Analysis of granule breakage in a rotary mixing drum: Experimental study and distinct element analysis

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A B S T R A C T

Rotary drums are commonly used in particulate solid industries for mixing, coating and reactions. The process is often accompanied by undesirable breakage of granules. For this reason, a scaled-down version is sometimes used as an attrition testing device. In this work, the attrition of granules inside a rotary drum at 18, 35 and 52 rpm drum rotation speeds for 4000 cycles is studied. The granules used in this study have been produced by extrusion and spheronisation with a size range of 500 to 1000 μm. The rotary drum has an internal diameter of 0.39 m, axial length of 0.3 m and a single baffle. The extent of breakage is quantified by sieving out fine debris which is two sieve sizes smaller than the feed particles. To relate the extent of breakage in the drum to granule characteristics, single granule impact tests have been performed on one type of granule at several velocities. The effects of particle size and impact velocity are analysed and a power–law relationship is fitted between impact velocity and single granule breakage. This information is then used to simulate granule breakage in a rotary drum by Distinct Element Method (DEM). The drum is simulated for 5 rotations at the rotational speeds stated above and the breakage rate is extrapolated to 4000 cycles where it is compared to experimental results obtained. The trends for particle breakage in both experiments (determined by sieving) and extrapolated DEM simulations are in agreement however the orders of magnitudes are different. The comparison shows that the extent of breakage obtained from extrapolated simulations is overestimated at drum speed of 35 and 52 rpm and underestimated at 18 rpm. There is close agreement between experiments and extrapolated DEM simulations for particle breakage at 18 rpm only after 4000. Furthermore, the effect of air drag on the attrition of granules by impact at a drum rotation speed of 52 rpm is investigated, where it is found to significantly reduce the breakage results.

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1. Introduction

Rotary drums have been used in processes such as drying, mixing and spraying in most powder handling industries. In the pharmaceutical industry the rotary drum is used as a method to test the strength of tablets and to quantify the amount of broken material [1]. From an occupational hygiene perspective, it has been used as a method to test the dustiness of materials, where the amount of airborne dust is measured by analysing drawn air through a drum [2]. To understand how particulate material breaks or finer material becomes airborne inside a drum, knowledge of the powder dynamics is essential. Inside a rotary drum, material may typically experience impacts and wear with the drum walls and shear deformation within the powder bed. For such simple process equipment, the powder motion is very complex. Rutgers [3] and Henein et al. [4] mapped out six characteristics regimes for solids motion in drums using Froude number and fill ratio. Froude number is defined as the ratio of the centrifugal force to gravitational force and is calculated by:

\[ Fr = \frac{\omega^2 r}{g} \]  

where \( r \) is the drum radius, \( \omega \) is the drum angular velocity, and \( g \) is the acceleration due to gravity. The six regimes with increasing Froude number are slipping, slumping, rolling, cascading, cateracting and centrifuging [4]. Several models have been developed for the slipping, slumping and rolling regimes, linking properties of solids and geometry to volumetric flowrate by Saeman [5], residence time by Scott and Davidson [6], bed turnover time and rolling velocity by Ding et al. [7]. Furthermore, the motion of particulate solids in a drum has been investigated experimentally using PEPT analysis (positron emission particle tracking) by Parker et al. [8], Spurling [9] and Ding et al. [10]. PEPT measurements involve placing a radioactive labelled particle (tracer) within a bulk of particle with similar properties. The motion of the tracer particle is then tracked in 3-dimensions with time. This allows real time data to be recorded. In some cases good
agreement has been observed between the analytical models and PEPT analysis [9].

Distinct Element Method (DEM) simulations have been extensively performed to study mixing and segregation in rotary drum systems [11–13]. The flow regimes of Henein et al. [4] have been observed using DEM by Walton and Braun [14] and Yang et al. [15]. Several authors [16,17] have validated the velocity profiles obtained from DEM by comparing to PEPT or high-speed video analysis. Yang et al. [16] and Pandey et al. [17] found good agreement between experimental data and those obtained by DEM for spatial velocity fields inside rotary drums.

For attrition testing, two types of rotary drums have been used; these are plain drums and drums containing axial vanes (baffles) to lift particles [18]. Grant and Kalman [19] investigated the fatigue behaviour of potash particles inside a rotary drum with two baffles. It was concluded that an increase in drum rotation speed leads to more particulate breakage up to a critical point. Beyond this point the centrifugal forces became more dominant and led to less attrition occurring. Grant and Kalman [19] also found that decreasing sample weight leads to more attrition.

