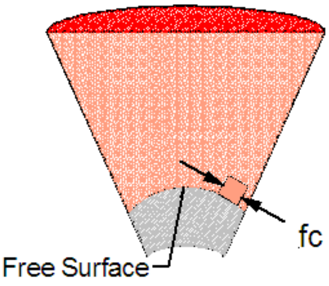

Figure 1. Typical arch in process equipment

Critical Arching and Rathole Dimensions. The critical conical arching dimension is the smallest span of a conical hopper that will prevent arching of the bulk material. It is a function of the material's unconfined yield strength and storage time in the vessel. The conical hopper must have an outlet at least this bit to prevent stable arch formation from occurring (Figure 2). Plane flow hoppers can have hopper widths about ½ as wide and still prevent stable arch formation. The critical arching dimension is also a small function of the bin size and, hence, is usually associated with a calculation basis which represents the approximate size of a given bin geometry. The critical rathole dimension is the size of the largest flow

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In This Issue

At a Glance: Optimizing Feedstock Particle Size

There is a movement in the biomass industry to optimize particle size of the feed stock to maximize the yield of products that may be used as key energy feed stocks or chemical building blocks. Much of the work is focused on getting the yield right. However, material handling is also very dependant on the choice of feedstock particle size. Because of the dominant role of the handling segment of biomass energy systems, the role of particle scale properties can not be ignored. Development to maintain property yields must be done in tandem with work to obtain the best flowing material. This suggests that the choice of milling and sizing operations will be a key factor in any modern biomass project.

Materials decrease in particle size for a variety of reasons. Some materials are brittle and fracture (break in half) when subjected to impact events. Some materials are insensitive to direct fracture, but chip off surface defects as the particles undergo an oblique impact and slide across the surface. Some materials are sensitive to particle breakage due to stress/strain events

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Figure 2: Arch of biomass in typical (improper design) storage hopper

critical rathole dimension is the size of the largest flow channel that will result in stable rathole formation in a funnel flow bin design. The active flow channels in a funnel flow bin must be greater than this value to prevent stable rathole formation. It is important to note that ratholes cannot form in mass flow hoppers. The critical rathole dimension is a function of the maximum stress level in the bin and, hence, depends on the maximum diameter of the bin.

Wall Friction Angle. Bulk solids obey a columbic frictional behavior against container and process equipment surfaces. Wall friction angle is the angle of slide under normal gravity flow for a given bulk solids against a particular wall surface finish. It is a function of the stress level applied to the wall surface as well as the temperature of the bulk material and wall surface. It is measured by heating material to a given temperature, placing it in a cell on a given wall sample plate, applying a normal pressure to the bulk material, and then inclining the plate until the material slides. The angle measured from the horizontal is the wall friction angle. It is used to determine mass flow / funnel flow behavior in bins and hoppers and is, therefore, a critical piece of data required for "right the first time" process design. Friction angle is also is used to determine velocity profiles in process equipment.

Recommended Mass Flow Angle. The friction angle is used to compute the recommend mass flow angle for conical bins. This mass flow angle represents the slope angle of the conical hopper measured from the vertical that will produce flow along the walls. Conical hoppers must be steeper than this to cause flow along the walls. It is important to point out that the recommended mass flow angles are a function of the shape of the bin. Plane flow hoppers converge in one direction at a time and also have a recommended mass flow angle that will produce flow along the walls. However, plane flow mass flow angles generally require about 10 to 12 degrees flatter than corresponding conical angles to achieve mass flow. It is also important to point out that mass flow does not mean plug flow. Substantial velocity gradients can exist in mass flow bins. The recommended mass flow angle also depends on the solids contact stress in the bin. The stress level in a given bin depends on the position in the bin. We compute the range of pressure expected in a given bin configuration and then use the worse case friction angle in this stress level range to compute the recommended mass flow angle. It is important to note that the recommended mass flow angles are for flow in a conical hopper.

Bulk Density. Bulk density may seem like an intrinsically simple property. It is the weight of the particles divided by the combined volume of the particles and the interstitial voids surrounding the particles. It is a function of the stress level and strain history of the material. We measure it using uniaxial compression of a loosely packed bulk material. It is a function of the temperature of the bulk material as well as moisture content and particle size. It is used, along with the permeability characteristics of the bulk material, to determine the limiting rates of particulate materials. It is also used to determine the ability of a given powder to store entrained air. We have identified two distinct density values that are useful in characterizing the behavior of the bulk material. The first density is the density at the hopper outlet (FDI, feed density index). It is the density at low solids contact pressures and describes the density leaving the process equipment it is used to compute mass flow rates from volumetric flow rates. The second density value is the average density of the bulk material within the process equipment (BDI, bin density index). It is measured at higher solids contact pressures and is used to quantify the mass of material stored within the process equipment.

