Measurement of particle shape using digital imaging techniques

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Abstract. This paper presents an investigation into the suitability of imaging based sensors to measure particle shape and the effects of shape size on measurement consistency, testing the often used assumption that imaging based particle size analysers are insensitive to changes in particle shape. The imaging system employed is introduced and the definitions of shape used here are explained. A number of varying shaped ‘particles’, in the form of static test images, are observed with the imaging system and the effect of varying shape size on the resulting measurements is investigated. In general the results suggest that reliable shape measurement is possible but that the effects of image quantisation do lead to variations in measured quantities under real-world conditions.

1. Introduction
There are many industries where particulate materials are employed. The measurement of particle size is widely accepted as important if process operation is to be optimised. There are many methodologies that may be employed to achieve this and one of the most promising is the use of digital imaging [1]. The digital imaging approach not only allows size measurement but also provides the opportunity for some form of particle shape quantification. Variation of the shape of particles could result in a change of actual (3D) surface area – this could be a very important parameter in, for example, the pharmaceuticals industry, where the surface area of particles may affect the rate of reaction of a given mixture of chemicals. The importance of particle shape in industry has been accepted for some time [2,3] not only in terms of product quality (broken particles would exhibit jagged edges for instance) but also the handleability of particles in bulk form [4,5].

The imaging based approach developed by the authors in the past [1] can be used to provide some quantification of shape – only a cross sectional view of the particles is available but, within these bounds, it is possible to produce some relative indication of the shapes of particles within each image. Such work is not new [6] but it is often assumed that imaging systems are insensitive to variations in particle size (in relation to shape) and that, therefore, shape quantification is independent of these parameters. These assumptions are based on theoretical concepts and it is accepted that past attempts at shape characterisation leave room for improvement [7].

The present work investigates the suitability of an established imaging based particle size analyser for measuring particle shape and studies the effects on such measurements caused by shape size variation under real-world conditions.
2. Imaging Sensor and Measurement Principles

2.1. Imaging Sensor

Particles may be imaged for the purposes of analysis through being laid on a flat surface upon which is focussed a CCD camera. The basic concept is illustrated in Figure 1. Once the images have been obtained, digital image processing techniques can be applied to extract information such as particle size distribution and shape. Such a system has been found capable, in its present form, of achieving a basic sizing accuracy of ±1.5% when used with particles in the 150µm to 25mm range [1]. Since full details of operation for the imaging sensor have been described elsewhere [1] only a brief summary of the operating principles and limitations of this novel sensor will be given here in the interests of convenience. It should be noted that, whilst for the present discussion only static particle analysis is considered, the imaging sensor has been successfully employed for on-line analysis of live-flows with the addition of laser sheet illumination [1]. It can, therefore, be assumed that particle shape measurement can also be attempted on-line.

Once images of the particles are available they must be processed in order to extract the necessary information. It is this processing that represents the heart of the imaging sensor. After image acquisition it is first necessary to correct the images for any distortion that may arise due to the lens arrangement etc (typically there will be both ‘pincushion’ and ‘trapezoid’ or ‘barrel’ distortion present in the images). Individual particles must now be detected within the images. This is achieved through the use of a novel adaptive thresholding technique tailored specifically toward particle imaging applications [1]. Once the image has been segmented into background and particles it is possible to count, size and assess the shapes of the particles present.

Whilst imaging based particle measurement is not entirely new [8,9] the method employed here harnesses novel algorithms and simple optical arrangements in order to achieve rugged and cost-effective operation that is viable in industry. To this end a standard interlaced CCTV type video camera is used and images are processed using standard PC equipment.

2.2. Determination of Particle Shape Parameters

Particle shape is quantified in two ways by the current system. Firstly an aspect ratio determination is made. Aspect ratio is, in general, the ratio between the longest and shortest dimensions of a particle and is defined more specifically in this instance as the ratio of the longest and shortest particle radii that pass through the geometric centre of the particle. This is illustrated in Figure 2 (it should be noted that this figure is illustrative rather than technically accurate in terms of minimum and maximum radii).

The second determination is defined here as a ‘shape factor’ that attempts to quantify shape as a single number. This is not easy and there have been many attempts in the past. Early work on the quantification of particle shape centred upon morphology studies in the field of soil mechanics. Wadell[10] defined a ‘roundness’ characteristic of particles (the ratio of the curvature of the corners and edges of the particles to that of the overall particle) whilst Krumbein[11] defined ‘sphericity’ (the...
ratio of a particle's volume to that of the smallest circumscribing sphere). Both of these parameters were required for complex subjective analysis of particle features and were applied, for practical purposes, through the use of comparative charts[11,12]. Heywood[13] suggested a shape coefficient which used measurements of surface area and volume to categorize particles into rough categories such as 'tetrahedral', 'sub-angular' and 'rounded'. Work in the field has continued and more recently image analysis techniques have been suggested working on a number of principles, from the comparison of individual particles to standard forms [6] to fractal analysis [14] and Fourier analysis of particle perimeters [7]. In much recent work definitions of particle form and texture originally created by Barrett [15] are used though there is still no generally accepted, standardised, method through which particle shape may be quantified by image analysis.

