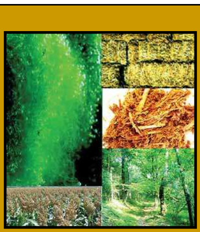
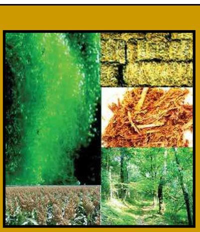


Fiber Focus



Spring 2013 Volume 3 No B

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

Viscous Properties of a Straw Slurry

Background. Biomass slurries are difficult to handle, particularly when the solids content size 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. In this Fiber Focus Newsletter, we will explore conditions under which biomass 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.

From raw cut wheat straw to a prepared wheat straw slurry

The Experiment. Viscosity tests for straw biomass material were carried out using a rotational DV-E-HB Brookfield shear device with a specially designed vane spindle to accommodate hot liquid. Measurements were made by heating liquid and placing straw in the warm liquid at a 5% solids mixture. The straw was held in the heated liquid bath for 5 minutes before beginning the test. The temperature was maintained constant (±1°C) during the course of the experiment. Ph value was measured prior to heating the liquid, and was found to be 1.5 Ph. The raw data gives rise to the apparent viscosity and the shear torque. This shear torque can be converted to a shear stress.

Figure 1. Viscosity of a straw slurry

Figure 2. Vane viscometer used in experimental tests

Figures 3 and 4 summarize the data acquired from the vane shear cell. It is evident from these figures that the material tends to a constant shear stress condition at low rotational speeds. This implies that straw biomass has a yield strength value somewhere close to 400 Pa. For the purpose of this experiment, we assume that straw slurries can be approximated by a Hershel-Bulkley fluid. The Herschel–Bulkley fluid is a generalized model of a non-Newtonian fluid in which the strain experienced by

(Continued on page 2)

In This Issue

At a Glance: Influence of Gas Pressure Effects on the Development of Mass Flow or Funnel Flow in Process Equipment

The ability of a given piece of process equipment to achieve flow along the walls when any material is discharged is an important behavior called mass flow. In its most simplistic form, achieving mass flow depends on the wall friction angle and the process geometry as well as the effective angle of internal friction. However, when additional body forces are added, they modify the ability of materials to flow at the walls. Gas pressure gradients can help or hurt this ability, depending on the direction in which they act. Stress gradients can induce flow along the walls where current theory suggests material will not flow. The goal is to achieve a steady, predictable movement of material through the process equipment. The best way to achieve this is by ensuring mass flow in the bin or hopper.

It should be pointed out that ratholes cannot form in bins that induce flow at the hopper walls

(Continued on page 4)

the fluid is related to the stress in a non-linear way. Three parameters characterize this relationship: the consistency *k*, the flow index *n*, and the yield shear stress τ_O. The consistency is a simple constant of proportionality, while the flow index measures the degree to which the fluid is shear-thinning or shear-thickening (Wikipedia definition).