In this paper, a rotary drum with a single baffle is used to analyse the breakage behaviour of one type of enzyme placebo granule (breakage resistant). Furthermore, using experimental results from single particle impact tests and Distinct Element Method (DEM), the amount of particulate breakage that occurs per impact in the drum is estimated and compared to experimental data.

2. Experimental

Approximately 200 g (1% drum fill) of placebo granules was placed inside a rotary drum with a diameter of 0.39 m, axial length of 0.3 m and with a single baffle with a height of 0.04 m. The drum was lined with stainless steel, the baffle was made from aluminum and the ends of the drum were made out of transparent Perspex to visualise the movement of the granules. A schematic diagram of the experimental setup is shown in Fig. 1.

Tests were conducted at 18, 35 and 52 rpm for 4000 cycles. The breakage of the particles is assessed by gravimetric sieve analysis at 500, 1000, 2000 and 4000 cycles. After each sieving stage, the mother powder (ground placebo granule) was sieved, and the debris from the sieve analysis was stored for further analysis. The placebo granule breakage results at three different drum rotation speeds are shown in Fig. 2. The breakage trends for the placebo granules increase with rotation speed. One observation is that these granules experience significantly more attrition at 52 rpm than at 18 and 35 rpm. In fact at 18 and 35 rpm the granule breakage that occurs is similar and therefore it is thought that the number and velocity of granule impacts are similar. This is addressed in the next section using DEM.

3. Simulation by Distinct Element Method

3.1. Methodology

To enhance our understanding of the microscopic and macroscopic processes that occur in the rotary drum with a baffle, the flow of particles was simulated using Distinct Element Method (DEM). The simulations were performed using PFC3D software developed by ITASCA and based on the methodology originally proposed by Cundall and Rackliffe [21]. The mechanical properties of placebo granules were estimated by several methods and are shown in Table 1.

In the simulations, 7830 particles with the above properties (equivalent to 2 g of material giving a 1% drum fill) were generated inside a drum (internal diameter of 0.39 m similar to the experiments) with a single baffle 0.04 m in height. In this work the entire axial length of the drum was not simulated and instead a periodic space 3 mm in length (4 to 5 particle diameters) was used to speed up simulation time. In total 5 drum cycles were simulated at 18, 35 and 52 rpm.

The attrition was estimated using a similar method to that originally proposed by Han et al. [22] for pneumatic conveying where the breakage function proposed by Ghadiri and Zhang [20] was used to estimate the volume/mass of chips formed at a given normal impact velocity. Single granule impact tests were performed on the

\[ R = \frac{M_{de(i)}}{M_{n(i)} + M_{de(i)}} \]
placebo granules at several normal velocities to estimate the extent of breakage by Eq. (2). For these granules no breakage occurred below 2.5 m/s. The effects of particle size and impact velocity are analysed and a power–law relationship is fitted between impact velocity and granule breakage. This is shown in Fig. 3, where the extent of breakage is plotted against the difference between velocity squared and threshold velocity squared times particle size, following the analysis of Ghadiri and Zhang [20]. This is shown in Eq. (3), where the experimental data obtained from these normal impact tests are fitted to a power–law relationship and the mass that is broken off a granule is estimated. In Eq. (3) $\alpha$ is a constant (equal to 0.03206 $s^2/m^2$) which is obtained experimentally and is proportional to $H/K_c$ (i.e. the ratio of hardness to the square of fracture toughness; for details see the work of Ghadiri and Zhang [20]). $D$ is the particle diameter, $M_i$ is the mass of the particle, $v$ is the impact velocity of the particle and $v_{th}$ is the threshold velocity equal to 2.5 m/s below which no breakage occurs.

$$M_i = \alpha DM_i \left( v^2 - v_{th}^2 \right)$$

(3)

The extent of breakage for the particle is then calculated by Eq. (4), shown below:

$$R^* = \frac{\Sigma_{i=1}^{n} M_i}{M}$$

(4)

where $M_i$ depends on particle size, $M$ is the total mass of particles in the system and $n$ is the number of particles. This breakage model is applied in the DEM simulations for particle impacts with the walls with a resultant velocity above 2.5 m/s. Due to a very small mass of particles breaking (comparable to a minuscule chip) at each impact, the size and shape of the particles will not change significantly, therefore in the simulations the size and shape of the particles are fixed. The initial simulations are performed in vacuum conditions where the effect of air drag is not taken into account. In addition, attrition due to shear deformation, fatigue and wear is not considered as it is assumed to be negligible.

