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TITLE

Inference of Bulk Properties and Particle Size Data in Coal Preparation Plants using Low-Cost Imaging Techniques

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Synopsis

Consistent coal quality and productivity depends on the availability of frequent and reliable information. The difficult operational conditions at a coal preparation plant provide a challenge for much conventional instrumentation. In this environment, quality indicators ("ash", "handle-ability", "size") are typically obtained by regular sampling and off-line laboratory analyses. This provides a slow feedback route for control of quality. The authors describe improvements to an established non-contact method, profile analysis, which can be used to determine bulk flows and size analysis on line. In conjunction with a belt weigher, estimation of bulk density allows ash content to be inferred.

The authors describe recent improvements to the technique of profile analysis to infer size and volume in near real time. Improvements in camera technology have allowed the capture of smaller features, the exploration of profile edges in greater detail, better resolution and lower noise. The authors show how this can be used to scrutinise particles invisible to earlier methods and the computation of bulk volumes in greater accuracy.

The modest cost of such technology allows for several measurement stations to be incorporated at disparate locations in a plant. The volume and size balances across several streams can be used to reason about the contributions to the final product which accrue from stages in the processing. Intelligent use of such information can close the gap between information needed at frequent intervals and that provided by sampling etc.

1. Introduction

Inference of bulk characteristics such as ***size consist***, ***bulk volume flow-rate, bulk density*** (from which ***true density*** and ***ash content*** may be inferred) in a working coal preparation plant presents an enormous challenge to conventional instrumentation. In many cases sampling and rapid analysers can report by the following shift, but a time gap remains during which unforeseen natural fluctuations in size and quality of run-of-mine can damage the quality of output from the plant. This paper contains recent advances in a non-contact method for obtaining real-time bulk information as to the quality and size consist of conveyor burdens by image analysis of their silhouette profile. The modest cost and robust nature of these techniques opens the intriguing possibility that multiple measurement stations can be used within a plant to control the constituents as they are prepared. Jones and Hall (1998)[1] have already shown that volume and size balances across several streams would enable machine intelligence to be applied to the improvement of the operation of the plant as a whole. Schindel et al (1998)[2] emphasise the importance of sensor development in fulfilling this aim.

Park and O'Brian (1984)[3] established an innovative optical belt-volume sensor using a video camera and electronics to quantify the cross-sectional area at the head-drum of a conveyor. In competition with belt-weighers this optical volume flow-rate was inexpensive, but in combination with belt-weighers a rapid determination of bulk-density could be obtained. Jones (1984)[4] showed that ***particle sizes*** and ***particle size distributions*** could be extracted from the exposed edge of the profile by first entering ordinates into an on-line PC. Allen (1993)[5] used Fourier transformation on flat particle profiles in the laboratory. The problem of isolating a train of particles from a naturally-formed heap was an enduring problem however. Coulomb's historic memoir (1773)[6] conceived an underlying continuum in a structure of particles when postulating internal friction in soil against retaining walls. Adapting this concept, Jones and Maxwell (1995)[7] modelled a particle heap as a relatively smooth underlying profile upon which was superimposed an approximately fractal ***particle train*** at the free edge. Using this, and assumptions about the approximate shape of the particles, Maxwell (2000)[8] was able to determine a sampling line through the edge of the profile which threaded most particles of a given size. From the chord distributions actual particle sizes could be re-constituted, based on the spherical particle which would best fit the exposed dimensions (the ***reconstituted circle*** method). Langston and Jones (2001)[9] proposed a probabilistic method of inferring size distributions from the distribution of chord widths using Bayes Theorem.

2. The Profile Analysis Technique

2.1 Optical Bulk Volume

The determination of belt volume from video images of the burden at the head-drum of a conveyor has been documented (Park and O'Brian 1984)[3] and the technique has been used in several field investigations since. Figure 1 shows one configuration to obtain a shadow image against a light background.

