# The effect of process conditions on the fluidization behaviour of gas fluidized beds

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## Abstract

The flow properties of three powders differing in size and density and fluidized at various rates of aeration have been studied by means of a mechanically stirred Fluidized Bed Rheometer (msFBR). A correspondence between the fluid bed expansion and the torque measurements for the three powders was found: the higher the capability of the powder to expand, the lower the torque needed to stir it; increasing aeration diminished the energy needed to stir the materials. A shear stress/shear rate relationship was derived from the experimental curves and a rheological model was fitted to the data, highlighting a yield stress behaviour at gas velocities below the minimum fluidization velocity ($u_{mf}$) and power law behaviour at gas velocities above $u_{mf}$.

## 1. Introduction

The framework that encompasses this work is the understanding of the effect of realistic process conditions, such as temperature and particle size distribution, on the fluidization behaviour of fluidized powders. Process conditions can greatly influence the balance between hydrodynamic and interparticle forces and some times drastically change the fluidization behaviour [1]. In particular, several authors [2,3] have reported on the beneficial effect on fluidization of adding fine particles (<45 μm) to the bed and it is common practice in industry to employ between 10-50% by weight of fine material in order to maximize reactor performance. However, the relative importance of the various fine sub-cuts (0-15, 15-25, 25-38 and 38-45 μm) on the improvement of fluidization represents an issue which as not been fully understood as yet.

In order to tackle the problem of assessing the fluidization behaviour of powders at process conditions, we adopted a twofold approach: on one hand the investigation of the fluidization behaviour at process conditions by means of standard fluidization tests; on the other hand the characterization of the flow properties of powders at process conditions by means of rheological tests. The basic idea is to find a methodology to link the rheological measurements to the fluidization behaviour observed and therefore develop a technique that may offer the “tantalizing hope” of some sort of universal powder characterization test at realistic process conditions.

To this end, a novel technique to measure the rheological bulk properties of aerated/fluidized materials at process conditions was developed: a mechanically stirred Fluidized Bed Rheometer (msFBR).

In this paper we focus on the rheological aspect of the project. In particular, we report here a preliminary set of experiments carried out in order to test the capability of the msFBR to discriminate different fluidization behaviours and different rates of aeration, at this stage at ambient temperature only.

Previous work reported elsewhere [4] was conducted to study the effect of fines size distribution and temperature on fluidization. This showed that even small changes in the fines size distribution caused some significant differences on the fluidization behaviour of the powders investigated. Ongoing work is to link the two aspects of the project by studying the effect of fines size distribution on the rheological properties measured using the msFBR technique.

## 2. Experimental apparatus and materials

The mechanically stirred Fluidized Bed Rheometer has been designed, built and commissioned at University College London. A 140 mm diameter × 300 mm tall Pyrex vessel with a wall thickness of 3 mm fitted with a very fine sintered stainless steel distributor plate is used as a fluidising vessel. A 70 mm high windbox is located below the distributor plate. Nitrogen is used as fluidizing gas, its flow rate being controlled via a set of rotameters before entering the windbox. The pressure drop across the bed is measured by means of an ultra low pressure differential sensor. The heaters shown in Figure 1 were not used in the preliminary experiments reported here.

The agitator used in this study consists of a 165 mm long stainless steel shaft, fitted with a two-flat-bladed paddle (36 mm diameter × 7 mm height and 0.7 mm thickness). The shaft is driven by a rotational rheometer (Contraves Rheomat 30), which is clamped to the vessel.

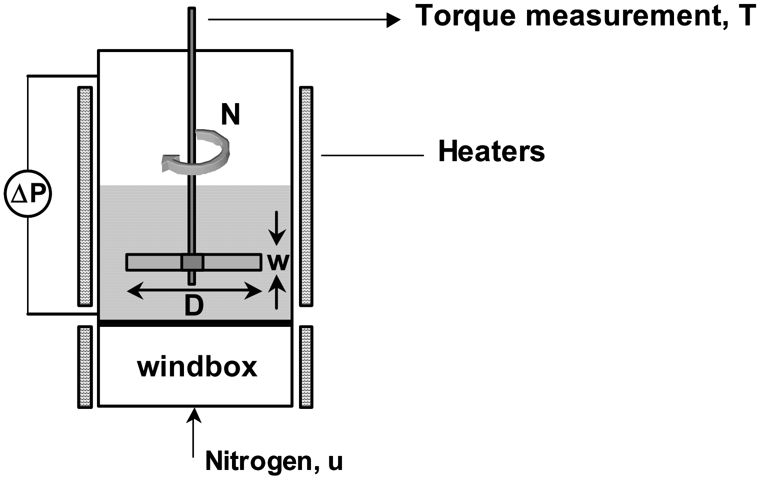

**Figure 1:** mechanically stirred Fluidized Bed Rheometer (msFBR)

In order to test the capability of the msFBR technique to reproduce expected/measured fluidization behaviours, the materials for this preliminary study have been selected so to span a range of particle size and density as wide as possible. Table 1 reports the mean particle diameter and the density of the three powders used.

