Fuel Processing Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Assessment on bulk solids best practice techniques for flow characterization and storage/handling equipment design for biomass materials of different classes

Diego Barletta [a,*], Robert J. Berry [b], Sylvia H. Larsson [c], Torbjörn A. Lestander [c], Massimo Poletto [a], Álvaro Ramírez-Gómez [d]

[a] *Dipartimento di Ingegneria Industriale, Università di Salerno, Italy*
[b] *The Wolfson Centre for Bulk Solids Handling Technology, The University of Greenwich, Chatham, UK*
[c] *Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, Division of Biomass Technology and Chemistry, SE 901 83 Umeå, Sweden*
[d] *BIPREE Research Group, Universidad Politécnica de Madrid, Spain*

ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form 15 June 2015
Accepted 18 June 2015
Available online xxxx

Keywords:
Lignocellulosic biomass
Particle size
Particle shape
Flowability
Arching
Explosion

ABSTRACT

This paper shows the results of a collaborative project in which four different laboratories have carried out complementary characterization tests on samples of the same set of lignocellulosic biomass materials with the objectives of better understanding their properties and identifying any critical features of the different characterization procedures. Three different types of material were used as model biomasses: 1) Scots pine wood chips, as an example of a coarse and flaky particulate biomass with some elastic properties; 2) chopped straw of reed canary grass as a nesting biomass having long and flaky fibers; and 3) Scots pine wood powder as a fine particulate with elastic and cohesive properties. Particle size and shape analyses were carried out with; calipers, 2D image analysis, 3D image analysis (ScanChip) and through mechanical sieving. Applications and validity limits of each of these techniques are evaluated and discussed. The flow function and internal friction were determined with a Schulze ring shear tester, a Brookfield powder flow tester and a large ring shear tester. No significant differences in the results generated by these shear testing techniques were found. Wall friction measurements were carried out with a Schulze ring shear tester; a Brookfield powder flow tester; a large Jenike shear tester and a Casagrande shear box. Results, in this case, showed significant differences with a higher wall friction coefficient obtained with the larger shear cell. Additionally, tensile strengths of biomass materials were measured by the use of a novel measurement technique. Arching tests were carried out in a pilot scale plane silo with variable hopper geometry and results were compared with those predicted by applying the Jenike procedure and a modified procedure which assumed that tensile strength was the controlling material property (rather than unconfined yield strength). Finally, safety of handling and storage was assessed by carrying out explosion tests on dusts from Scots pine and reed canary grass.

1. Introduction

The interest in solid biomass has been increasing over the last decades for their potential as renewable energy sources and as raw material for biorefineries, producing a great variety of added-value products in well integrated production chains [1–3]. Industrial use of lignocellulosic biomass implies an increase in demand for robust and reliable bulk solids handling. When compared with liquid processing plants, those involving the use of solids are characterized by significantly longer start up times, larger start up costs and by plant through-puts which may be significantly reduced with respect to their design value [4]. Furthermore, lignocellulosic biomass feedstocks are inherently variable including; the raw materials, by-products, residuals, and wastes. There are differences between plant species but also in structural elements within individual plants (e.g. phloem, xylem, bark, leaves/needles, roots, and fruits) adding more variation to physical and chemical properties [5], besides that of moisture content and potential contaminants. Moreover, mechanical and thermal pretreatments before feeding to conversion plants can significantly change the properties of biomass solids. In particular, milling [6–8], densification [9,10] and thermal treatment [11–14] affect particle size and shape distribution, bulk density and energy density. With specific reference to solids from particulate biomasses, handling and feeding present further difficulties due to peculiar properties both at particle level and at bulk level that make these materials even more unpredictable than other granular materials traditionally processed by industry, especially in terms of flow reliability and control [15–17]. As a result these materials often require a semi-empirical approach to correlate discharge and flow property data with composition [18,19]. Robust and reliable characterization methods for off-line measurements of particulate biomass flow properties are urgently needed, as well as biomass structure and composition

---

[*] Corresponding author.
E-mail address: dbarletta@unisa.it (D. Barletta).

http://dx.doi.org/10.1016/j.fuproc.2015.06.034
0378-3820/© 2015 Elsevier B.V. All rights reserved.

Please cite this article as: D. Barletta, et al., Assessment on bulk solids best practice techniques for flow characterization and storage/handling equipment design for biomass mat..., Fuel Processing Technology (2015), http://dx.doi.org/10.1016/j.fuproc.2015.06.034

characterization methods, suitable for on-line analysis of rapid material streams enabling fast non-destructive biomass classification procedures, e.g. spectrometry [20–22].

Flow problems can be correctly addressed through knowledge of flow properties of bulk solids and by the availability of reliable design methods for industrial silos. However, standard characterization methods used for flow properties of common granular solids are not always suitable for biomass materials. A significant problem is that conventional shear testers have been mainly developed for measuring frictional and cohesive properties of bulk solids with non-fibrous rigid and generally homogeneous particle shapes as well as with particle top sizes below a few millimeters [23–25]. Few biomass materials have particle size, stiffness and shape distributions that meet these requirements. Thus, for large biomass particles one possibility is to use a larger scale shear tester [26]. However, for biomass materials that consist of elongated particles or fibers, like straws and grasses, there are more fundamental questions regarding the validity of shear testing as a characterization technique. These materials are highly compressible and comprise particles that are severely entangled, hindering the formation of a well-defined shear zone and the attainment of steady state flow conditions [27–29]. Moreover, preliminary studies indicate that tensile strength could be a more relevant flow property than compressive strength due to mechanical interlocking caused by entanglements between fibrous solids [30]. These observations indicate that there is a need to more deeply assess both the validity of elasto-plastic constitutive models and the choice of suitable testers for the characterization of the flow properties of biomass particulate solids.