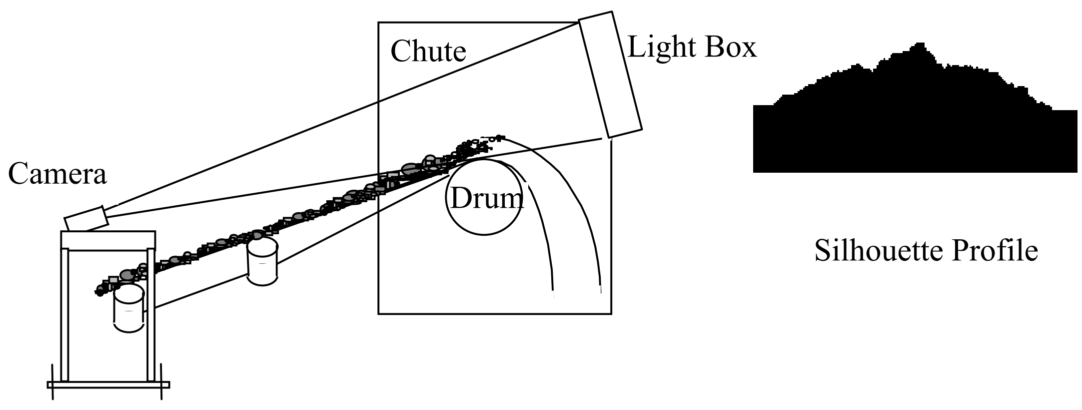

Figure 1: Profile Image Capture at the Head-Drum of a Conveyor

The purely electronic means of assessing the area of shadow described by Park and O'Brian has given way to image capture by means of a digital camera, and advances in technology have enabled the exploration of surface features invisible to lower-resolution methods.

Belt volume flow-rate is fairly easily obtained from the cross-sectional profile area in pixels as follows.

$$\dot{V} = N_p \times A_p \times U$$

where

$\dot{V}$ = volume flow rate / m^3 h^{-1}

N_p = number of pixels in the shadow profile (removing shadow pixels below the belt level)

A_p = the real-life area at the head-drum of one image pixel / m^2 (obtained by calibration)

U= the linear belt velocity ($= \Omega \times \pi D \times 60$)

Ω = revolution rate of drum / rev min^{-1}

D = mean diameter of the drum / m

The factor N_p (number of pixels per square metre) is a calibration figure based on known dimensions in the image and is a simplification based on the assumption that pixels are perfectly square. Usually target pointers are placed within the image plane in both horizontal and vertical orientations. This allows calibration in both horizontal and vertical directions.

2.2 The Estimation of Bulk Density with Upstream Belt Weigher

Given a belt-weigher upstream on the same belt, real-time determinations of bulk-density are obtainable as follows.

$$Bulk\ \ density,\ \rho = \frac{weight\ \ flow\ rate(t - \Delta t)}{volume\ \ flow\ rate(t)}$$

The time delay between the belt-weigher reading and the head-drum, Δt, can be determined from the belt-speed $(\Omega \times \pi D \times 60)$ and the distance from the centre of weighing to the crown of the head-drum. Another, and possibly more accurate, method using time-series analysis to determine Δt is described by Jones *et al* (2000)[10].

2.3 The Inference of Ash Content

Modelling a typical coal stream coal as a simple mixture of low density "coal" particles and high density "shale" particles, the relationship between the ash-content of the mixture and its density can be shown to be a reciprocal one. Assuming that masses of coal and shale are conserved in the mixture, we write the ratio of mass of coal to the total as α. We can then write equations of conservation of ash-mass and particle volume as follows.

$$A_C \alpha + A_S (1 - \alpha) = A \qquad [1]$$

$$\frac{\alpha}{\rho_C / (1 - n_C)} + \frac{(1 - \alpha)}{\rho_S / (1 - n_S)} = \frac{1}{\rho / (1 - n)} \qquad [2]$$

where

n, n_C, n_S	are the bulk porosities of the whole, the coal component and the shale component respectively
ρ, ρ_C, ρ_S	are the bulk densities of the whole, the coal component and the shale component respectively
A, A_C, A_S	are the ash - content of the whole, the coal component and the shale component respectively

We then make the enabling assumption $n_C = n_S = n$ to yield

$$\frac{\alpha}{\rho_C} + \frac{(1 - \alpha)}{\rho_S} = \frac{1}{\rho} \qquad [3]$$

eliminating α from [1] and [3], we obtain

$$A = -\frac{1}{\rho} \times \left(\frac{A_S - A_C}{\frac{1}{\rho_C} - \frac{1}{\rho_S}} \right) + \frac{1}{\rho_S} \left(\frac{A_S - A_C}{\frac{1}{\rho_C} - \frac{1}{\rho_S}} \right) + A_S \qquad [4]$$

$$\therefore A = -a \times \frac{1}{\rho} + b$$

where *a* and *b* are positive constants for a given mixture of components. The slope should always be negative and the intercept should always be positive as long as shale can be characterised as the component of highest ash-content and highest density.

At Longannet Mine (Scottish Coal) a conveyor belt for power station blends is provided with a Ram-Feed Coal Quality Monitor (analysing for moisture and ash)[11,12] and two weighers. We are grateful to Scottish Coal for allowing us to obtain timed belt profiles, time series weigher readings and ash-content from the monitor. The poor lighting conditions and partially obstructed view of the head-drum gave rise to some uncertainties in the determination of optical bulk volume, but the results were reasonably encouraging (Figure 2).

