Precision powder feeding

Renewal proposal submitted to IFPRI
Prabhu R. Nott, Indian Institute of Science

Summary: This renewal proposal outlines a study that aims to further the understanding of powder flow through screw feeders that was achieved during the first term of the project. The proposal has three main elements: the first is to extend the theoretical model we have developed to cohesive powders, with the aim of linking feeder performance to powder properties and feeder geometry. The second element is to study the inlet hopper-feeder interaction by experiments and DEM simulations, as that was found to be a key bottleneck in effecting a steady feed rate. We hope to arrive at strategies to mitigate jamming blockages and flow fluctuations from the inlet hopper, which in turn will lead to smooth flow flow at the feeder exit. The third element is to derive simple scaling relations or correlations for the feed rate, its fluctuations and the shaft torque with feeder and material properties, to enable industry professionals to use the results of our work more easily. While we foresee challenges in the proposed work, the success of our efforts in the first term gives us confidence that we will make good progress.

1 Progress made during the first term of the project

A brief account of our accomplishments during the first term of the project is in order. We first constructed a mechanics-based model to predict the feed rate as a function of the feeder dimensions. As the geometry and the flow are complex, we made analytical progress by making the simplifying assumptions that gravity is absent, the feeder is fully filled and the material moves as a plug. By enforcing the balances of force and torque on the wedge-shaped element shown is Fig. 1a, we derived the relation for the feeding velocity v_z when the screw and shaft surface are frictionless,

$$v_z = \omega R_b \frac{\pi p/(2R_b)}{\pi^2 + (p/(2R_b))^2} \qquad (1)$$

where all the symbols are defined in Fig. 1a. The relation predicts that the feed rate reaches a maximum when the ratio of the pitch to diameter $p/(2R_b)$ of the screw equals π.

To test this non-trivial prediction, we conducted DEM simulations wherein one pitch length of the feeder was simulated using periodic inlet and outlet boundaries. As shown in Fig. 1(b), when the screw is frictionless and gravity is absent in the DEM simulations, the results are in perfect agreement with the prediction in (1).

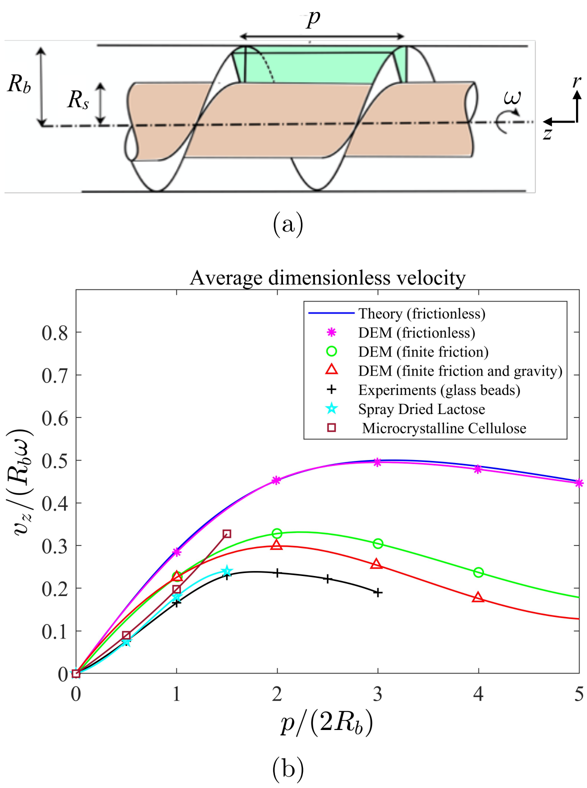
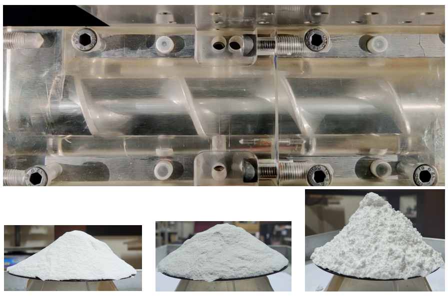