The flow patterns of solids in the drum at 18, 35 and 52 rpm are shown in Fig. 4a and b for the simulations and experiments, respectively. In Fig. 4a, the colours show particle velocities and the snapshots have been taken at the moment the last particles are about to leave the baffle. The simulation and experiment patterns are in good agreement at all rotation speeds, where the last particles leave the baffle at 11, 12 and 1 o’clock positions, respectively. From the simulations, impact velocities of up to 3 m/s were observed and the average normal stress inside the granule bed was less than 100 Pa.

### 3.2. Number of impacts

The total number of particle impacts above 0.25 m/s i.e. impacts at 1/10th the breakage threshold velocity of 2.5 m/s with the walls for the first five rotations is fitted and the results are extrapolated to 500, 1000, 2000 and 4000 cycles using a linear trend. This is shown in Fig. 5a and b. Only five drum rotations were simulated due to limitation in computational time. It is assumed that after five rotations the particulate breakage that occurs will be at a steady state level. An interesting observation is that the pattern of the number of impacts at 18, 35 and 52 rpm with the rotation cycle shown in Fig. 5a is similar to the experimental breakage results obtained for these granules (shown in Fig. 2), i.e. the data for 18 and 35 rpm overlap, but those of 52 rpm are distinctly different. A similar approach (to that used for 0.25 m/s impacts with walls) was used to extrapolate the data obtained on the number of particle–wall impacts above 2.5 m/s as shown in Fig. 5c and d. The extrapolated number of impacts above 2.5 m/s does not show a comparable trend to the experimental breakage results as the trends of the two lower speeds are not overlapping. This may suggest that the fatigue effect that occurs through repeated impacts at lower velocities (in this case below 2.5 m/s) could be very important and should be included in future attrition models.

![Fig. 3. Relationship between $(v^2 - v_{th}^2)D$ and breakage for the placebo granules obtained from experiments.](image-url)
3.3. Calculation of particle collision power

The power from collisions above 0.25 m/s (i.e. impacts at 1/10th the breakage threshold velocity of 2.5 m/s), $P$, is calculated from the contact kinetic energy from particle–drum impacts using the following equation:

$$ P = \sum_{i=1}^{n} \frac{1}{2} M_i v_i^2 t $$

where $M_i$ is the mass of the particle, $v_i$ is the impact velocity of the particle, $t$ is the time from start of rotation, and $n$ is the number of particles. This is shown in Fig. 6 for the simulation performed at 18, 35 and 52 rpm. It is evident that after the first rotation, above 0.25 m/s the power inputs of the particles at 35 and 52 rpm are similar, but as the number of rotations increases, the power input at 52 rpm increases, whilst there is little change for the former. If the power input after five rotations is steady-state then the difference in the

![Flow patterns at 18, 35 and 52 rpm](image)

**Fig. 4.** Flow patterns at 18, 35 and 52 rpm — a) DEM simulation snapshot, b) experimental snapshot.

**Fig. 5.** (a) Number of particle–wall collisions above 0.25 m/s for the first five rotations obtained from DEM simulations. (b) Extrapolated number of particle–wall collisions above 0.25 m/s from DEM simulations. (c) Number of particle–wall collisions above 2.5 m/s for the first five rotations obtained from DEM simulations. (d) Extrapolated number of particle–wall collisions from DEM simulations above 2.5 m/s.
power input between 35 and 52 rpm is much larger than that between 18 and 35 rpm. In fact, significantly more breakage occurs at 52 rpm and this is inline with Fig. 6, where the power is higher at 52 rpm than 18 and 35 rpm. The experimental power was not measured and hence no comparison can be made for power consumption.

3.4. Attrition from breakage model

In order to calculate the attrition of granules in the drum, the breakage model from single particle impact tests (described in Section 3.1) is applied to the DEM simulations. The simulated breakage values ($R^*$) for the first five cycles are fitted and the results are extrapolated to 500, 1000, 2000 and 4000 cycles using a linear trend. The attrition obtained from this method is compared to experimental results below in Fig. 7.