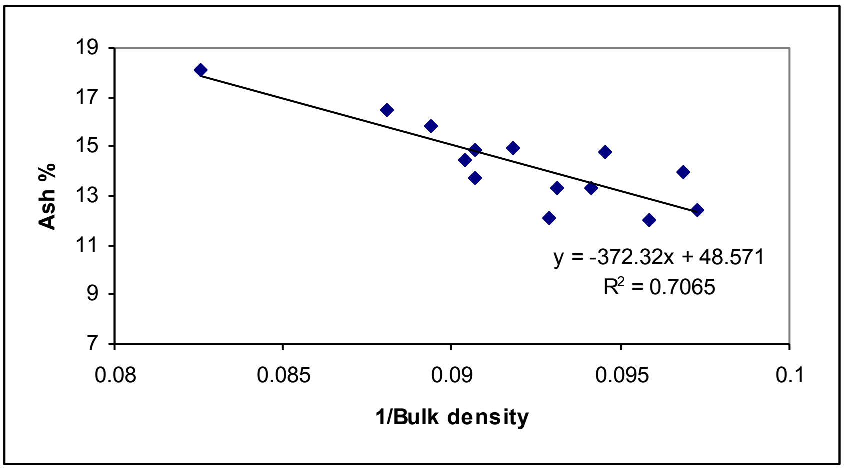

Figure 2: Bulk Density-Ash Correlation, Longannet Colliery

2.4 Particle Size Determination

Belt profile analysis has been in use since 1984 [2,3] to determine belt-volume flow rate and/or particle sizes. By far the most difficult problem has been the reliable estimation of particle sizes from partial exposures at the surface of a heap. This series of particle "fragments" and voids is termed the *particle train* and its accurate identification is the key to the technique. Once the relatively smooth undulations of the heap continuum have been defined, the line threading through the major features (particles and voids), the *sampling line*, can be used for analysis. We shall be demonstrating an example in the course of this paper. The surface features are in fact mildly fractal, and a series of increasingly convoluted sampling lines must be used as reducing sizes are sought. This is analogous to a series of sieves used to classify a sample of particulate material although the overlap between classes would be much less for sieves. The final stage is to reconstitute the particles from salient features of their surface profile. A useful model to perform this construction is the *reconstituted circle model.*

2.4.1 Determination of Sampling Lines

Sampling lines are merely smoothed versions of the surface profile. A simple spatial filter can be found which will separate the *underlying profile* from the *particle train*. This will thread the largest particles and voids in the surface. Since the surface is mildly fractal, more serpentine lines must be defined to thread smaller particle features. Maxwell[8] modelled the heap with a series of sliding average filters.   He suggested that a length of sliding average filter equal to approximately twice the particle size would create a sampling line which intersected most particles of that size.   Current investigations have refined the smoothing algorithm based on the distribution of chord sizes to be expected.

2.4.2 Representation of the Particle Train

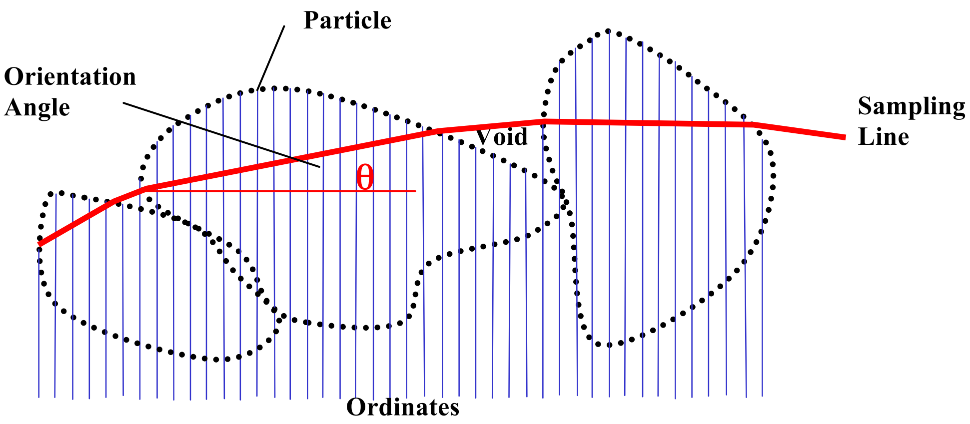

Figure 3: Detail of the particle train and the sampling line

A major simplification of the particle train data is its representation as a set of evenly spaced ordinates as shown in Figure 3.   Figure 3 shows a slight distortion of re-entrant parts of the profile (particularly the voids) in comparison with full co-ordinate (x,y) representation, but the significant reduction of volume of data is important for analysis in real time.   Notice that the sampling line is idealised to a straight chord as it passes through each particle.   The reason for straightening of the chord will be explained later.   In general, ordinates are not at right angles to the chord formed by the sampling line.