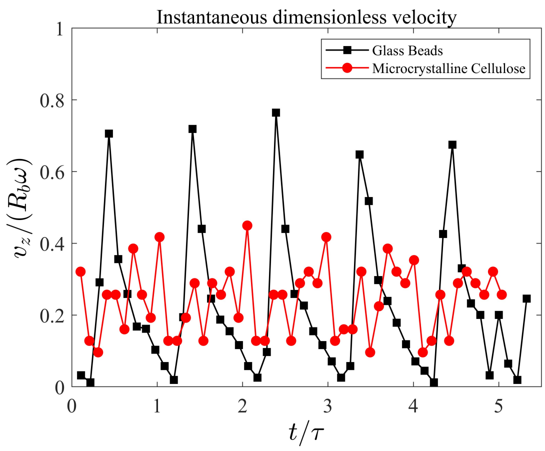
Figure 1: (a) Schematic of the screw feeder. The green wedge is the differential element over which the force and torque balances are applied. (b) Feed rate as a function of the pitch to diameter ratio. The prediction of (1) is compared with the resuts of DEM simulations and experimental meassurements.

More interestingly, even when the conditions in the simulations depart from the simplifying assumptions used to derive (1), the qualitative features of the v_z versus $p/(2R_b)$ plot remain unaltered (green and red lines in Fig. 1b; v_z always attains a maximum at an particular value of $p/(2R_b)$.

We then built an experimental screw feeder assembly instrumented to make measurements of the feed rate, and velocity and stress profiles at the barrel surface Fig. 2(a). The front half of the barrel is constructed of transparent plexiglass and the rear of aluminium; a translation stage bearing a sensitive force sensor is mounted on the latter. We studied the flow of cohesionless glass beads and three cohesive powders sent to us by Pauline Janssen of DFE Pharma. Data for the feed rate (averaged over one revolution of the screw) for glass beads and two cohesive powders are shown in Fig. 1b; for glass beads, the maximum in v_z is clearly seen, but for the two cohesive powders data for larger $p/(2R_b)$ is yet to be obtained. Nevertheless, the data for spray-dried lactose strongly hint at the presence of a maximum. Thus, the experimental data are in qualitative agreeement with the prediction of the simple model and the results of DEM simulations. However, the mean feed rate does not convey the full picture, as there are large fluctuations. Figure 2b plots the instantaneous feed rate against time, where it is clear that the fluctuations are large are periodic for the free-flowing glass beads, but somewhat random for the cohesive microcrystalline cellulose powder. Feed rate fluctuations are of considerable interest to industry, as it is usually desirable to minimize them to maintain product quality. We were able to relate the fluctuations to the variation of the free surface slope near the exit – the variation is periodic for free-flowing glass beads, and stochastic for the cohesive lactose powder.



(a)



(b)

Figure 2: (a) The experimental feeder assembly with a transparent front face. The back face houses the force sensor mounted flush against the surface of the barrel (not shown). The images at the bottom are heaps of the three cohesive powders on which experiments were performed. (b) Temporal fluctuations in the feed rate for glass beads and microcrystalline cellulose. Time is scaled by the period of revolution of the screw.

Equation (1) is derived by making the gross simplification that the material moves as a plug. To account for the variation in the velocity, a constitutive model is needed. It is known that classical plasticity theories suffer from serious deficiencies, such as mathematical ill-posedness and kinematic indeterminacy [1, 2]. During the first term, we have developed of a non-local model for the flow of non-cohesive granular materials [2] that resolves these deficiencies. Crucially, the model incorporates shear dilatancy in sustained flow, an important feature of granular materials, which no other model does. The predictions of the model are in excellent agreement with the results of DEM simulations of simple shear. The constitutive relation for this model is

$$\boldsymbol{\sigma} = -p\,\boldsymbol{\delta} + \frac{2\mu\, p_{\mathrm{c}}}{\dot{\gamma}}\,(\boldsymbol{D} - \ell^2\,\nabla^2\boldsymbol{D}), \tag{2a}$$

$$p = p_{\mathrm{c}}\left(1 - \frac{\mu_{\mathrm{b}}}{\dot{\gamma}}\boldsymbol{\nabla\cdot v}\right) - \ell^2\Pi\,\nabla^2\boldsymbol{\nabla\cdot v}, \qquad p_c = \Pi(\phi) - \ell^2\,\frac{\mathrm{d}\Pi}{\mathrm{d}\phi}\,\nabla^2\phi. \tag{2b, c}$$

Here $\boldsymbol{\sigma}$ is the stress tensor, p is the pressure, ϕ is the powder volume fraction, $\boldsymbol{D}$ is the strain rate tensor whose scalar magnitude is $\dot{\gamma} \equiv (2D_{ij}D_{ji})^{1/2}$, and $p_{\mathrm{c}}(\phi)$ is the pressure at the *critical state* of isochoric deformation [7], and $\Pi(\phi)$ is critical state pressure in the absence of non-local effects. The model parameters are the Coulomb friction coefficient μ and the bulk plastic modulus μ_{b}. All the terms multiplied by ℓ^2 represent the non-local contributions, ℓ being the mesoscopic length scale that characterizes non-locality.