In addition to this, common design methods for storage units to ensure flow, based on Jenike analysis [31], have not yet been proven to work for biomass bulk solids. The tendencies of different biomasses to arch or bridge across hopper outlets have been investigated in several studies. Flat bottomed containers with an opening slot were initially used to experimentally derive the critical outlet size for arching as a function; of particle size distribution, particle shape and moisture content of the biomass sample [32–35]; of air promotion flow [36] or of the milling procedure [37], but without considering consolidation stresses. A similar apparatus based on the same method was also recently proposed as a reference method for European standardization [38]. However, the applicability of these results to larger (real scale) silos and to conical or wedge-shaped hoppers has not been proven. A clue to the effect of increasing vessel size (and hence increasing magnitude of consolidation stress) is provided by the observation that the critical arching dimension increases as the filling level of biomass in the vessel is rising [32,35]. The role of consolidation stress has been confirmed by arching tests on biomass beds compacted by an external load [39,40]. Barletta and Poletto carried out a direct assessment of the Jenike design method performing experiments on a wedge shaped hopper [41,42]. Results from these studies indicate that the design procedure is adequate for the tested wood powder samples in a hopper with a capacity of about 0.3 m^3. However, further investigations are needed to complete the assessment, for a wider range of materials and to better understand the effect of the consolidation stress magnitude (related to bed height and container diameter) on the arching behavior and the critical outlet size.

Furthermore, safety issues related to dust generation during [43] biomass handling need to be addressed. Fires (due to self-heating during storage) and dust explosions are two important issues in biomass bulk handling, because they may result in worker injuries, loss of life, considerable economic costs and environmental damage. A dust explosion is the result of rapid combustion of fine particles dispersed in air. In the presence of an ignition source they react with oxygen, generating an exothermic chain of reactions. If these reactions occur inside a vessel the system pressure increases rapidly [44,45]. Under these circumstances, venting devices are designed to release pressures, and indeed, as protection measures usually are the only options. Explosion pressures can reach 7–10 bar in a closed vessel with no protective system. Considering that walls and roofs of typical biomass containers are not designed to bear such pressures, explosions may lead to serious structural damages, including complete silo destruction. The most significant parameters characterizing the violence of an explosion are the maximum pressure reached ($P_{\max}$) and the maximum rate of pressure rise (K_{st}). However, there is a lack of data concerning these parameters for biomass materials. Still, the majority of reported industrial explosions had their origin in organic (carbon) dusts that have compositional similarities with biomass materials, which suggests that these materials present a significant explosion risk.

This paper shows the results of a collaborative project (Bio4Flow) in which four different laboratories have carried out complementary characterization tests on three sets of biomass samples with the purpose of better understanding their material properties and highlighting possible critical features of biomass characterization procedures. The laboratories involved are:

- the Biofuel Technology Centre at the Swedish University of Agricultural Sciences, Sweden (SLU BTC);
- the Wolfson Centre for Bulk Solids Handling Technology at the University of Greenwich, United Kingdom (UG Wolfson);
- the Powder Technology Group of the University of Salerno, Italy (US PTG);
- the BIPREE Research Group of the Technical University of Madrid, Spain (UPM BIPREE).

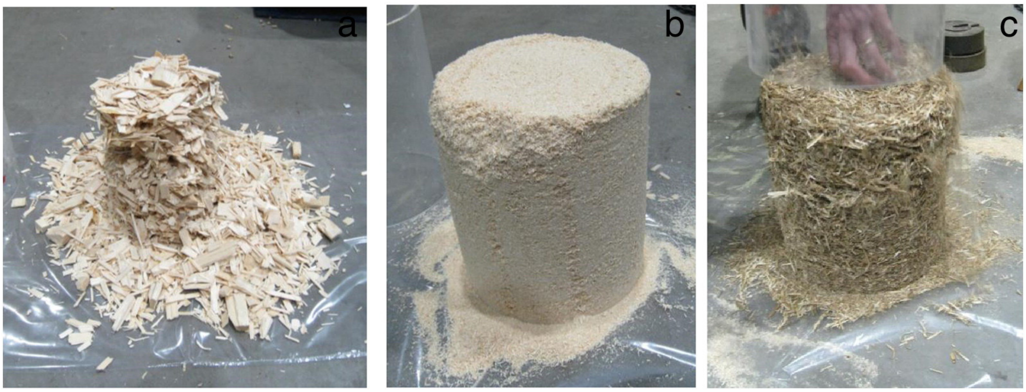

Fig. 1. Biomass materials used in the experiments: a) Scots pine (*Pinus sylvestris*) wood chips; b) Scots pine (*P. sylvestris*) wood powder; c) reed canary grass (*Phalaris arundinacea*) straw chops.

Please cite this article as: D. Barletta, et al., Assessment on bulk solids best practice techniques for flow characterization and storage/handling equipment design for biomass mat..., Fuel Processing Technology (2015), http://dx.doi.org/10.1016/j.fuproc.2015.06.034