Particle Attrition in Small Clearances

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Abstract

Attrition is commonly found in the clearances of equipment where a mechanical device moves relative to a wall. Particles are trapped and broken in these regions, hence promoting attrition. This work concerns a cell where a blade rotates parallel to a wall. A cone cell design allowed for various gap sizes, particle velocities and blade tip speeds. The breakage rate of particles changed dramatically with gap size. Breakage commenced at a gap size close to a half particle diameter but had a definite minimum between one and one-and-half particle diameters. Little breakage was experienced if the gap much exceeded two particle diameters. When the other conditions of cell are changed, firstly the blade speed and secondly the flow rate of particles through the cell, the effect of gap size on breakage pattern is not changed. The product size distribution can be quite complex and is not simply related to the gap size. Segregation and a changed packing structure may each influence the breakage of a mixture.

1. Introduction

Attrition of solid particles has been and remains a major problem in processing equipment. It can change physical properties such as particle size, particle size distribution and shape. It results in the generation of fine material which may escape to the environment. Here the term “attrition” encompasses any unwanted particle breakage created during processing or handling of a material. Although the work was initially motivated by the need to reduce attrition, there are of course those processes where particle breakage or comminution is desired. Comminution has already been subject to research in great detail, resulting in a number of classical theories, but the detailed processes are still not understood and we remain far short of a scientifically-based design process.

It can be argued that attrition in the bulk of a particulate solid is caused by the occurrence of failure zones which are formed between coherent blocks of material moving against each other and creating intervening regions of high strain. These regions have been reported to be up to ten to twenty particle diameters in depth, Roscoe (1) and Bridgwater (2). Paramanathan and Bridgwater (3, 4) and Neil and Bridgwater (5, 6) showed that whilst failure zones of up to ten particle diameters exist in bulk, in an annular attrition cell a half failure zone of five particle diameters was created. They also demonstrated that attrition could be studied rationally and systematically related to stress and strain; in some cases satisfactory scaling laws could be obtained (6). Modelling of particle motion, stress transmission and particle breakage in failure zones is becoming accessible from computer-based modelling studies and are starting to show encouraging confirmation of the experimental findings, Ghadiri (7).

There is a lack of understanding of attrition even though there are many testing procedures, principally those developed for coals or grains, which can be exploited. There are no generalisations, since the various test methods are not comparable. The array of tests suitable for assessing attrition have been collected together and evaluated by Bemrose and Bridgwater (8).

The damage inflicted by mechanical equipment on solids can be quite substantial. One of the main areas of attrition occurs when a particle has to pass

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Through a clearance in equipment, examples being in a screw auger used for conveying solids or in a pusher centrifuge with breakage caused by abrasion or fracture. This study is concerned with attrition in clearances. One might infer from previous work that moving mechanical equipment which breaks material at the vessel wall should do so with gaps of up to ten particle diameters, but we shall see below that this is far from the case.

When a mechanical moving part comes close to a vessel wall, creating a gap where particles can be trapped and broken, attrition products are generated. The work here concerns the construction of a new piece of testing equipment which simulates the flow of material through a gap between a moving blade and a stationary wall. It has the facility to increase or decrease the gap size whilst allowing continuous flow of material at various flowrates and different blade rotation speeds. The aim of the work is to obtain an understanding of the mechanisms existing when attrition takes place in such a clearance.

2. Equipment and Procedure

Figure 1 shows a schematic view of the design. The material under study flows downwards in a conical hopper of 60° inclined angle with an inlet diameter of 197 mm. The solids move downwards past the blade which has a height of 30 mm and a thickness of 4 mm, controlled by the rate at which solids are withdrawn from the hopper base by a vibrating feeder. The blade inserted into this flow is suspended from a motor above the conical hopper and may be rotated. Some of the solids pass through the gap between the blade edges and the sloping wall. The blade edges are arranged to be parallel to the vessel wall to achieve a constant gap thickness along the length of the blade edge. By adjustment of the vertical position of the conical hopper, the gap between the blade and the sloping hopper wall can be increased or decreased. The main design problem was to ensure the motor drive shaft was located exactly above the centre of the cone whatever the vertical position. The design allowed particles to be supplied steadily to the clearance between the wall and the rotating blade and the product to be extracted below. The volume between the blade tip and the wall was typically 100-1000 (mm)$^3$.

