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Experiments and discrete element simulation of the dosing of cohesive powders in a simplified geometry

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ABSTRACT

We perform experiments and discrete element simulations on the dosing of cohesive granular materials in a simplified geometry. The setup is a canister box where the powder is dosed out through the action of a constant-pitch coil feeder connected to a motor. A dosing step consists of a rotation followed by a period of rest before the next step. From the experiments, we report on the operational performance of the dosing process through a variation of dosage time, coil pitch and initial powder filling mass. We find that the mass per dose shows an increasing linear dependence on the dosage time and rotation speed. In contrast, the mass output from the canister is inversely proportional (as expected) to an increase in the number of coils.

After calibrating the interparticle friction and cohesion, we show that DEM simulations with upscaled particles can quantitatively reproduce the experimental findings for smaller masses but also overestimate arching and blockage. For some parameters, with appropriate homogenization tools, further insights into macroscopic fields can be obtained.

This work shows that the calibration of (upscaled) meso-particle properties is a viable approach to overcome the untreatable number of particles inherent in experiments with fine, cohesive powders and thus opens the gateway to simulating their flow in more complex geometries.

1. Introduction and background

The dynamic behavior of granular materials is of considerable interest in a wide range of industries (e.g., pharmaceutical, chemical and food processing). In these industries, every step in the product manufacturing process contributes to the final quality of the product. Hence, if uniform product quality is to be achieved, a full understanding and control of the different stages of the production process is essential. In many applications, the transport and conveying of granular materials is a common process that forms a critical part of many production and delivery techniques. For example, transport to silos, process transport, controlled drug delivery and dosing of beverages all rely on an effective and uniform delivery of granular materials. Dosing consistently the correct amount of a soluble beverage powder is for instance the first step toward preparing a high quality beverage, but this process is also naturally conditioned by how the powder interacts with the water surface [1]. Also, the design of products for these processes is hugely dependent on having a good understanding of the transport behavior and metering process of granular assemblies.

When granular materials are being transported, the behavior of the granular material and the efficiency of the process will depend on several material properties including particle shape [2–4], particle size [5,6], surface roughness [7,8], frictional properties [9], cohesion [10] and moisture content [11] among others. Discontinuities and inhomogeneities in the micro-mechanical behavior of bulk assemblies of granular materials are ever-present, hence, changes in the operating conditions affect the flow behavior of granular assemblies [12]. Also the geometry of the transport media (boundary conditions) including wall friction [13] and the loading/preparation procedure will play an important role [9,14,15].

Over the past decade, the mechanisms during transport of granular materials have attracted significant interest and efforts from researchers. These efforts can be grouped into three classes namely, experimental, numerical modeling and developing constitutive models to predict granular flows in conveying mechanisms [16,17]. The numerical modeling of granular flows has been based on Discrete Element Method (DEM) as proposed in Ref. [18]. The earlier (more favored) experimental approach mostly involves the design and construction of

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experimental models of such applications followed by series of studies and benchmark tests to determine quantities of interest and fine-tune the process to desirable levels. Thereafter, a scale-up of the process can be performed [19,20]. In this case, the challenging task is the selection of relevant parameters and boundary conditions to fully characterize the flow rheology in these systems.

A degree of knowledge in characterizing dry, non-sticky powders exists. For example, rotating drum experiments and simulations to determine the dynamic angle of repose have been studied extensively as a means to characterize non-cohesive powders [21,22]. What has been less studied is the case where the powders are sticky, cohesive and less flowable like those relevant in the food industry. For these powders, dynamic tests are difficult to perform due to contact adhesion and clump formation. Inhomogeneities are also more rampant and flow prediction becomes even more troublesome.

Screw conveyors are generally used in process industries for an accurate and steady transport of bulk materials. Materials like cereals, tablets, chemicals, pellets, salt and sand among others can be transported using screw conveyors. As simple as this process may seem, problems of inaccurate metering, unsteady flow rates, bridging, channeling, arching, product inhomogeneity, segregation, high start up torques, equipment wear and variable residence time have been reported [23–26]. In addition, the design and optimization of screw conveyors is not well understood and has been based on a semi-empirical approach or experimental techniques using dynamic similarities as pointed out in Ref. [26]. Earlier researchers have investigated the effect of various screw (auger) parameters including choke length (the distance which the screw projects beyond the casing at the lower end of the intake) and pitch–diameter ratio (See Refs [27–29] and references therein). Robert and Willis [29] reported that since grain motion is largely influenced by its centrifugal inertia, augers with large diameters attain maximum output at lower speeds compared to those with small diameters. They also reported that for maximum throughput during conveying, longer chokes are necessary for larger diameter augers.

