Power Law Behavior in Granular Matter Rheometry

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ABSTRACT

Early work with a commercial rheometer, which functions as a Couette-type rheometer with a rotating inner cylinder and a stationary outer cylinder. No-slip is ensured with a profiled surface of the inner cylinder. Measurements were performed for increasing shear rate with different powders. Furthermore for one powder two different degrees of aeration was investigated.

It was found that the powders exhibited power law behaviour, with some interesting deviations at low shear rates. Aeration increased the particle mobility, which in turn decreased the viscosity of the powder in accordance with previous findings in literature.

INTRODUCTION

Many techniques have been used to measure powder flow. The most famous is probably the shear cell first introduced by Jenike in 1964[1] for the design of silos. Different versions of the shear cell is used in the literature and industry, but the most significant innovation upon Jenike's original cell was making the shearing motion rotational as exemplified in the rotational split-level shear cell[2]. In a shear cell a powder sample is precompressed to a certain degree, after which the force required to shear the powder at various normal pressures is determined. This then indicates the resistance to flow in the powder. Shear cells have been criticized for working poorly with free-flowing powders[3] and it follows from the working principle that it cannot be used to measure flow of powders not under normal pressure.

Many other techniques have been used to indicate powder flow throughout history, with the measurement of angle of repose or Hausner Ratio as examples. Juliano and Barbosa-Cánovas gave a good review of many of these in 2010[4]. These are all criticised for being quite dependent on the user and have low reproducibility. They have also shown poor ability to discern powders with relatively low differences in flowability. Powders have also been assessed under conditions of greater mobility through avalanching[5]. It is rather difficult to extract useful data from this technique (because of chaotic movement patterns) and it has a limited region of usefulness, because of the high degree of movement.

Some attempts have been made to produce rheometers reminiscent of those used to measure fluids, but to the knowledge of the authors, these have not seen widespread use in industry. These will include some stirring mechanism and typically, some form of vanes meant to ensure non-stick conditions on the walls[6-9]. To gain access to the different packing configurations available in a sort of ensemble average these rheometers included a way to vibrate the powders. Many interesting phenomena have been observed using these setups, but few relations to industrial processes have been determined.

EXPERIMENTAL SETUP

The measurements were made using a commercially available rheometer fitted with a powder cell specifically developed for powder rheometry. Both are produced by Anton Paar and while a brief description will be given here, detailed specifications are available online or from Anton Paar themselves. The rheometer is the MCR 301 with the Anton Paar Powder Cell. The measurements presented here are performed using a profiled cylinder as a stirrer. This means the geometry is comparable to a Couette rheometer with a fixed outer cylinder and a rotating inner cylinder. The profiling of the inner cylinder was in the shape of small convex contours, which were filled with particles when the powder cell was filled in preparation for measurements. This moves those particles in the grooves, thus ensuring a non-stick surface, which meant the internal friction in the powder was measured, rather than the friction between powder and cylinder. In no measurements were slip on the outer surface observed.

The setup allows dry air to be blown through the sample from below at a controlled flow rate. This makes accessible different degrees of compaction.

For all samples, the same weight was used to ensure a comparable load on the powder during testing. An initiation sequence is carried out after loading and before each measurement to clear the memory from any previous handling or measurements. This increases reproducibility and removes dependency on the device user.

The results shown here were carried out for a maltodextrin powder and for three different industrial powders. The details of the latter cannot be disclosed. For the three industrial powders shown, no aeration was used, while two different aeration degrees are used for the maltodextrin, namely 1.2 and 6 l/min.

RESULTS

All results will be reported as viscosity as a function of shear rate. Fig. 1 shows the three different industrial powders, while Fig. 2 shows the two maltodextrin.

The industrial powders shows slightly erratic behaviour and powders A and B in particular seem to increase for very low shear rates.