A test was conducted as follows. The separation between the blade tip and the hopper wall was set and then the hopper was filled with the material under test to the top of the cone. The material was then levelled with a brush. Beneath the hopper was placed a vibrating feeder, the setting of which determined the solids flow rate out of the cone. From the end of this feeder, the material fell onto a 40 cm diameter Russel Finex 22 shaker which captured unbroken material. The undersize material passed through a chute to a set of vibrated BS 410 sieves. The experiment was initiated when the blade, the feeder, the shaker and sieve vibrator were started simultaneously and ended when the cone emptied. Any dust left in the feeder was brushed into the nest of sieves and agitation continued until a total of 20 minutes had elapsed. The unbroken material was then weighed, the dust on the under-pan wiped into the nest of sieves and the operation of the BS 410 sieves continued for five more minutes. Then sieve weighings yielded the size distribution. Semi-batch operation was employed to limit the problems of handling material and to create an experiment useable in the laboratory.

The first step in the procedure was to assess the
breakage that appeared to occur in the absence of blade rotation in a so-called standard test. First of all there will be an effect due to the imperfect initial sizing there to be material outside the size range. Breakage arises since particle damage will occur during sieving, and since some breakage occurs due to the hopper wall friction and due to the action of the feeder. In this standard test switching on the feeder, sieve shaker and timing clock but not the rotating blade, the batch of material was emptied from the cone and the size distribution found. The results from this standard test were then subtracted from the experimental results obtained when the blade was rotating. The standard test was repeated after every six experiments to ensure reliability of the experimental data.

The materials used were:

| Sieve size range (mm) | Average crushing force (N) | Number tested |
|-----------------------|---------------------------|---------------|
| Urea                  | 1.4-1.7                  | 202           |
|                       | 1.7-2.0                  |               |
|                       | 3.15-3.55                |               |
| Molecular sieve beads | 1.4-1.7                  | 74            |
|                       | 1.7-2.0                  | 80            |
|                       | 3.15-3.55                |               |
| Catalyst base         | 1.4-1.7                  | 46            |
|                       | 1.7-2.0                  | 123           |

Each size range had been cut from a bulk sample to give sufficient for testing. It was necessary to have 1-1.5 kg samples for use in each test in the cone cell.

Urea, the least spherical of the three, had been manufactured using a prilling tower process. The material was white with a crystalline internal structure, the crystals being 1-2 μm in size. Results varied depending if the day were dry or wet, but this was not found to be significant as the error was in the range 5-15%.

The molecular sieve beads are normally used as adsorbents in chemical processes. The manufacturing route used for these particles is agglomeration. Sub-micron crystalline metal aluminosilicates in powder form are formed into agglomerates by adding a clay binder to a wet mix. The mix is then granulated into beads which are calcined to form a strong composite. Its behaviour was not dependent on humidity.

The catalyst base particles were constituted of alumina, made by the sol-gel process, and was only available in the size range 1.4-2.0 mm. Its behaviour was not dependent on humidity.

3. Results and Discussion

Mechanisms

The tests on urea were carried out using gap increments of 0.1 mm, and sample results are given in Figure 2 showing the percentage of material broken, or breakage, B (%), against the gap size G. If the particle size is changed, then it is found that similar behaviour is observed with the gap sizes for the maximum and minimum in breakage rates being raised by an increase in the initial particle size. If the data of Figure 2 are recast by introducing a dimensionless gap size, D, expressed as a number of particle diameters, the ratio of the gap size G to the initial particle diameter d, then we get the representation shown in Figure 3. Within experimental error, the maximum and minimum for the three particle sizes occur at the same dimensionless gap size.