Figure 3. Strength of wet biomass is characterized in a large-cell uniaxial test cell

Permeability (gas/liquid). Permeability is the superficial velocity of gas or fluid passing through the bulk material when the pressure drop across the bulk material equals the weight density of the bulk. It can be thought of as an incipient fluidization velocity, except that it is measured as a function of the stress applied to the bulk material. However, the value of the permeability extrapolated to zero stress is identically equal to the incipient fluidization velocity. Permeability data is used to determine the pressure drops in packed bed operation. It is also used to determine the limiting flow rates where the resistance to gas and fluid flow is the key limiting factor to solids flow. Together, the bulk density and permeability values are required to determine limiting flow rates of the material through process and handling equipment.

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Designing for Proper Biomass Handling

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Limiting Flow Rates. Permeability and bulk density are used to compute the limiting flow rates of a given material in particular hopper geometries. Two things can limit the flow of a bulk material through a hopper subject to gravity feed conditions. The converging nature of the hopper results in an increase in velocity which can not cause accelerations greater than gravitational accelerations. This limiting flow rate is typically high with coarse granular and fibrous large-particle biomass materials. Finer powders (such as sawdust or wood powder) pose another potential flow rate limit. Fine materials consolidate as they flow through a bin. If this consolidation occurs slowly, then the gas contained in the interstitial voids of the bulk material leaves the bulk material through the top material surface. As this compressed and de-aerated material approaches the hopper outlet it must expand to flow from the outlet. This expansion results in a negative gas pressure formation near the hopper outlet. Gas attempts to rush in to equalize this negative gauge pressure. If the permeability is low, this process takes time. The negative gas pressure gradient then persists, resulting in partial support of material flowing from the outlet and creating a very slow flow rate through the hopper. Both the compressibility and the permeability of the bulk material are required to compute the value of this rate limitation. Generally, this problem occurs with fine powders, but it can also happen in granular or fibrous material subject to adverse gas pressure gradients during processing.

Figure 4. Fine sawdust feedstock and cut cornstover feedstock

Viscosity. Biomass slurries are difficult to handle, particularly when the solids content are so large. This is specifically due to the fibrous nature of the particles. Biomass particle fibers typically manifest significant yield stresses during shear. If biomass fibers are small, the slurry behaves as a homogenous material and traditional methods can be employed to measure the viscous behavior of the biomass slurries. However, at some particle size the material behaves more like a bulk solid with fluid surrounding the mass. The viscosity value of a biomass slurry determines when the slurry can be treated as a typical non-Newtonian fluid, and when the material must be treated as a two-phase system with bulk solid surrounded by fluid.

Spring-back. Spring-back is a property of elastic materials and related to the change in density as the material is placed under pressure and then relieved of the pressure forces. At Material Flow Solutions, both density and spring-back are measured using uniaxial compression of the loosely packed bulk biomass material. Spring-back is measure by placing material in a cylindrical test cell and applying a load. The density at this load is recorded and then the load is slowly removed and the density during the unloading process is measured. The operation is repeated using a series of increasing loads. Plotting the data yields a series of density spring-back curves. We can also compute the percent spring-back of a biomass material as the percent change in density relative to the maximum density obtained just prior to unloading in this procedure. A spring-back value of 0% indicates that the material density after unloading is identical to the maximum density obtained at the maximum stress applied. A spring-back value of 100% suggests that the density after spring-back would equal zero (please note that 100% spring-back is totally unrealizable and could not happen with real materials). Most materials have spring-back of about 3% and any spring-back value over 12% denotes a very elastic material. Biomass materials measured at MFS possess spring-back values between 22% and 52%, indicating that great care must be taken when handling and designing for these materials.

Biomass may become elastically bound in equipment due to lack of volume change

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Future Topics

– Putting you at the cutting-edge of industry

In future editions of Fiber Focus we will discuss:

- Milling Biomass – in depth
- Feeding Biomass
- Expanded Flow Properties of Biomass material

We encourage and welcome your suggestions and special requests for fiber flow topics which you would like to see included in future editions of the Fiber Focus Newsletter.