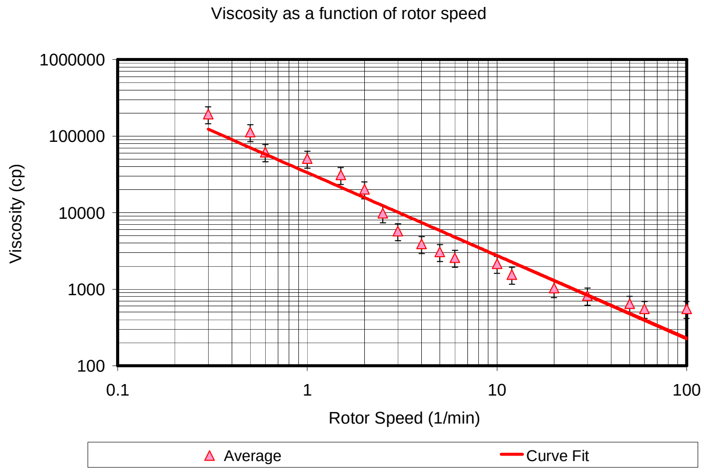


Figure 3. Viscosity as a function of the rotor speed

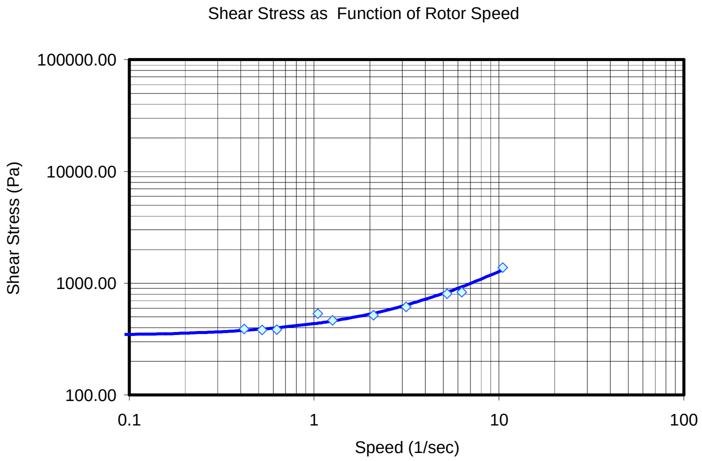


Figure 4. Shear strength as a function of the rotor speed

Using the Brookfield data to determine viscosity of straw slurries. Traditional viscosity testing using rotational torque testers can be carried out using concentric cylinders arranged to produce coquette flow between the cylinders. Either the inner cylinder is rotated while the outer cylinder remains stationary or the outer cylinder rotates while the inner cylinder remains stationary. If the fluid between these cylinders is a Newtonian fluid, then the shear rate and shear stress can be found from the torque data using equations 1 and 2.

$$\gamma = \frac{4 \cdot \pi \cdot S \cdot r_c^2 \cdot r_{vane}^2}{r_{vane}^2 \cdot \left(r_c^2 - r_{vane}^2\right)} \qquad \textbf{\textit{Eq. 1}}$$

$$\tau = \frac{T}{2 \cdot \pi \cdot r_{vane}^2 \cdot H_{vane}} \qquad \textbf{\textit{Eq. 2}}$$

Where:

γ	is the shear rate (1/sec)
τ	is the shear stress (Pa)
S	is the rotor speed (1/sec)
r_c	is the radius of the outer cylinder/vane (3.44 inch)
r_{vane}	is the radius of the vane or inner cylinder (0.86 inch)
H_{vane}	is the height of the vane (1.71 inch)
T	is the torque

These equations are used by Brookfield to reduce viscosity data from their viscometers assuming a Newtonian fluid. However, they cannot be directly applied to non-Newtonian flow. The computed shear rate was based on this assumption. The shear stress calculation is mostly independent of the type of fluid, but the shear rate calculation depends heavily on the type of fluid used. This is especially true when dealing with fluids that exhibit a yield stress. In these cases, the velocity profile through part of the annular region is a constant. The change in velocity occurs near the moving plate or cylinder. At some point in between these plates or cylinders the velocity reduces to zero in the annular direction. If this critical point occurs at the outer wall, then the strain rate can be computed using the inner and outer radius values. If this critical value occurs somewhere between the plates, then the strain rate will be a function of the inner vane or cylinder radius and the radius at which the velocity reduces to zero. This critical point depends on the yield stress value of the fluid. If one knows the yield stress, then one can compute this critical radial position where the velocity tends to zero. In this experiment, the fluid can be approximated by a Herschel-Bulkley fluid model. Shear stress can be related to the critical radius through equation 3. Although there are seldom analytical solutions to the equation above, equation 3 can be numerically solved to determine the critical radius (r_0) as a function of the yield stress (τ_0) and the rotational speed (S). Note that the critical radius will never exceed the outer diameter of the viscosity cup. We measured the torque values of this vane viscometer and used these to compute the critical

$$\gamma = 0 \qquad \text{when } \tau < \tau_0$$

$$\tau = \tau_0 + k \cdot \gamma^n \qquad \text{when } \tau > \tau_0$$

(Continued on page 3)