Transferring attention to the molecular sieve beads and the catalyst particles, we find behaviour of the same character, as is shown in Figures 4 and 5. A dimensionless presentation is again satisfactory. In every case, the behaviour is characterised by an absence of breakage at the lowest gap widths, followed on increasing the gap width in turn by a first maximum breakage rate, a distinct minimum breakage rate and a second maximum breakage rate. Finally, breakage becomes undetectable with a further increase in gap, when D > 2.2.

The findings are summarised in Table 1. Column A lists the gap size and the dimensionless gap at the start of breakage.
ly due to the small quantities of breakage product and hence there is scatter in the data. One can argue that the breakage be initiated at a gap of around 0.5D. If the gap is less than this value, the particle will need to be deformed before it passes under the blade whereas if the gap exceeds 0.5D, then the particle can be deformed by being caught between the wall and the blade. The start of breakage is rather less consistent from one material to another than the other events described below.

Examining column B, the first high breakage rate for the range 1.4-1.7 mm occurs at D=0.97 for urea and 0.71 for catalyst. This disparity may be caused by the difference in the shapes of the particles or in the friction experienced at the wall. If the initial material is of size 1.7-2.0 mm, the maximum varies from 0.76 for the catalyst, 0.81 for the molecular sieve beads and 0.97 for the urea. For the largest size, we find 0.90 for urea and 0.84 for molecular sieve beads. The high breakage rates occur at similar values for a given material i.e. urea 0.9-0.97, molecular sieve beads 0.81-0.84 and catalyst 0.71-0.76. Under such circumstances it is logical to conceive of the particle being caught and jammed against the wall and there by breaking.

The minimum breakages listed in column C lie between D=1.10 and 1.32. One might anticipate a minimum with material simply being swept by the blade over a monolayer of particles at the wall.

The second maximum in breakage rate occurs when the dimensionless gap D is 1.6-1.8, slightly less than one particle diameter above that for the first high breakage rate. This second maximum rate, however, sometimes markedly lower than the first maximum rate which is consistent with the particles forming a structure less prone to promote gripping and hence breakage.

The last column E gives an end point to detectable particle breakage and indicates that the dimensionless gap size giving an end of breakage is approximately independent of material. The absence of breakage in clearances larger than 2-2.2 particle diameters may be ascribed to the ability of the structure, both between the wall and the blade, and in the bulk to reorganise itself. There is thus for this system no significance of the failure zone of, say, ten particle diameters. The inference is that the particles structure can be reorganised to create free space and thereby prevent particle breakage.

A further cone was built having a small glass section within it where the particle motion could be recorded by the use of a video system. This work

Table 1  Gap sizes(mm) and dimensionless gap size(D) for various events in a series of tests on various materials

| Material | Size Range (mm) | Start of Breakage | First High Breakage Rate | Minimum Breakage Rate | Second High Breakage Rate | No Further Breakage |
|----------|----------------|-------------------|--------------------------|-----------------------|--------------------------|--------------------|
| Urea     | 1.4-1.7        | 0.90 0.58         | 1.50 0.97                | 2.05 1.32             | 2.70 1.74                | 3.4                |
|          | 1.7-2.0        | 1.20 0.65         | 1.80 0.97                | 2.40 1.30             | 3.30 1.78                | 4.0                |
|          | 3.15-3.55      | 1.50 0.45         | 3.0 0.90                 | 4.25 1.27             | 5.80 1.73                | 6.60               |
| Molecular Sieve | 1.7-2.0 | 0.50 0.27 | 1.50 0.81 | 2.20 1.19 | 3.25 1.76 | 3.90 2.19 |
|          | 3.15-3.55      | 1.60 0.48         | 2.80 0.84                | 4.15 1.24             | 6.0 1.79                 | 7.20               |
| Catalyst | 1.4-1.7        | 0.50 0.32         | 1.10 0.71                | 1.70 1.10             | 2.45 1.58                | 3.3                |
|          | 1.7-2.0        | 0.50 0.27         | 1.40 0.76                | 2.05 1.11             | 2.90 1.57                | 3.8                |