Contact: Susan at 352-379-8879

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at or near outlets. The arching potential for elastic biomass material in bins and hoppers is high. For this reason, flow along process vessel walls must be allowed for these very elastic materials. Failure to design process equipment for elastic relieve will result in costly hang-up issues. Measuring biomass spring-back gives design engineers and plant managers critical data to make the process work “right the first time.

Table I: Reduced material properties data with index numbers for a Biomass Material tested at 20 deg C

Technical Data Sheet for a Biomass Material at 20 deg C					
Effective density leaving process (Feed density index FDI) Density leaving a process is a function of the solids contact pressure at the outlet (Dout)					
Outlet Diameter			Dout = 0.5 ft	Dout = 0.8 ft	Dout = 1.0 ft
Bulk Density FDI (pcf)			21.77	22.87	23.95
Effective density in process equipment (Bin density index BDI) Density in process equipment is a function of the maximum size of the bin (Db). Bin density index (BDI) is computed assuming a standard cylindrical bin with a 2:1 height-to-diameter ratio.					
Bin/Equipment Diameter	Db = 2.0 ft	Db = 4.0 ft	Db = 6.0 ft	Db = 8.0 ft	Db = 10.0 ft
Average Bulk Density BDI (pcf)	37.56	50.25	60.34	68.93	76.51
Critical Rathole Dimension (RI) in process equipment in (ft) Critical rathole dimension is a function of the maximum size of the bin (Db). Rathole index (RI) is computed assuming a standard cylindrical bin with a 2:1 height-to-diameter ratio.					
Storage Time in (hr)	Db = 2.0 ft	Db = 4.0 ft	Db = 6.0 ft	Db = 8.0 ft	Db = 10.0 ft
0	2.13	3.08	4.16	5.27	6.41
1	3.98	6.39	8.97	11.60	14.26
Critical Arching Dimension (AI) in process equipment in (ft)					
Storage Time in (hr)			Dout = 1.0 ft		
0			1.17		
1			2.02		
Limiting Flow Rates for a Biomass Material at 20 deg C Limiting flow rate is a function of both the maximum consolidation stress and the stress value at the outlet. Limiting flow rates computed here are based on the maximum size of a typical mass flow bin (D_b) and the outlet sizes specified (D_o). Limiting flow rate is computed assuming a standard cylindrical bin with a 2:1 height-to-diameter ratio.					
	Limiting Flow rate in (ton/hr) for max bin diameter of				
	Db = 2.0 ft	Db = 4.0 ft	Db = 6.0 ft	Db = 8.0 ft	Db = 10.0 ft
Dout = 0.5 ft	18.40	16.51	15.67	15.18	14.86
Dout = 0.8 ft	45.72	38.61	35.71	34.08	33.02
Dout = 1.0 ft	83.49	66.01	59.51	56.01	53.79
General Comments	Limiting flow rate may be a problem if the process flow rate is greater than flow rates listed above				
Approximate Settlement time in 10.0 ft diameter bin that is 20.0 ft tall. Settlement time in (min)			0.21 (min) Low flooding and flushing potential		

Using flow properties to optimize system design. Once the engineer has measured and reduced flow rate data, he can create the optimal design for a system to handle biomass material effectively. Table 1 contains example data that can be deduced from measured flow properties – including optimal hopper outlets and flow rates of material exiting the bin.

All bulk materials have weight and some processes operate in such a way as to induce external stresses in the material. If the combination of process geometry, material weight, and external forces can induce stresses greater than the yield strength in all portions of the equipment, then the material will flow. In simple geometries, this means that the hopper outlet is wide enough to prevent arching and the hopper slope is steep enough to induce mass flow. It is entirely possible that a given geometry may not have sufficient strength to induce hang-up over the outlet (arch) but have more than enough strength to induce stagnant formation along the container walls (rathole). The method of design for standard materials is to measure standard flow properties and then compute the stress level expected in the design to determine if the material will arch and rathole. If the material is sufficiently cohesive to rathole over the outlet, then consider changing the outlet to a plane flow design. This will significantly decrease arching problems. You will need to make the sloping walls of the hopper steep enough to induce flow at least up to the critical rathole dimension. At this point, the design should be checked from a flow rate standpoint to assure that material will flow at the required flow rate. It should be pointed out that there are dozens of mass flow designs that will work with any given material. Thus, there is rarely just a single solution.