Viscous Properties of a Straw Slurry

(Continued from page 2)

radius where the fluid velocity profile tends to zero between the rotating cylinder and shell (Figure 5). As a point of reference we plotted the vane radius as indicated by the horizontal line in Figure 5. The zone of stagnant material in the experiment is very close to the rotor. It can be shown that the shear rate correction factor to the Newtonian shear rate is found by equation 4 below, provided the critical radius occurs between the rotating cylinder or vane and the stationary vane. When this correction factor is used with data for straw slurry at a solids content of 5%, the relationship between shear stress and shear rate can be determined. This strain rate relationship is presented in Figure 6 and shows some agreement to a Herschel-Buckley curve fit. The curve fits for both shear stress and viscosity presented on the same graph. We biased the curve fit results to make the viscosity readings more accurate, suggesting that the assumed Herschel-Bulkley fluid analysis is a reasonable assumption. This data can be used to compute the viscosity of the material as a function of strain rate.

Eq. 3

$$\left(\frac{\tau_0}{k\cdot S^n}\right)^{1/n}=\frac{1}{\displaystyle\int_1^{r_0/r_{vane}}\left(\frac{1}{\xi}\cdot\left(\left(\frac{r_0/r_{vane}}{\xi}\right)^2-1\right)\right)^{1/n}\cdot d\xi}$$

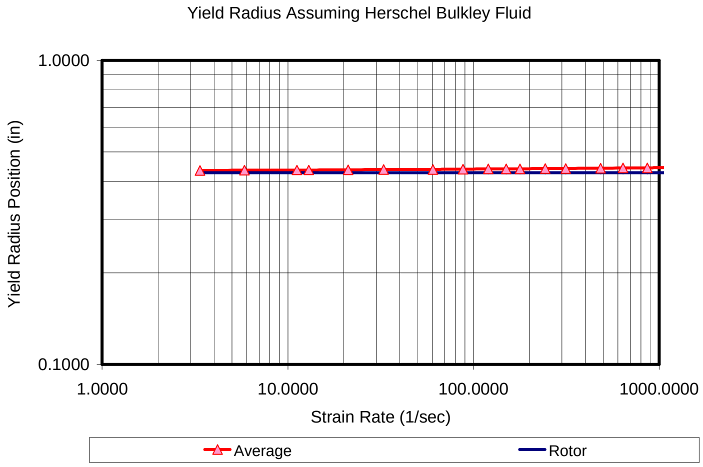


Figure 5. Expected critical radius as a function of strain rate after 5 minutes exposure to 1.5 pH liquid at elevated temperature

It is important to note that these viscosities are those reported from the Brookfield instrument and assume apparent viscosities as measured by Newtonian methods. The actual apparent viscosity could be different, as computed from the actual fluid law. Additionally, easy separation of the fluid and the straw in the slurry was observed. In fact, we needed to mix the material between measurements to assure uniform properties during testing. Finally, it is very apparent from this experiment that viscosity is a strong function of the size and shape of the particles that make up the mixture.

Eq. 4

$$\gamma=\frac{\gamma_{newtonian}}{\displaystyle\int_1^{r_0/r_{vane}}\left(\frac{1}{\xi}\cdot\left(\left(\frac{r_0/r_{vane}}{\xi}\right)^2-1\right)\right)^{1/n}\cdot d\xi}\cdot\frac{\left(\left(\left(\frac{r_c}{r_{vane}}\right)^2-1\right)\cdot\left(\left(\frac{r_o}{r_{vane}}\right)^2-1\right)\right)^{1/n}}{2\cdot\left(\frac{r_c}{r_{vane}}\right)^2}$$