From Fig. 7, on a logarithmic scale, the difference between the breakage of granules measured experimentally at 18, 35 and 52 rpm is not as significant as the extrapolated simulation results. The experimental and extrapolated simulation results at 18 rpm and 4000 cycles are comparable; however, at 500, 1000 and 2000 cycles the extrapolated simulation results underestimate attrition for 18 rpm. At 35 and 52 rpm for all drums cycles, the extrapolated simulations all overestimate the breakage by an order of magnitude. The overestimation of the simulated results may be due to a number of reasons discussed further:

- The estimation of breakage using a linear trend is crude and in fact, as the experimental results, suggests that the breakage-cycle gradient decreases with drum rotations.
- Experimentally, the placebo granules inside the drum may experience work-hardening with time and little fatigue. The granules may decrease slightly in size as the surface coating of the granules is removed, reducing the granule mass and kinetic energy from each impact.
- The higher breakage gradient during early cycles may be due to weaker granules in the drum breaking and the stronger granules surviving over time (survival of the fittest).
- Lubrication of larger granules by debris.
- The granules are rounded cylinders (spheronised extrudates) and during early cycles the surface asperities or edges of these granules may break off leading to more spherical granules which break less in further rotations.

None of the above was incorporated in extrapolated DEM simulations. Furthermore, all the simulations discussed were performed in vacuum conditions. An interesting observation is that the breakage that occurs at 18 rpm is much lower than at 35 and 52 rpm, suggesting that velocity of impacts is higher at faster rotation speeds. If the simulations were performed in air, the velocity of some particles at 35 and 52 rpm may have decreased below the threshold velocity set as 2.5 m/s. This is analysed further in the next section. Finally, in this work periodic boundaries were used whereas experimentally friction of the drum side walls may stop particles from being lifted and falling at higher velocities.

3.5. Effect of air on breakage

The simulation at 52 rpm was repeated and performed in the presence of air. The air is modelled using a “fixed course grid” fluid scheme which solves a combination of the continuity and Navier–Stokes equation for incompressible fluid flow numerically in a Eulerian Cartesian coordinate system. For more details refer to Tsuji et al. [23]. The presence of air will lead to particles experiencing a drag force as they fall. The air density and viscosity used in the simulation were 1.225 kg/m$^3$ and 1.8 × 10$^{-5}$ Pa s, respectively. The cell size selected was approximately 10 times larger than the particle diameter. The attrition from this simulation is compared to experimental and simulation without air results in Fig. 8 (the $R^*$ value from the simulations is fitted and the results are extrapolated to 500, 1000, 2000 and 4000 cycles using a linear trend). The attrition in the presence of air shows an underestimation of breakage when compared to the experimental results. Clearly, the sensitivity of these results to air drag is highlighted here and the effects of fatigue, work hardening, reduction of particle size and survival of the fittest all need to be considered for more accurate results. Another reason for this underestimation may be due to not accounting for particle–particle impacts in the breakage data.

A further sensitivity analysis was carried out where a simulation at 52 rpm was performed in the presence of air with a granule breakage
threshold velocity of 2.4 m/s. The attrition increased further when a lower threshold velocity of 2.4 m/s was used as shown in Fig. 8. It should be noted that altering the threshold velocity would be an inaccurate approach as this is not in agreement with the initial experimental observations.

4. Conclusions

The attrition of placebo granules in a rotary drum rotating at 18, 35 and 52 rpm is analysed using DEM. Visual analysis shows that there is good qualitative agreement between experiments and DEM simulations for the rotary drum flow patterns. The trends for particle breakage in both experiments (determined by sieving and gravimetric analysis) and DEM simulations (based on extrapolation) are in agreement however the orders of magnitudes are different. The comparison shows that the extent of breakage obtained from extrapolated simulations overestimated the particle breakage at 35 and 52 rpm and underestimated it at 18 rpm. There is close agreement for particle breakage at 18 rpm only after 4000 cycles. Whilst the simulations overestimated the attrition in vacuum at 35 and 52 rpm, it is shown that in the presence of air at 52 rpm the attrition is underestimated. Consequently the sensitivity of these result to air drag is highlighted here and in future models the effects of fatigue, work hardening, reduction of particle and survival of the fittest all need to be considered to engineer more accurate models.

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