**Table 1**

| | **Ballotini** | **Alumina** | **Silica** |
|---|---|---|---|
| **$d_p$ (μm)** | 350 | 46 | 26 |
| **$\rho_p$ (kg $m^{-3}$)** | 2500 | 1730 | 460 |

## 3. Results and discussion

### *3.1 Fluidization behaviour*

The fluidization behaviour of the three powders was examined by means of standard fluidization tests: the pressure drop profile and the expansion profile. All the powders, including the silica powder, showed good fluidization behaviour, as the full bed support was achieved for each powder. Table 2 reports the minimum fluidization velocity, extrapolated from the pressure drop profiles, and the maximum bed expansion attained by each powder.

**Table 2**

| | **Ballotini** | **Alumina** | **Silica** |
|---|---|---|---|
| **$u_{mf}$ (cm $s^{-1}$)** | 10.7 | 0.36 | 0.045 |
| **%$\text{Expansion}_{max}$** | 1.6 | 13.9 | 67.1 |

### *3.2 Effect of aeration on torque measurements*

Figures 2a-2c show the torque measurements recorded at different impeller velocities for each powder.

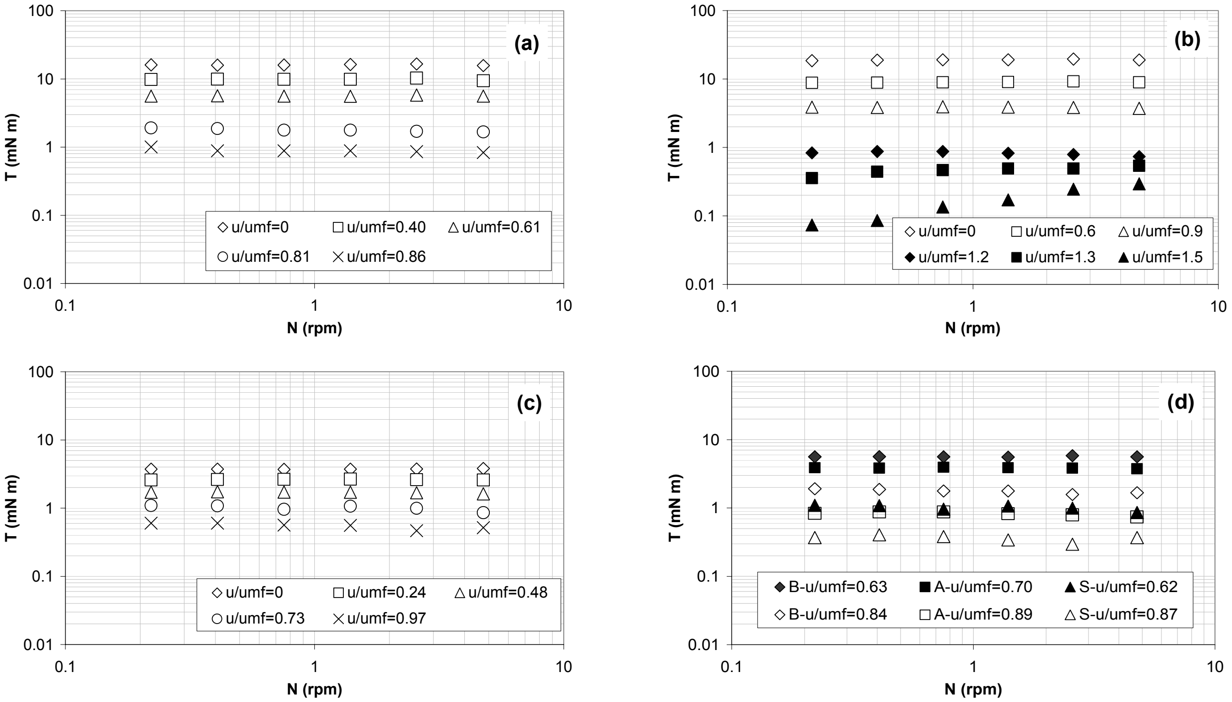

**Figure 2 -** Torque profiles with increasing aeration – (a) ballotini; (b) alumina; (c) silica; (d) powders comparison

The torque measurements showed that for each type of powder investigated the effect of aeration is to decrease the torque needed to stir the material. It ought to be pointed out that for the silica powder no measurements were possible at rates of aeration greater than $u/u_{mf}$=0.97, as the resolution of the equipment did not allow the measurement of such small values of the torque. On the other hand, the effect of aeration for the alumina powder was investigated also at rates of aeration above the minimum fluidization. This was not possible for the ballotini because the presence of bubbles, typical of the fluidization state of Group B powders at $u>u_{mf}$, would cause a great fluctuation of the torque measurements due to the sudden loss of resistance when a bubble is passing in the vicinity of the impeller.