It is not the intention with the present research to solve the long standing problem of particle shape definition, or indeed to attempt to standardise on a particular definition, but rather to assess the ability of an imaging based system to consistently produce a shape measurement of some kind and prove its usefulness. The definition of shape factor used in this case is based on the measurement of the length of a large number of particle radii passing through the geometric centre (similar to the two used for aspect ratio determination). Firstly the root mean square (RMS) deviation in particle radii length is found. This may be defined mathematically as:

\[ r_{rms,d} = \sqrt{\frac{(r_{max} - r_{mean})^2 + (r_{mean} - r_{min})^2}{2}} \]  

(1)

Where \( r_{rms,d} \) is the RMS deviation of radii lengths and \( r_{min}, r_{mean} \) and \( r_{max} \) are, respectively, the minimum, mean and maximum radii lengths. It should be noted that the RMS deviation is the RMS value of the deviation in radii lengths and not the RMS radius length. The shape factor itself can now be defined as \( r_{rms,d} \) normalised to the mean length, i.e.:

\[ S_p = \frac{r_{rms,d}}{r_{mean}} \]  

(2)

This definition of shape factor has been found to give consistent results and is simple enough to allow high performance processing (an important factor as the present imaging sensor was originally designed for on-line work). It is also of greater relevance to irregular shaped particles than other shape factors (or 'circularity' definitions) that are commonly defined in such a way as to give a result equal to one for a perfect circle – as the shape deviates from the circular the resulting figure becomes smaller. This is acceptable where objects are expected to be circular and any deviations from this are small but, when working with particles that are consistently irregular in shape, the results will consist of very small numbers where accuracy to several decimal places is important – this is not considered desirable, effectively limiting the amount of deviation that can be recorded, and so the current definition was set up differently: Perfectly circular particles will generate a value of zero and this figure will increase with the deviation from circular of the particles. This means that there is no limit to the variations in shape that the present definition will allow to be highlighted – it will, in theory, produce a single, unsigned, figure that can vary from zero to infinity which describes particles varying from a perfect circle to infinitely non-circular (i.e. a straight line).

3. Experimental Set-Up
The experimental arrangement used in the present work was simply a CCD camera fixed accurately over a matte black imaging surface and illuminated uniformly using a ring light. The general arrangement is shown in Figure 3.
Images of various shaped particles were created and printed out using a high resolution ink jet printer. These images were then placed under the camera arrangement and observed by the sensor as though real particles. A number of different sized examples of each shape were created in order that the effects of size variation on shape measurement could be assessed. Examples of the shapes used are shown in Figure 4 – these are not supposed to resemble real particles but represent shapes of varying complexity with which to experiment.

![Shapes used during testing](image)

**Figure 4.** Shapes used during testing

### 4. Results and Discussion

Results consist of absolute accuracy of shape measurement and variations in measured quantities when shapes were changed in size. Absolute results are shown in Table 1.

| Shape     | Aspect Ratio | Shape Factor |
|-----------|--------------|--------------|
|           | Theoretical | Measured | Error (%) | Measured |
| Circle    | 1.000       | 0.97      | 3.0        | 0.01     |
| Square    | 0.707       | 0.71      | 0.4        | 0.19     |
| Star      | N/A         | 0.60      | N/A        | 0.26     |
| Cross     | 0.447       | 0.48      | 7.4        | 0.34     |
| Explosion | –           | 0.49      | N/A        | 0.36     |
In this table theoretical aspect ratio values, along with the accompanying errors, are given for the circle, square and cross. The other shapes, whilst reproducible, were generated automatically by a paint package and their exact geometric properties were not known. Theoretical absolute shape factors are not given since real results would be expected to vary due to limitations on the number of particle radii that may be scanned practically. It is the relative changes in this quantity that are important.

It can be seen that, although the aspect ratio results are reasonable the percentage errors are quite high. This is thought to be related to image quantisation effects (i.e. images are of finite resolution). The shapes have been arranged, in Table 1, in order of complexity (based on the number of ‘sides’ each possesses) and a relationship can be seen between complexity and measured shape factor. Whilst a direct, reliably quantifiable, relationship between the complexity of a shape and its shape factor was not the intention, this relationship (figure 5) may be viewed as an indicator that the defined shape factor is a useful way of quantifying shape.

The main purpose of testing the shape measurement system was to determine the independence of the shape measurement from shape size. During the tests four sizes were used for each shape. Figures 6 and 7 show the results for aspect ratio and shape factor measurements, respectively.

It can be seen that, through a 100% increase in size, variations remain below ±4%. All shapes show variation that is, in essence, linear. The circle and square, which are the simplest shapes, show the least change in relation to size. These are followed by the cross, which is more complex but is limited to 90° corners, and then by the shapes featuring very ‘sharp’ corners or features – the star and explosion. This size dependant change in aspect ratio and shape factor can be explained by considering the
quantised nature of video images – as the sizes of the shapes change they must be represented by the nearest combination of whole pixels that is available. The square is the only shape that can be represented realistically with a Cartesian grid of pixels and it is the square that shows the least variation here. The curved circular shape must always be an approximation when represented by a pixel based system. Pixel related limitations of the image will have the greatest effect on shapes with sharp corners since approximations in shape will cause relatively large percentage changes in shape dimensions at the points. It may be noted that the circle is not represented in Figure 7 because its shape factor is such a small number that relative error calculations produce unrealistically high values.

5. Conclusions
It is clear that the imaging based sensor used here is capable of measuring particle shape successfully and the shape factor defined has been shown to be a useful representation of particle shape complexity. The real-world effects of limited resolution images are, however, considerably greater than might be supposed through empirical consideration and previous assumptions that imaging based particle analysis systems are fundamentally insensitive to particle size (in relation to shape measurement) should be carefully reconsidered for real-world applications. Variations of up to ±4% in measured parameters were recorded when increasing the size of shapes by 100% although this magnitude of error was only experienced with extreme shapes that are not necessarily representative of those found in real particles. Simpler shapes suffered only from variation in the order of ±1% under similar conditions – an acceptable result. It is envisaged that on-line measurement of particle shape could be performed when the present technique is combined with previous on-line sizing work.

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