



Review

Advances in shape measurement in the digital world

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ABSTRACT

The importance of particle shape in terms of its effects on the behaviour of powders and other particulate systems has long been recognised, but particle shape information has been rather difficult to obtain and use until fairly recently, unlike its better-known counterpart, particle size. However, advances in computing power and 3D image acquisition and analysis techniques have resulted in major progress being made in the measurement, description and application of particle shape information in recent years. Because we are now in a digital era, it is fitting that many of these advanced techniques are based on digital technology. This review article aims to trace the development of these new techniques, highlight their contributions to both academic and practical applications, and present a perspective for future developments.

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Contents

Introduction.....	19
Shape measurement.....	21
2D measurements.....	21
2.5D measurements.....	22
3D measurement.....	23
Shape identification and extraction using software.....	24
Shape description.....	24
Single factors.....	24
Parametric series.....	25
Shape presentations and representations.....	27
Use of shape information.....	27
Concluding remarks.....	28
References.....	28

Introduction

Most workers who regularly deal with particles would probably agree that particle size is one of the most important parameters for particle characterisation. Many of these workers would also appreciate that, for non-spherical particles, there is no such thing as “the” definitive particle size, because the so-called size may have many different values, depending on the measurement method used, the

definition of “size”, and the purpose of the “size” determination (Allen, 2003; Jennings & Parslow, 1988). This is all because of the particle shape. Non-spherical particles do not have the isotropy of a sphere, which means the results of even direct measurements of their linear dimensions, such as with a ruler or virtually using a computer, may vary with the direction of measurement. The results of indirect measurements (e.g., via light scattering or sedimentation) can even differ for spheres (Allen, 2003; Andrès, Réginault, Rochat, Chaillot, & Pourcelot, 1996), let alone non-spherical particles (Agrawal, Whitmire, Mikkelsen, & Pottsmith, 2008; Black, McQuay, & Bonin, 1996; Blott & Pye, 2006; Califice, Michel, Dislaire, & Pirard, 2013; Di Stefano, Ferro, & Mirabile, 2010; Eshel, Levy, Mingelgrin, & Singer, 2004; Mühlenweg & Hirleman, 1998; Naito,

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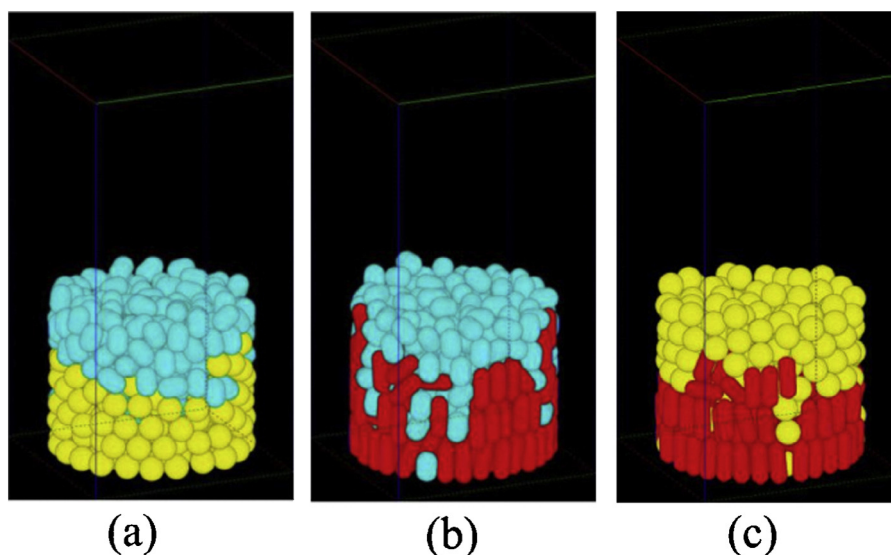


Fig. 1. Illustration of shape segregation experiments involving iso-volume particles of three shapes: (a) S–SS mixture, (b) SS–LS mixture, and (c) S–LS mixture. The trend is somewhat unexpected when compared with a typical Brazil nut effect, demonstrating the importance of particle shape for predominantly size-related effects. Images were generated using DigiPac software for illustration under the conditions used in the experiments by [Ramaoli \(2008\)](#).

[Hayakawa, Nakahira, Mori, & Tsubaki, 1998](#); [Tinke et al., 2008](#); [Walther, 2003](#); [Xu & Di Guida, 2003](#); [Xu, 2006](#)).