### *3.3 Comparison with fluidization behaviour*

Figure 2d reports the torque profiles for the three powders at two specific rates of aeration. These results show that for similar rates of aeration, the torque required for shearing ballotini is the greatest, followed by the alumina and the silica.

An interesting correspondence can be noticed between the fluidization behaviour of the three powders and the torque measurements. The higher the capability of the powder to expand (Table 1), the lower the torque needed to stir it (Figure 2d).
Moreover, a correspondence can be found also between the torque profiles and the size and density of the powders: the denser and the bigger the particles, the higher the torque needed to stir them.

### *3.4 Rheological analysis*

In order to analyse aerated powders in terms of their rheological properties, a methodology was developed to obtain a shear stress/shear rate relationship from the experimental torque profiles. This is based on the theory of mixing of non-Newtonian fluids developed by Metzner and Otto [5] and it is reported in details elsewhere [6].
Figure 3 shows the rheogram obtained for the alumina at different rates of aeration.

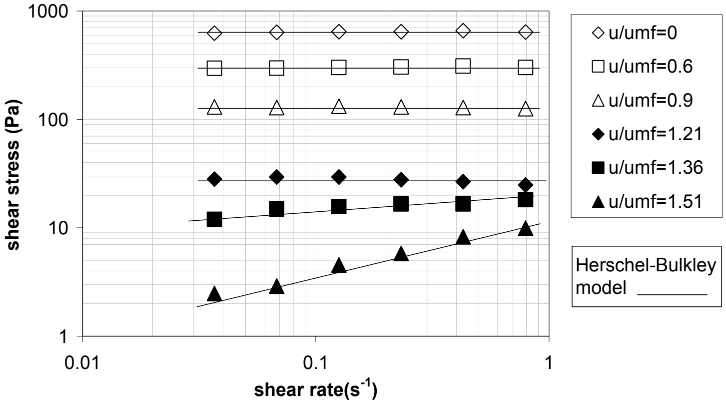

**Figure 3 –** Rheogram - Alumina

A rheological model, called Herschel-Bulkley model, was fitted to the shear stress/shear rate curves for each rate of aeration:

$$\tau = \tau_y + k\dot{\gamma}^n$$

This model encompasses Bingham plastic for *n*=1, power law for $\tau_y$=0, yield stress (solid like) for *n*=0 and Newtonian for $\tau_y$=0 and *n*=1.
Values for the Herschel-Bulkley parameters were calculated for each rate of aeration and for each powder.

**Table 3**

| **u/u$_{mf}$** | **$\tau_y$** (Pa) | **k** (Pa s$^n$) | **n** |
|---|---|---|---|
| 0 | 640.6 | 0 | 0 |
| 0.6 | 301.7 | 0 | 0 |
| 0.9 | 129.5 | 0 | 0 |
| 1.21 | 27.8 | 0 | 0 |
| 1.36 | 0 | 19.1 | 0.11 |
| 1.51 | 0 | 11.4 | 0.46 |

Table 3 reports the parameter of the HB equation for the alumina and it shows that:

1. below the minimum fluidization velocity and around the point of incipient fluidization the powder behaves like a yield stress material. The yield stress decreases as the upward fluidizing gas increases.
2. above the minimum fluidization velocity there is no yield stress, $\tau_y = 0$ (fluid like behaviour) and the aerated materials behave like a power law fluid with flow behaviour index (*n*) increasing with increasing aeration. It is worth noting that *n* is of the same order of magnitude of that typical of liquid suspensions (*n* = 0.3).

The ballotini and the silica, which were analysed only at rates of aeration below $u_{mf}$, showed the same behaviour as described in point 1.

## 4. Conclusions

The msFBR was proven to be capable of discriminating between different rates of aerations and fluidization behaviours. A possible avenue for interpreting the experimental results in terms of rheological parameters has been investigated and has produced reasonable results. These findings seem very encouraging and work is currently ongoing to span as many operating conditions as possible (fines size distribution, temperature etc.) in order to test the potential of the msFBR technique as a tool for powder flow characterization at process conditions.

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## Notation

| | | |
|---|---|---|
| $d_p$ | Particle diameter | (m) |
| D | Impeller diameter | (m) |
| k | “Fluid consistency” in Herschley-Bulkley equation | (Pa $s^n$) |
| n | “Flow behaviour index” in Herschley-Bulkley equation | ( - ) |
| N | Impeller speed | (rps) |
| T | Torque exerted on the impeller | (Nm) |
| u | Fuidizing gas velocity | (m $s^{-1}$) |
| $u_{mf}$ | Minimum fluidization velocity | (m $s^{-1}$) |
| w | Impeller height | (m) |

| | | |
|---|---|---|
| $\dot{\gamma}$ | Shear rate | ($s^{-1}$) |
| $\rho_p$ | Particle density | (kg $m^{-3}$) |
| $\tau$ | Shear stress | (Pa) |
| $\tau_y$ | Yield Stress | (Pa) |