When the non-local model (2) is applied to flow in a screw feeder, we find that the predicted feed rate matches exactly with that of the simple model (1) for the case of a frictionless screw. The model prediction of the wall stress is also in good qualitative agreement with the DEM results and experimental measurements. The solution of the model equations for the case of frictional screw and in the presence of gravity present is underway; we expect to complete it by the end of the project term.

2 Proposed programme of investigation

We propose to continue our strategy of employing a three-pronged approach that combines theoretical modelling, DEM simulations and experiments. The synergy achieved by combining these elements has proved to be very useful in the first term, and we expect the same to continue in the second. Our main thrust in the second term will be to understand, model and verify the flow of cohesive powders in screw feeders, as we believe that a reasonably good understanding of free-flowing or non-cohesive powders has been achieved thus far. The rationale and details of our modelling approach are expanded in §2.1. As in the current term, we will use DEM simulations to guide us in model development, and to test the predictions of the model. We propose to expand our experimental investigation to look more closely at the hopper-feeder interface, as we believe that to be a key bottleneck in effecting smooth flow of cohesive powders. Apart from the new thrusts outlined below, we will tie up and complete the few elements of our ongoing work that remain incomplete.

2.1 Extending the theoretical model for cohesive powders

Our work so far has demonstrated that the non-local model (2) performs well in steady and transient simple shear flows [2–4] and in the screw feeder for non-cohesive powders [5]. Some aspects of our modelling effort remain to be explored, such as the flow of non-cohesive powders in partially filled feeders – these as primarily computational challenges, which will be undertaken once the investigations of the current term are completed.

The next phase of our modelling efforts will concentrate on incorporating cohesion in the constitutive model (2). Classically, cohesion has been incorporated by simply adding an extra contribution to the yield stress. However, this extension says nothing about how the material deforms post yield. To answer that question, we much extend the flow rule to incorporate cohesion; to our knowledge, this aspect that has not been considered in any previous study. The flow rule is a relation between the deformation rate and the stress; for non-cohesive powders, it has the form [7]

$$D_{ij} = \dot{\lambda}\frac{\partial F}{\partial \sigma_{ij}} \tag{2}$$

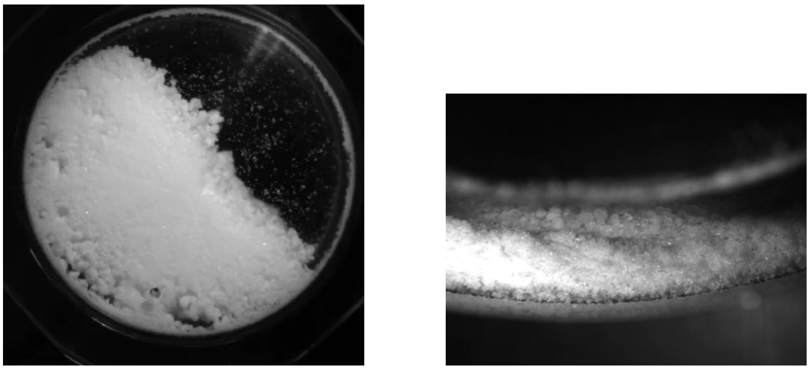


Figure 3: (a) Grain agglomerates or clumps adhered by cohesion in (a) horizontal drum and (b) a Couette shear device. The cyan coloured text link to movies corresponding to each image.

where $F(\boldsymbol{\sigma})$ is the yield function that attains the value zero when the materials yields and $\dot{\lambda}$ is the flowability. For simple choices of the function $F(\boldsymbol{\sigma})$, such as the extended von Mises yield condition, it is easy to show that [8]

$$\dot{\lambda} = \dot{\gamma} \equiv (D_{ij} D_{ij})^{1/2}, \tag{3}$$

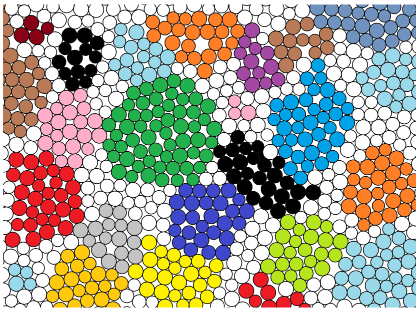
i.e., it is the scalar invariant of the deformation rate tensor $\boldsymbol{D}$. Thus the greater the value of $\dot{\lambda}$, the more the material deforms.