Fig. 3 The attrition of urea at various gap sizes, the latter now expressed as the ratio of gap size to mean initial particle diameter, D.
confirmed many of the above points but several other factors became evident. In a number of experiments conducted with 1.7-2.0 mm molecular sieve beads, with a blade tip speed of 0.5 cm/s and a particle velocity of 0.04 cm/s, the observations made as the gap size increased were as follows:

0.1-1.0 mm-A block of particles pushes against the blade as it rotates. These are moved along the wall by the blade with no breakage being apparent. Particles in contact with the lower blade edge move below the blade and are replaced at the top of the blade edge by others. The overall appearance is a block of particles in front of the blade being pushed along the wall with a gradual flux of material from the top to the bottom.

1.1-1.6 mm-Particles are still being pushed by the blade, but now the blade begins to nip a few particles. The space between the blade and wall is largely free of particles. Those few particles being nipped and broken are seen to break and fall immediately to the bottom of the blade via the gap existing between the blade and wall. As more particles are broken, the space begins to fill with broken particles and, at the maximum rate occurring at about 1.6 mm, becomes completely full of material. These broken particles flow from the bottom of the gap into the bulk below. It is possible to see each particle being nipped then breaking under the stress applied by the blade, all this occurring at the blade edge. The broken material then flows out of the breakage zone before it can be nipped again. However if the blade were rotating more quickly or the flow rate slower, broken particles would remain in the breakage zone. Consequently unbroken particles enter the breakage zone less quickly and less breakage takes place.

1.7-2.7 mm-Here the amount of breakage decreased with increased gap size, and particles begin to move under the blade until a state exists at around 2.1 mm where all the particles move under the blade and no breakage is evident. Up to 2.7 mm, no further change is detectable.

2.8-3.3 mm-Again an increase in breakage can be seen corresponding to the second breakage maximum. The particles at the wall, i.e. the first layer do
not break, but the particles in the second layer, those directly in contact with the blade, are pushed against the first layer and broken. The fragments then pass into the area of the first layer.

3.3-4.0 mm—When the gap exceeds 3.3 mm, a decrease in particle breakage is observed until no breakage is evident and the particles flow past the blade with no disturbance being observed.

Particle Velocity and Blade Tip Speed
Two further variables of importance are the flow rate of the particles and the blade tip speed.

Figure 6(a) shows an increase in particle breakage for each gap size as the tip speed is increased. Increasing the blade tip speed allows a higher number of particles to come into contact with the blade edge. The two high breakages both show greater attrition, with the first high breakage conditions showing a more rapid increase than the second. Figure 7(a) shows the extent of overall attrition as a function of blade tip speed. However, the rate of increase in breakage falls with increased blade tip speed. These data show that the general relationship between breakage and gap size is unaffected by the tip speed.

Figure 6(b) relates the breakage to the particle velocity through the cell, demonstrating how higher velocities result in lower percentages in broken material. Particle velocity is here defined as the ratio of the distance from the top of the cone to the top of the blade divided by the time taken for the

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**Fig. 6** Attrition of 1.4-1.7 mm molecular sieve beads. (a) Influence of blade tip speed, \( t \), (b) Influence of particle velocity, \( V \).
Fig. 7  Attrition of 1.4–1.7 mm molecular sieve beads.  
(a) Influence of blade tip speed, t.  (b) Influence of 
particle velocity, V.

Product size distributions

Product size distributions are now reported under the conditions pertaining to Figures 2–5. These are summarised in Figures 8, 9 and 10 for urea, molecular sieve beads and catalyst respectively. In each plot mass per cent per micron $\phi$ versus gap size (G) is shown, which is a bar chart distribution. For clarity of presentation, the points have been joined to allow results to be superimposed. $\phi$ is found by
considering the mass of product and dividing it by the weight of material of one product size by the size range encompassed by the limits of the sieves.