If hang-up is due to particle interlocking (often the case with biomass material), then the outlet size must be at least 6 times the particle size. For conditions where the particle size distribution is wide or multi-modal, the decision of which particle size to use is based on engineering judgment. In the case where the hang-up is caused by elastic constraint issues, traditional yield strength does not control flowability. In essence, the condition in the process equipment is in a confined state and the yield strength is defined for an unconfined state. This results in a pseudo-strength that is due to the extra confining pressure. In this case, it is critical that the design induce flow along the walls to prevent or release the elastic constraining condition. Traditional mass flow design principles do not apply. Finally, external forces, gas pressures, vibrations, etc. can induce additional compaction stress or reduce major principle stress required to knock down hang-ups. Mass flow designs are possible in these conditions, but the external body force terms must be included in the design to assure reliable flow without hang-ups.

For more information Contact: Kerry Johanson at 352-303-9123

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ance: Feedstock Particle Size

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ush particles at a given stress level and strain in process equipment. Some particles require significant strain to ld and are sensitive to cutting or tearing as close tolerance moving parts pinch the material and disrupt the particle fiber structure, creating smaller particles. A typical biomass material is subject to several of these mechanisms.

It is critical to match the particle size reduction mechanism experienced by a given biomass to the particular milling method or set of events present in the unique plant production facility. For example, if impact during processing dominates the milling process flow behavior, then particle size reduction due to impact behavior is the critical property to measure. Using a tester that causes size reduction due to stress and strain behavior may give erroneous results when applied to processes which are impact dominated. Ideally, you would use process steps that are effective in optimizing the particle breakage. If the biomass is sensitive to cutting, but not fracture, then mills that induce sufficient particle strain to cut or tear particles apart should be considered. In this case, an impact mill would be of little use. However, once the particles are cut or chipped, impact may be useful in further reducing the particle size of the milled product. This change in behavior is due to the fact that many biomass materials are anisotropic and exhibit different breakage behaviors with the grain and against the grain.

Since particle size largely determines the success (or failure) of energy production from biomass material, it stands to reason that knowledge of the type of breakage occurring with a given material, as well as the magnitude of breakage, is critical when considering the type of system to use to prepare the biomass material for eventual use in fermenters and reactors. At Material Flow Solutions, we have developed several tests that isolate the different types of particle break-age mechanisms. These tests can be used to determine how sensitive a given material may be to a prescribed breakage mechanism. We couple this data with population balance models to determine the magnitude and type of breakage occurring with each material. This information is needed to make an educated decision about using a particular mill or piece of process equipment in biomass handling facilities. These tests will help optimize mill selection or predict mill effectiveness if the mill is already in place. Population balance models allow identification of critical particle breakage mechanisms through computation of breakage selection coefficients. When this is coupled with a structural examination of the biomass particle, a powerful tool evolves which allows enhanced particle breakage modeling based on particle structure and breakage mechanism – resulting in cost-effective solutions based on sound scientific principals.

http://cen.acs.org/articles/91/i32/Seeking-Biomass-Feedstocks-Compete.html

Learning the Trade – Flow Properties Principles

Knowing and understanding key material properties is power to characterize bulk material flow behavior. We will empower you quarterly as we discuss one of these fundamental flow properties and its industrial application.

Wet biomass as it shears under applied stress load in a large (12") uniaxial test cell

Bulk strength is a primary flow property that governs the development of hang-ups in process equipment. As defined in our lead article, it is the major principle stress that will cause material in an unconfined state to fail in shear. Knowing the strength of your biomass feedstock is critical to properly determine the critical arching and rathole dimensions for optimal design of your system hoppers and/or bins. We know that all hang-ups in process equipment result in the formation of a free surface. Although the stress acting normal to any free surface is zero, stresses acting along the free surface may not be zero. When biomass hangs up in the hopper, material on the free surface is supported by stresses that act along that free surface. This equals the bulk strength of the feedstock material.

One obvious industrial application of knowing your material's bulk strength is for the proper design of a new or retrofitted handling system. However, sometimes an engineer must work with an existing system – without the option of modification. In this instance, measurement of the bulk strength for variously sized feedstock options allows the engineer to choose the optimal material based on the existing system parameters. Please note that, when evaluating the biomass bulk strength, the size of the test cell must be compatible with the particle size of the biomass material so as to yield data relevant to actual process parameters. For this reason, at Material Flow Solutions we use large cells especially designed to accommodate the large particle size of biomass feedstocks.