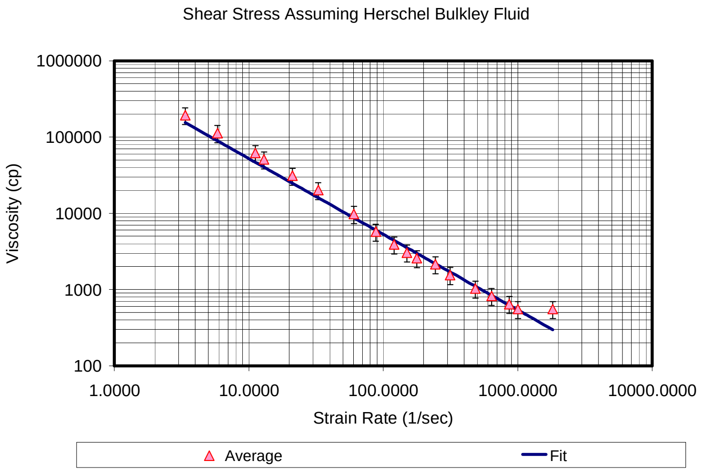


Figure 6. Expected shear stress versus strain rate relationship after 5 minutes exposure to 1.5 pH liquid at elevated temperature

Future Topics

– Putting you at the cutting-edge of industry

In future editions of Fiber Focus we will discuss:

- Handling System Design
- Milling Biomass – in depth
- Feeding Biomass
- 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.

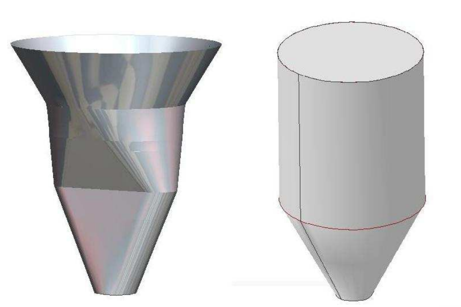
Contact: Susan at 352-379-8879

$\gamma = 0$

ance: Gas Pressure Effects

(continued from page 1)

w). Conical hoppers, if steep enough, can induce mass flow, but plane flow hoppers can be about 11 degrees flatter and still induce mass flow. These plane flow hoppers have the added advantage that they can also prevent arching more effectively than can conical hoppers. Measurement of the key bulk material flow properties is crucial to achieving mass flow in equipment processing fibrous biomass materials. One of the significant flow properties of any material is the permeability value.



Examples: a mass flow (Diamondback®) hopper and a conical hopper

Permeability is another flow property that affects process operation with biomass. It is defined as the amount of air flowing through the pores in a bulk material which causes pressure drop based on the local size of the pores, length of the void path, and the local gas velocity. In general, the resistance to flow depends on the arrangement of pores in the bulk material. It may be possible to construct a material with different air flow resistances in different directions. This gives rise to a tensorial permeability coefficient (*K*) which relates the gas pressure gradient to the gas velocity through the linear vector equation. Three things to bear in mind when considering biomass feed stock:

- Permeability decreases as density increases.
- Permeability decreases with finer materials and with materials that have wide size distributions.
- Permeability is a measure of the rate of the release of gas stored within the bulk material.

$$U = \frac{K}{\gamma \cdot g} \cdot \nabla P \cdot \frac{\mu_o}{\mu}$$

Where:
***U* is superficial gas velocity**
***K* is permeability**
∇*p* is the gas pressure gradient
γ is a reference bulk density

As a gas or fluid passes through biomass material, it induces stresses that act in the direction of flow. These stresses can consolidate material, causing the material to increase in strength and, thereby, resulting in arch formation. Sometimes gas flow also supports the weight of the biomass, reducing the ability of gravitational forces to break arches. In situations where gas, steam, or fluid interact with biomass, it is critical to understand and measure the permeability of the material and calculate these additional body forces.

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.

Liquid permeability determines the flowability (or lack thereof) of wet biomass materials

Liquid Permeability as a flow property. Liquid permeability is the superficial velocity of a 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 fluid flow is the key limiting factor to solids flow. It is important to know the liquid permeability value of biomass materials because, with an understanding of permeability, engineers can calculate the necessary de-aeration time and installation parameters of flow-aid devices in the equipment to achieve required process flow rate and/or break bridges and ratholes that are negatively affecting the system. Material Flow Solutions measures the liquid permeability of your material to assist you in designing or retrofitting a new or existing solids flow processing system when your primary goal is to “get it right the first time.”

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