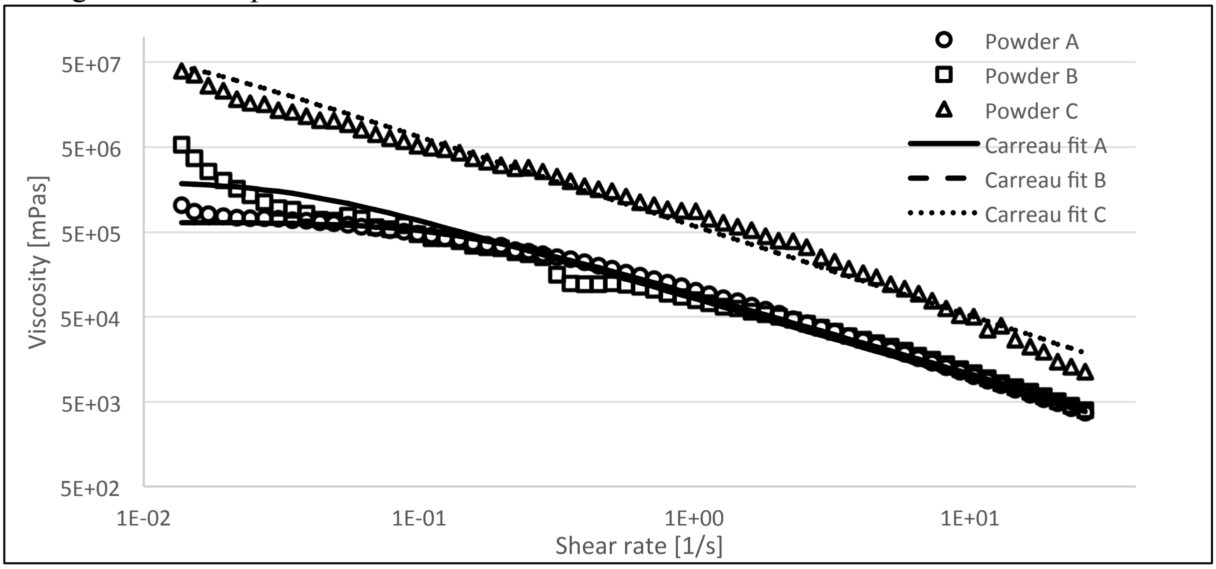

Figure 1. Viscosity as a function of shear rate for three industrial powders plotted with fits of the Carreau model included. Parameters used in the fit may be found in Table 2. Powders were not aerated for any of the measurements shown here.

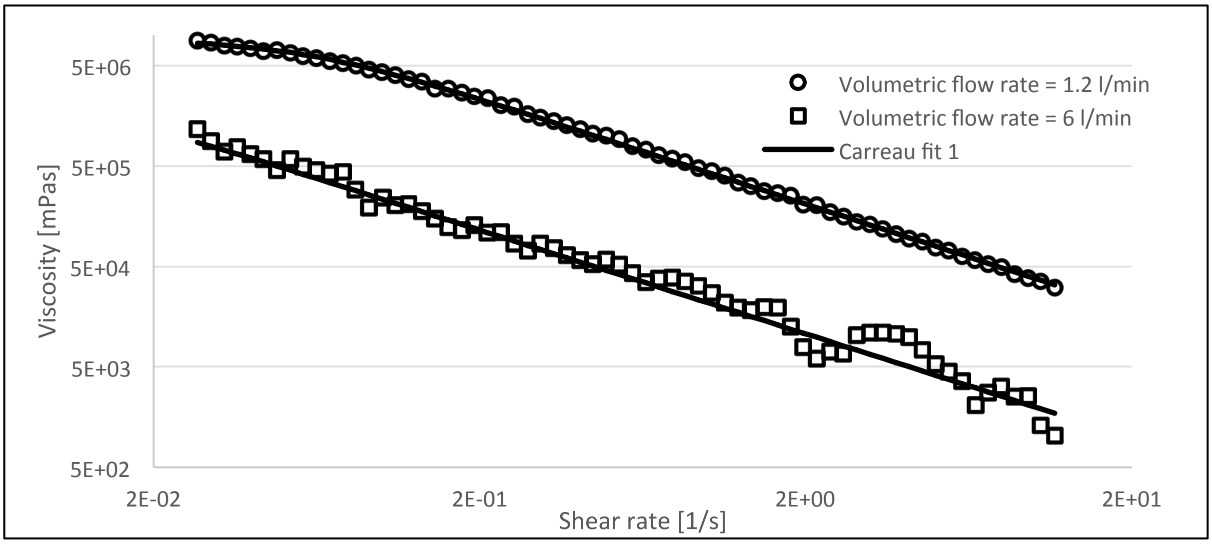

Figure 2: Viscosity as a function of shear rate for a maltodextrin at two different degrees of aeration. Fits of the Carreau model are included. Parameters used in the fit may be found in Table 2.

The maltodextrins show very smooth curve for the low aeration rate, but for 6 l/min is more erratic. This will be discussed more in the next section.

DISCUSSION

The increases in viscosity observed for low shear rates for powders A and B could be an actual feature, but it is also possible that the initiation of movement is resisted more. Increasing the range of shear rates could help elucidate this. It seems for both, that there is a plateau at slightly higher shear rates, which could indicate that the increase is an artefact.