In theory, particle shape maybe as important as particle size in the characterisation of particles for various applications. For example, many of the physical properties of powders, including their effective conductivity, their mechanical strength, and their flowability, depend on the contact characteristics between the particles. Regardless of size, contact characteristics between spheres are very different to those for contact between non-spherical particles. Spheres make only point contacts, and while such point contacts do in reality have a finite size (i.e., contact area and depth), their sizes and distributions around spherical particles are comparatively far more uniform than those for non-spherical particles. Non-spherical particles can have area (face) and line (edge) contacts along with point contacts. Given the mechanisms that underlie properties such as shear resistance, flowability, and electrical and thermal conductivity, it is obvious that particle contact characteristics have a profound effect on these powder properties.

The actual effects of particle shape on powder properties and behaviour have been reported by many researchers ([Cho, Dodds, & Santamarina, 2006](#); [Dixon, 1988](#); [Kaye, 1997](#); [Melo, 1977a, 1977b](#); [Santamarina & Cho, 2004](#); [Swanson & Vetter, 1985](#)). Some of these effects will be described briefly in a later section, and only a few illustrative examples are given here. The Brazil nut effect in particle mixture segregation is well known, and particle size difference is considered to be the key factor ([Möbius, Lauderdale, Nagel, & Jaeger, 2001](#); [Williams, 1976](#)). However, when different shapes are mixed, segregation can occur even when particles are of the same “size” by certain measures. Experiments by [Ramaoli et al. \(2005\)](#) demonstrated this point well. Three shapes with equal volume (i.e., S = spheres, SS = short sphero-cylinders, and LS = long sphero-cylinders) were used to form three binary mixtures. After 20 min of vibration, all three mixtures showed clear segregation. As shown in [Fig. 1](#), SS tend to rise to the top with random orientation; LS fall to the bottom and are mostly oriented vertically. The S–SS case may be as expected because the SS appear to be larger to the eye, and larger particles are expected to be on top in a typical Brazil nut effect. However, in the S–LS and SS–LS cases, the reverse occurs. In the pharmaceutical industry, in an attempt to minimise segregation in blending processes, one common practice is to use particulate ingredients of the same or similar sizes. However,

segregation remains problematic in these operations ([Cullen, Románach, Abatzoglou, & Rielly, 2015](#); [Shah, Farag Badawy, Szemraj, Gray, & Hussain, 2007](#)) and particle shape difference is often blamed. A simple geometric explanation by [Caulkin, Jia, Fairweather, and Williams \(2010\)](#) is that segregation results from different relative mobilities that are determined by particles having different coordination numbers because of their size and/or shape differences while in relative motion. According to a dissolution model proposed by [Jia and Williams \(2007\)](#), in the dissolution of solids, particle shape (for standalone particles) or granular structure (if the particles form agglomerates) determines the relative dissolution rates, and the rankings are not affected by stirring (which merely reduces the dissolution time). Because dissolution occurs at the particle surface, the surface-area-to-volume ratio must be a factor in this behaviour; this ratio is highly dependent on particle shape, with the minimum value being obtained by spheres ([Pólya & Szegő, 1951](#)).

Given the inherent and intricate links between particle size and shape, it is only logical to state that when size matters, shape must also matter. The influence of particle shape on powder material properties and behaviour has long been recognised ([Allen, 2003](#); [Chow, 1980](#); [Cumberland & Crawford, 1987](#); [German, 1989](#); [Gray, 1968](#); [Seville, Tüzün, & Clift, 1997](#)), but because of the difficulties associated with shape measurement and description, little could be done to acquire and use shape information until fairly recently (i.e., the last 15 years or so). In the 1990 edition of the classic textbook on particle sizing by [Allen \(1990\)](#), only 16 of the 800+ pages were devoted to particle shape. In another authoritative volume, the Powder Technology Handbook ([Gotoh, Masuda, & Higashitani, 1997](#)), the situation was similar: only 13 of 900+ pages addressed particle shape.

Shape is usually described using a combination of qualitative and quantitative descriptors. The former help the reader to mentally visualise the shape; the latter are used to make comparisons and calculations. Depending on their purpose or application, quantitative descriptors (or shape quantifiers) can be classified into three categories. Shape coefficients are typically used to link particle size to particle volume or surface area. Shape factors are dimensionless scalars and are typically used to quantify a single aspect of a shape. Shape indices are size ratios or shape factor ratios that are proposed specifically to link particle shape to

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