Equation (3) is very unlikely to hold for cohesive powders. A key feature of cohesive powders is that the particles form agglomerates or clumps that continuosly form and break during flow. Evidence of this phenomenon is apparent in Fig. 3, which shows the flow of a cohesive powder in a horizontal drum (Fig. 3a) and in a Couette shear device (Fig. 3b). The cyan text in the caption are links to the movies from which the images in the figure are extracted. It is clear from the figures that clumps of various sizes are present; the movie corresponding to Fig. 3a shows the clumps repeatedly forming and breaking up. On the other hand, the movie corresponding to Fig. 3b shows that once clumps form they remaining largely integral, and do not undergo breakage. Unsurprisingly, it is clear from both the movies that the powders become more 'flowable' when they form clumps. This information is missing in (3). Our proposal is to incorporate the size distribution of clumps and their susceptibility to break up in the flow rule. We see two ways of incorporating this feature: one way is to modify the yield function $F(\boldsymbol{\sigma})$ to incorporate the size distribution and rigidity of the clumps, and use the flow rule (2) as such. Another is to propose an alternative flow rule that incorporates the above mentioned features of the clumps. It appears to us that the former is more desirable, as the resulting constitutive relation will automatically satisfy the requirements of an acceptable constitutive model, such as positive dissipation and rate independence of the stress. The non-local extension of the model would then be the same as (2), but with $\dot{\gamma}$ replaced by $\dot{\lambda}$.

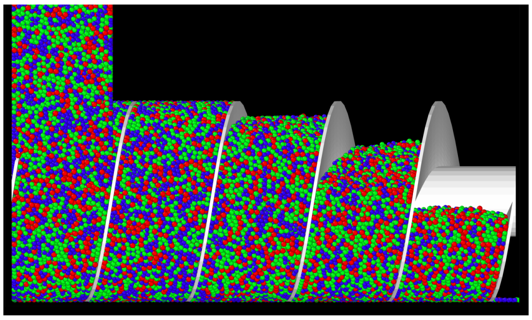
A clear and definite recipe for generalizing the yield function in the manner described above is not clear a priori. We propose to use DEM simulations to guide this effort. An elaboration of how DEM simulations of cohesive powders will aid in this model building is given in §2.2.

2.2 DEM simulations to guide model building and validation

As mentioned in §2.1, we propose to employ DEM simulations to guide efforts in building a constitutive model for cohesive powders. In recent work in our laboratory, we have gained useful insight by identifying clusters of particles that constitute a fragile network – we have demonstrated that the collapse of any cluster in the network leads to a slip event,



(a)



(b)

Figure 4: (a) Schematic showing grain agglomerates or clumps of different sizes adhered by cohesion. The colours indicate the mean strength of the agglomerates. (b) Snapshot of a DEM simulation for the full length of the feeder, from the inlet hopper to the exit.

and used this information to understand the slick-slip dynamics of granular deformation. The same idea can be extended to cohesive powders, but in a converse manner. DEM will allow identification of cohesion-bound particle agglomerates and estimate their strength, as shown in the schematic representation in Fig. 4a. If we are able to and correlate the motion and deformation of such clusters with the applied stress in a statistically averaged manner, we will have a relation for the yield stress that depends on the cluster size distribution and strength. This will enable extension of the von Mises yield condition for cohesive powders, and thereby determine the flowability $\dot{\lambda}$, as discussed in §2.1.

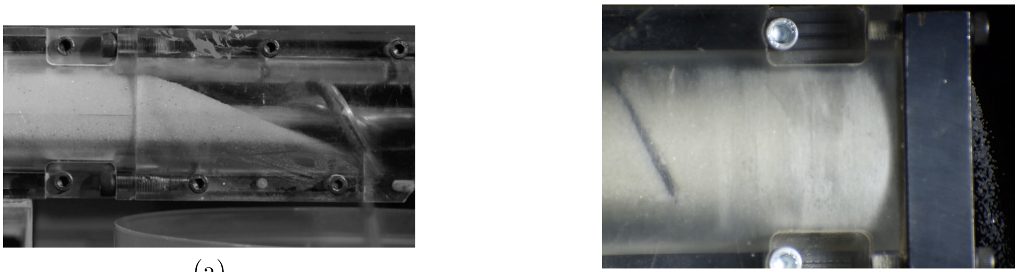
In parallel, we propose to conduct DEM simulations of the full feeder, from the inlet hopper to the exit (Fig. 4b), with particular attention to the inlet hopper-feeder junction for powders of different cohesion force. The DEM simulations we have conducted in the current term for cohesive powders are only for one pitch length of the feeder, with the assumption of periodic inlet and outlet conditions. These simulations did not yield much information on critical aspects of the dynamics, such as plugging at the hopper-feeder interface, spontaneous fluctuations or jamming within the feeder, and feed rate fluctuations at the feeder exit, as seen in the experimental data in Fig. 2. We expect the full feeder simulations to more realistic, thereby allowing more insight, and providing clearer testing validation (or otherwise) of our model for cohesive particles.

