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Mass flow and variability in screw feeding of biomass powders — Relations to particle and bulk properties

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ABSTRACT

Biomass powders often have high cohesiveness, low bulk density and poor material flow characteristics which cause interruptions and variations in feeding systems. In this study, a range of biomasses – commercial charcoal, torrefied Norway spruce stem wood, non-treated Norway spruce stem wood, and reed canary grass – were milled (screen size: 1 mm) using two different methods; cutting mill and hammer mill, to form eight types of biomass powders. The powders were analyzed for loose bulk density, Hausner ratio, compression ratio, angle of repose and for size and shape distributions. Size and shape were determined by mechanical sieving and optical particle size and shape analysis. Additionally, yield loci and wall yield loci were determined through standard bulk solid testing methods. Screw feeding properties of the eight biomass powders were determined by feeding the materials in a twin screw feeder — at constant rpm and at a constant feeding rate of 1 kg/h. Correlation analysis and principal component loadings were used to describe relations between material properties and feeding characteristics. When materials were fed at a constant rpm, feeding variability was closely correlated to the powder's angle of repose (long time) and Hausner and compression ratios (short time).

1. Introduction

To avoid feeding related downtime in an industrial process, it is important to be able to predict if a new feedstock will be prone to flow related problems during processing. There are several test methods capturing different aspects of powder flow behavior that might be used for the prediction of flow and feeding properties to see if better or worse behavior is to be expected with a new material. These include:

- free surface flow behavior e.g., angle of repose (AoR) for the discharge from the screw,
- bulk density based measurements e.g., compressibility and Hausner ratio as a screw feeder is a volumetric device, and
- shear cell tests to measure fundamental flow properties friction, cohesive strength/flow function that can be used to calculate stresses acting in the vessel under idealized conditions.

The AoR test is a simple procedure that is useful for powder characterization [1]. Its strength lies in the short measurement time which can be done in as little as 15 min and it does not require expensive equipment. One of the drawbacks of AoR is lack of a test standard. There are a variety of procedures proposed, and usually, results from different measurement setups cannot be compared with each other [2]. AoR is sensitive to several test parameters such as pouring velocity and sample size as well as the design and handling of the measuring equipment itself.

The Hausner ratio is the ratio between the tapped and loose bulk density of a powder and it has a long history of use in industry. A Hausner ratio above 1.4 indicates poor flowability and a ratio below 1.25 indicates good flowability [3]. One of the major problems with using the Hausner ratio is that there is no standard saying which loose bulk density to use, and there are several to choose between (aerated, poured, and apparent bulk density). There is also some difficulty with the tapped bulk density as it is sensitive to the procedure. Furthermore, the Hausner ratio is not able to differentiate flowability for highly cohesive materials [4].

Shear testing is an effective although time consuming method for testing powder properties. However, recent studies have shown that the method is not always well suited for biomass bulk solids [5,6]. The underlying assumption of spherical particles in Jenike's theories [7] works well with soil and most pharmaceutical and metallic powders but do not work well with flaky, elastic and fibrous biomass particles. Barletta et al. [8] tried to differentiate three different biomass fuels with regard to their arching behavior. Flow functions based on standard shear tests could not predict differences in flow behavior and resulting silo designs were heavily over-dimensioned compared to the results

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of actual arching tests. As a result, hoppers designed using the Jenike approach would have outlet sizes that would generate feed rates far in excess of those required. A common industrial approach in such a situation would be to use an agitated screw feeder, whereby the discharge of a poor flowing material through an outlet far below the critical dimension for gravity flow, is encouraged by the sweep of a rotary agitator. Industrial experience suggests that the vast majority of materials will discharge from these types of feeders. However, cohesive, elastic and low bulk density powders, such as biomass, still show problems with flow fluctuations, rat-holing and bridging causing either reduced flow rates or a complete feeding blockage.

As mentioned above, previous studies show that traditional silo and feeding equipment design methods have insufficient reliability for biomass materials. Lacking reliable prediction and analysis methods for biomass bulk handling and feeding causes construction delays and insufficient functionality in the uprising biobased industry. Thus, there is an outspoken need for more work towards better understanding and developed functional tools for prediction of feeding performance and flow properties for biomass powders (i.e., within the European Federation of Chemical Engineering Working Party on Mechanics of Particulate Solids).

Dai and Grace [9] investigated biomass screw feeding at mass flow rates of 20–600 kg/h and found that hopper filling level and high compressibility was positively correlated to feeding efficiency (i.e., materials were fed at a high densities) until a maximum level was reached when the torque was increased and blockages were triggered. Raw material moisture content was negatively related to mass flow. High moisture content as well as irregular particle size and shape increased torque and tendencies for blockage. Furthermore, torque was nearly independent of screw speed.

Additional to abovementioned feeding properties, occurrence of feeding disturbances, expressed as the flow variability (%) around the average mass flow, is detrimental for the process being fed. A general rule-of-the-thumb method to determine screw feeding variability is by measuring every 60 s for 30 consecutive minutes [10], but for high precision processes fed at rates around 0.5–5 kg/h, such as lab scale powder flame combustion, variations in feeding can affect the performance in less than a second. Thus, feeding variability has to be expressed at a relevant timescale.