For urea, the most prominent size fraction is always that directly smaller than the feed material and the proportion of the size fraction decreases as the size of the fraction decreases. There is, however, a significant difference in behaviour linked to initial particle size in that the proportion of fine material from the larger initial particle is much less, whether argued on absolute particle size or relative particle size, than that found with the smaller initial material. The urea particles were constituted of 2 μm crystallites; this length scale does not appear in any of the attrition fragments.

For molecular sieve beads, the larger material (Figure 9b) shows the same general relationship as that found for the urea particles, namely a decrease in product amount with a decrease in product size. However the 1.7-2.0 mm material forms more material of intermediate size, the sieve size below the feed material then not being the most prominent. This is an indication that the breakage pattern is sensitive to initial particle size.

For the catalyst, the product size distribution displays more complex behaviour. Thus for 1.4-1.7 mm catalyst, (Figure 10a) the size below the top

Fig. 8 Attrition product from urea at different gap sizes. Initial size: (a) 1.4-1.7 mm (b) 1.7-2.0 mm (c) 3.15-3.55 mm
sieve is not dominant in the first breakage peak. Material yet slightly smaller (1.18-1.4 mm) is virtually absent in that peak. Product of size 0.710-1.0 mm is present in abundance and there is a smaller, although appreciable, amount of material of 0-0.5 mm. In the second peak we now find a monotonic decrease in size. Thus the size directly below the initial material is the most prominent; there is still an appreciable proportion of product of size 0-0.5 mm. Related effects occur with the 1.7-2.0 mm initial material but, more strikingly, product of less than 0.5 mm is virtually absent.

Conclusions

A piece of equipment has been designed and built with the purpose of studying attrition in the clearance of a moving blade and wall. The information obtained from these tests is pertinent to a different regime of behaviour from that found in failure zones. Three spherical materials having differing internal structures, urea, catalyst and molecular sieve beads, have been used.

As the gap between the rotating blade and wall was increased, there was initially no breakage but then a maximum breakage rate was produced. The breakage rate then diminished until, at a certain gap size, a second maximum breakage rate was found. A third high breakage rate maximum might be expected, but this was not the case; attrition was not detectable once the gap exceeded 2.2 particle diameters. Similar phenomena were found with all the materials tested. Data from particles of the same type but different size could be presented in dimensionless form. There is an extreme sensitivity on breakage rate of gap size.

The pattern of breakage is somewhat affected by the gap size, the pattern is also affected by the rate of breakage. Consider now the concept of breakage function. This function commonly used to analyse breakage circuits, is that which, operating on an initial feed size distribution, gives the product size distribution. We see that the product size distribution is changed by machine design (the gap size) or an operating variable (the speed). This calls into question the concept of breakage function as found in the literature.
The cone system was operated at low normal stresses, and it could be said that a system of high stress could alter the breakage. However, it can be argued that the space occupied by the particle in the gap remains constant and it is this which controls attrition. The packing would be little unchanged. If stress is important it is likely to be concerned with how particles flow into the gap as in low normal stress system. Work is required in this area.

We are now seeing the growth of the use of methods to describe inter-particle forces, packing and breakage (7). The use of these to provide information on flow of particles into a gap and the consequent breakage should give a useful comparison with the findings here.

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Nomenclature

B : Breakage (percentage of feed mass that is broken) \( (\cdot \%) \)
D : Dimensionless gap size \( (\text{gap size/mean initial particle size}) \) \( (\cdot) \)
G : Gap size \( (\text{mm}) \)
t : Blade tip speed \( (\text{mm/s}) \)
V : Particle velocity \( (\text{mm/s}) \)
\( \varnothing \) : Mass percent of product per micron \( (\mu \text{m})^{-1} \)

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Author’s short biography

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Professor Bridgwater is Shell Professor of Chemical Engineering at the University of Cambridge. Previously he was professor at the University of Birmingham where these studies were performed. He is Chairman of the Board of Editors of the journal Chemical Engineering Science and is Chairman of the Organising Committee of the 3rd World Congress in Particle Technology to be held in Brighton, England in July 1998. In 1997-98 he is President of the Institution of Chemical Engineers. His current research interests include powder mixing and the rheology and extrusion of pastes.

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