We will continue to use the open source LAMMPS and LIGGHTS packages for our simulations.

2.3 Experimental investigation

In addition to our ongoing experimental investigations, we propose two new experimental thrusts. The first is to study the feeder-hopper junction by flow visualization and stress measurement. Our studies this far indicate that this is the bottleneck that determines whether or not smooth feeding of cohesive particles can be achieved. To achieve this, we have to modify our setup so that the feeder hopper junction has a single transparent (glass or acrylic) front face, so that the flow is clearly visible. We will use high speed videography to image the flow and extract the velocity field. We have thus far not been able to measure the wall stress during the feeding of cohesive powders, as the small particles get into the gap between the sensor and the barrel, thereby polluting the measurement. We now propose to fill the gap by a soft elastomer (such as PDMS) that will offer minimal resistance to the sensor but effectively prevent the particles from getting into the gap.

The second thrust is to study the effect of the exit geometry on the fluctuations of



(a) (b)

Figure 5: The fill level of the feeder when the exit slot is (a) at the bottom and (b) at the top of the end plate. The flowing material here is glass beads of 0.5 mm diameter.

the feed rate. For glass beads, feed rate fluctuations (see Fig. 2b) arise from temporal variation of the slope of the free surface near the exit. This is a result of a fall in the fill level in the feeder with axial distance, as shown in Fig. 4b. In very recent experiments, we have shown that moving the exit slot to the top of the end plate results in the feeder being fully filled all the way till the exit (see Fig. 5). We expect that this will significantly reducing the feed rate fluctuations. We propose to quantify the fluctuations for exit geometries and attempt to arrive at an optimal geometry that minimizes fluctuations.

2.4 Developing scaling relations or correlations for feeder function

While each element of our study will contribute to the understanding of powder flow through screw feeders, the utility of our study for industry would be significantly enhanced if we are able to come up with relatively simple scaling relations or correlations for the mean feed rate and its fluctuations, the torque required to drive the feeder, and other operation parameters. For non-cohesive powders, we have shown that the feed velocity obeys the simple relation

$$v_z = \omega R_B f(p/(2R_b)), \tag{4}$$

i.e., it is linear in the angular frequency ω of the screw and has a simple dependence on the pitch to diameter ratio $p/(2R_b)$ (black curve in Fig. 1. The data obtained so far indicate that v_z does not dependent of the material or barrel friction coefficient, though data for more powders are needed to confirm this. However, the amplitude of the fluctuations does depend on the friction coefficients, as fluctuations originate from the slope of the free surface at the exit.

The relationship for cohesive powders is expected to be more complex, but we expect that a combination of scaling and correlation will be possible. It will be our endeavour to distill the results of our theory, simulations and experiments to obtain such relations, as that will be of immediate use to IFPRI members and industry at large.

2.5 Expected year-wise accomplishments

Year 1: The DEM simulations of the full feeder for cohesive powders would be completed. Numerical solution of the non-local model (2) for the case of frictional screw would have been obtained. Construction of an inlet hopper-feeder module having a single transparent front face would have been completed and preliminary imaging data would be obtained.
Year 2: Detailed flow imaging and stress measurement near the inlet hopper-feeder for cohesive powders would be ongoing. DEM simulations of simple flows, such as plane shear, would be conducted to identify cohesion-bound aggregates and their kinematics. These results will guide the development of a constitutive model for cohesive powders.

Early results from application of the model for flow in screw feeders powders as outlined in §2.1 would be obtained.
Year 3: The model for cohesive powders would be refined and applied to feeder flow, and comparison with experimental data and DEM simulations would have been obtained. The scaling relations or correlations for the important aspects of feeder function, such as feed rate, fluctuations and torque would be developed.

References

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