Correlation and principal component analyses [11] are helpful tools for finding structural patterns in data sets. When starting fresh in the search for relevant prediction methods for biomass flow and feeding behavior, such analyses can provide relevant information and give input on where to put efforts in further work.

In this study, four biomass powders; one grass, one non-treated wood, and two levels of thermally treated wood were milled in two different mills; a cutting mill and a hammer mill, to form eight different biomass powders for feeding of a lab scale drop tube furnace reactor. The aim was to: i) determine particle and bulk properties and screw feeding performance for a range of different biomass powders, ii) perform correlation analysis for particle and bulk properties and feeding performance, displayed both numerically in correlation tables and visually through principal component analysis (PCA) to assess the most useful predictors for the actual feeding behaviors iii) make qualitative comparisons between material characteristics and feeding performance, and describe mechanistically how the material is flowing in the hopper/feeder to explain the observed results, iv) discuss particular difficulties with biomass particle and bulk property determination.

2. Materials and methods

2.1. Materials

Four types of biomass materials were evaluated in the study; Norway spruce (*Picea abies* Karst.) stem wood, torrefied Norway spruce stem wood, commercial charcoal, and reed canary grass (RCG) (*Phalaris arundinacea* L.). The Norway spruce stem wood and torrefied Norway spruce stem wood had a chip size of several centimeters before grinding. The torrefied Norway spruce was lightly torrefied to a mass yield of 76%. The charcoal, commercial BBQ coal (ICA Grillkol, ICA, Poland) consisted of charred hardwood and had a particle size of several centimeters. The RCG was spring harvested and shredded (screen size: 15 mm).

The studied materials were milled in two different mills: a cutting mill (Retsch SM200, Haan, Germany) and a hammer mill (Kamas Bac-50, Malmö, Sweden), both with screen sizes of 1 mm.

2.2. Characterization methods

2.2.1. Particle size and shape distributions

The particle mass size distributions were determined using a stack of sieves, mounted in decreasing order, with mesh sizes of 800, 720, 600, 400, 300, and 200 μm. All biomass powders were sieved in triplicates for 20 min, using a Fritsch Analysette 3 sieve shaker (Fritsch, Idar-Oberstein, Germany). Each material was sieved at individual optimal amplitude, determined in a short test at 4 levels (0.4, 0.8, 1.2, and 1.6 mm). For each sieving, the mass-% was determined for 1000–800, 800–720, 720–600, 600–400, 400–300, 300–200, and 200–0 μm size ranges. For each material, average values from the mass-% triplicates was calculated.

To provide information about particle length and shape, mechanical sieving was complemented with optical particle size analysis (QicPic, Sympatec Gmbh, Germany). Particle shape and size were determined using computer algorithms that condense irregular contour data into several different particle sizes and shape factors. Min and max Feret diameters (μm) were extracted, defined as the shortest (min Feret) and the longest (max Feret) distance between the two parallel lines that restrict a 2-dimensional projection of a particle. Min and max Feret data was presented in cumulative size distributions, and the Feret diameter sizes (μm) at 10, 16, 50, 84, 90 and 99% of the number of particles, were chosen for further correlation analysis.

2.2.2. Loose bulk density, Hausner ratio, compression ratio and angle of repose

Milled powders were analyzed for loose and tapped bulk densities according to the following procedure: Biomass powder was poured until overfilling into a pre-weighed cylindrical container of known volume (96.3 cm^3). Excess material was carefully scraped off before weighing and determining the loose bulk density (kg/m^3). For tapped bulk density, a removable extension ring with the same internal diameter as the container was mounted on top of the container, increasing the volume of the cylinder to roughly 190 cm^3, and the whole volume was filled with powder. The container was then tapped (dropped from a height of 1½ cm using a cam mechanism on a rotary drive) repeatedly until no noticeable volume change could be observed (charcoal ~450, torrefied spruce ~700, spruce ~500, RCG ~500 times). After tapping, the extension ring was removed, excess material scraped off, and the container weighed for determination of tapped bulk density (kg/m^3). An average Hausner ratio value was calculated from triplicate pairwise measurements.

The compression ratio was determined from the shear test procedure by dividing the bulk density at 4.2 kPa preshear stress with loosely poured bulk density. Thus, at the compressed state, both normal and shear stress was applied.

The angle of repose (AoR) was determined with a Mark 4 AoR tester (D Geldart, West Yorkshire, United Kingdom) by feeding powder at a controlled height and mass flow rate onto a plate [1]. Through this procedure, material formed a small half cone at the base of the wall. By using the inverse tangent of the height divided by the radius of the cone, the AoR (°) was calculated according to Eq. (1). Four replicates were carried out for each material and an average value was calculated.

$$\mathrm{AoR} = \tan^{-1}\left(\frac{h}{r}\right). \tag{1}$$