The subject of modeling screw conveying of granular materials with the Discrete Element Method (DEM) [18] is fairly recent. One of the earliest work on this subject was reported in Ref. [30] where the performance of horizontal and vertical screw conveyors are investigated and results are compared with empirical equations of the particle velocity in the horizontal or vertical (axial) direction, respectively for different rotation speeds (200 - 500 rpm). In a related work, Owen et al. [23] studied the performance of a long screw conveyor by introducing the so-called 'periodic slice' model. Along this line, Cleary [24] investigated the effects of particle shape on flow out of hoppers and on the transport characteristics of screw conveyors.

Experiments on the dosing of glass beads and cohesive powders along with DEM simulation of the dosing of glass beads have been reported by Ramaioli [31]. For dry (cohesionless) simulations of glass beads, Ramaioli scaled down the depth of his experimental box, thereby reducing the system volume and number of particles to be simulated. By studying the experimental mass per dose and profile of the powder surface for different screw designs, he obtained regular doses for screws with conical inserts. One question that remains – and that we attempt to answer in the present study – is the extent to which discrete element simulations can predict the dosing of cohesive powders. Also, issues relating to parameter identification, calibration and the scaling of DEM particles such that they represent the primary particles must be addressed to improve confidence in DEM results.

In the current study, we build on the work of Ramaioli [31] by using experiments and discrete element simulations to investigate the dosing of cohesive powders in a simplified canister geometry. The characterization of the experimental samples, experimental set-up and procedure are presented in Section 2. In Section 3, we present the force model, simulation parameters and homogenization technique followed by a discussion of experimental and numerical results in Sections 4 and 5, respectively Finally, the summary, conclusions and outlook are presented in Section 6.

2. Dosage experiments

In this section, we discuss in detail the experimental set-up and measurement procedure along with the material parameters of the experimental sample.

2.1. Sample description and characterization

The cohesive granular sample used in this work is cocoa powder with material properties shown in Table 1. The particle size distribution (PSD) is obtained by the "dry dispersion module" of the Malvern Mastersizer 2000 (Malvern Instruments Ltd., UK), while the particle density is obtained by helium pycnometry (Accupyc, Micromeritics, US). The relative span is defined as the difference between the 90% and 10% quantile divided by the 50% quantile. We tested a range of pressure in order to have a good dispersion of the cocoa particles during size distribution measurement. A pressure between 1 and 4 bar was sufficient to ensure minimal breakage and consistent results while pressures between 0.5 and 1 bar was found to lead to a decrease in the size distribution measured. Therefore, we use a pressure value of 2 bar in our analysis.

The dosing experiments were performed over a relatively short period under ambient conditions and samples are sealed in air-tight bags when not in use to minimize effects that could arise due to changes in the product humidity.

2.2. Experimental set-up

The setup is a simplified canister box where the powder is dosed out of the box through the action of a constant-pitch coil feeder connected to a motor. A schematic representation of the experimental set-up is shown in Fig. 1 along with the dimensions given in Table 2. A typical experiment begins with the careful filling of the canister with the exit closed until a pre-determined powder mass is reached. Care is taken to ensure that the initial profile of the powder surface is as flat as possible and that any pre-compaction that may arise due to shaking or vibrations are minimized. Subsequently, the dosing experiment begins with the rotation of the screw for a specified time duration followed by an intermediate rest before the next dosage. The dosed mass per screw turn is recorded through a weighing scale connected to a computer. The time difference between the powder exit from the box and the measurement is less than one second. Also, the weighing scale has enough time to equilibrate during the period of rest before the next dosage. The experiment is complete when the cumulative dosed mass recorded for three consecutive doses is less than 0.15 g indicating either the box is empty or the powder is blocked through arching in the canister. In addition, to obtain and post-process the profiles of the sample surface during the experiments, an external camera (Logitech HD Pro, Logitech Int'l SA) was mounted in front of the canister box and a video recording of each experiment was obtained.

2.2.1. Image processing

Snapshots of the profile of the powder surface during each experiments were obtained using a camera attached to the experimental set-up. To improve the quality of the snapshots and for comparison, we use the open-source software FIJI [32] to post-process the images

Table 1
Material properties of the experimental cocoa sample.

Property		Unit	Value
Size distribution	d_{10}	μm	31.55
	d_{50}	μm	184
	d_{90}	μm	979.19
Span	$(d_{10} - d_{10})/d_{50}$	[–]	5.151
Particle density		[kg/m^3]	1427
Specific surface area		m^2/g	0.088