In Fig. 2 it is clear that increased aeration rate, reduces the viscosity. This has been observed by researchers in the past and is typically attributed to the increased mobility of the particles. Parallels to temperature dependence of viscosity has been drawn in the past[6,8].

In the plots a curve has been fitted to each set of data. The curvea are fitted versions of the Carreau-Yasuda model[10]

$$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty} = (1 + (\lambda\dot{\gamma})^a)^{\frac{n-1}{a}} \quad (1)$$

As can be seen the fit is quite accurate for all graphs, although it performs especially well for maltodextrin at an aeration rate of 1.2 l/min. The Carreau-Yasuda model was chosen for the fit because it captures some of the behaviour observed for a few graphs, however the most important feature is the power-law dependence of viscosity upon the shear rate seen for all samples. The parameters used in the fits is shown in table 1.

CONCLUSIONS

A commercial rheometer resembling a Couette rheometer allowed for the measurement of viscosity of a powder. This was measured for increasing shear rate for a few different powders, with different degrees of aeration. It was found that the powder exhibited power law behaviour for

Table 1: Carreau-Yasuda model parameters used in the curve fits in Fig. 1 and Fig. 2.

	η_0 [mPas]	η_∞ [mPas]	Λ [s]	n [-]	A [-]
Powder A	1.3e6	0	8	0.53	2.0
Powder B	4e6	0	30	0.53	2.0
Powder C	1.5e8	0	100	0.521	2.2
Maltodex. 1.2 l/min	2e7	0	18	0.521	2.2
Maltodex. 6 l/min	5.6e8	0	100	0.53	2.2

most of the shear rate window, with slightly different behaviour appearing at the lower end. A plateau was seen for some powders, which was fitted well with a Carreau-Yasuda model. A few powders also seemed to have a higher viscosity early on, but this may be an artefact arising from increased resistance to flow initiation.

FUTURE WORK

This work is only a very early step into what is possible with the powder rheometer used. Experimentally, the first of two obvious next steps would be to assess how general the power law behaviour observed under some conditions is, including both more powders, aeration degrees and investigation of what happens at lower and higher shear rates. The second obvious next step is to investigate oscillatory shear. Researchers have observed elastic responses under certain conditions in different setups and it would be expected here as well.

Theoretically, the next step is to model the flow patterns within the cell. It seems obvious to start with an assumption of continuum behaviour. Alternatively, numerical tools could be used to model the particles as discrete elements.

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REFERENCES

1. Jenike, A.W.. (1964), "Storage and Flow of Solids, Bulletin no. 123", *Bulletin of the University of Utah*

2. Peschl, I.A.S.Z. (1989), “Quality Control of Powders for Industrial Applications”, *Powder Handling and Processing* **1**(4), 357-364

3. Koynov, S., Glasser, B., Muzzio, F. (2015), “Comparison of Three Rotational Shear Cell Testers: Powder Flowability and Bulk Density”, *Powder Technology*, **283**, 103-112

4. Juliano, P., Barbosa-Cánovas, G.V. (2010), “Food Powders Flowability Characterization: Theory, Methods, and Applications”, *Annu. Rev. Food Sci. Technol.*, **1**, 211-239

5. Lumay, G., Boschini, F., Traina, K., Bontempi, S., Remy, J.-C., Cloots, R., Vandewalle, N. (2012), “Measuring the Flowing Properties of Powders and Grains”, *Powder Technology*, **224**, 19-27

6. Marchal, P., Smirani, N., Choplin, L. (2009), “Rheology Dense-Phase Vibrated Powders and Molecular Analogies”, *Journal of Rheology*, **53**(1), 1-29

7. Dijksman, J.A., Wortel, G.H., van Dellen, L.T.H., Dauchot, O., van Hecke, M. (2011), “Jamming, Yielding, and Rheology of Weakly Vibrated Granular Media”, *Physical Review Letters*, **107**(10), 108303

8. Hanotin, C., de Richter, S.K., Marchal, P., Michot, L.J., Baravian, C. (2012), “Vibration-Induced Liquefaction of Granular Suspensions”, *Physical Review Letters*, **108**(19), 198301

9. Barois-Cazenave, A., Marchal, P., Falk, V., Choplin, L. (1999), “Experimental Study of Powder Rheological Behaviour”, *Powder Technology*, **103**(1), 58-64

10. Bird, R.B., Armstrong, R.C., Hassager, O. (1987), “Dynamics of Polymeric Liquids, Vol. 1: Fluid Dynamics”, John Wiley and Sons, 2nd Edition.