2.4.2 Reconstituted Circle Method.

Figure 3 shows the particles being threaded by a sampling line.   From the computed profile and the co-ordinates of the heap below the sampling line (the underlying profile), key dimensions of each particle must be obtained to construct a circular model of the particle profile (see Figure 4).

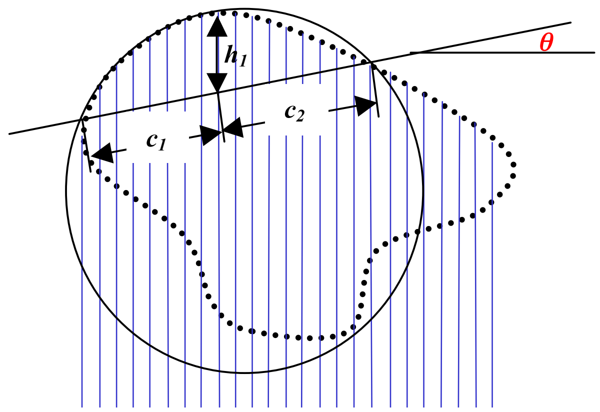

Figure 4: Dimensions from the profile image of each particle and its reconstituted circle

The method used to construct a reconstituted circle from the dimensions and orientation shown in Figure 4 can be obtained from simple geometry.

For the purposes of further examining the relationship, a series of simplifications is possible

Approximation 1
Assume the heap is small $\theta \rightarrow 0$

Approximation 2
Assume the difference $(c_1 - c_2)$ can be ignored.

Approximation 3
A further stage of approximation 2 is to put $c_1 = c_2 = R$, where $2R$= total chord width

In general the ratio of the chord length to the height of the particle is a crucial factor in this computation. The difficulty is with digitised shapes in which the height h_1 ,is rounded to a small number of pixels. The spacing of the ordinates is also influential in the accuracy of these results.

2.4.3 Validating the Reconstituted Circle Model

Ironically profiles of "real" particle heaps are not ideal for testing the size analysis method. The particles themselves would be classified by screening sizes, and there would be uncertainty as to the effective size of a given particle in the surface. A computer-simulated profile is preferable because the size of each particle in the profile would be very accurately known and any deviations would be attributable to deficiencies in the analysis method. An important proviso is that the computer-simulated profile would have to be realistically obtainable with real particles.

Simulated particle heaps were generated by the Distinct Element Model (DEM)[13]. DEM provided 'heap' profiles constructed from spherical particles of known sizes. The sizes were "reduced" sizes in that they did not have physical units of measurement, but were completely consistent with the overall scale of the image. Three heaps were constructed. The first was from particles of a single size, with a diameter of 1 reduced unit. The second was constructed with particle diameters ranging from 0.9 to 1 reduced unit and the third with diameters from 0.3 and 1 reduced units. The size selection of particle sizes for the third was in order to allow for packing of the smaller particles amongst the larger. The single size heap was initially evaluated using all four techniques employed for evaluation of the reconstituted circles. Figure 5 illustrates the DEM heap for a single particle size of 1 reduced unit with sampling line added.

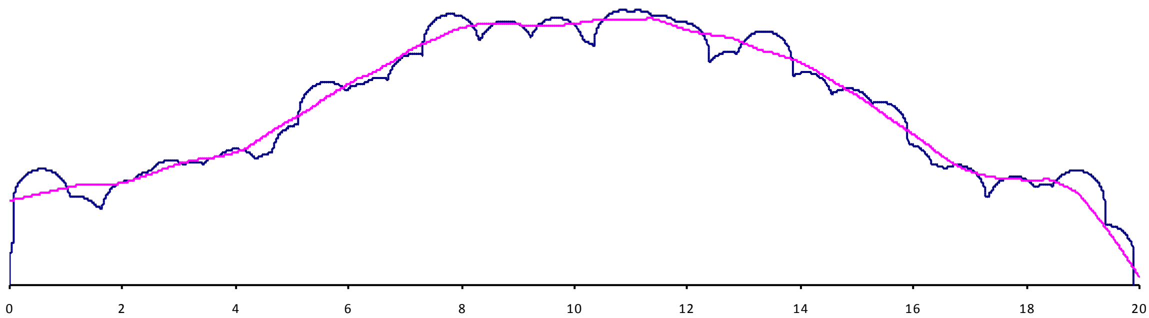

Figure 5: Particle train and sampling line for a DEM heap (size = 1 reduced unit)

Figure 6 illustrates the cumulative distribution function for the single particle size heap.

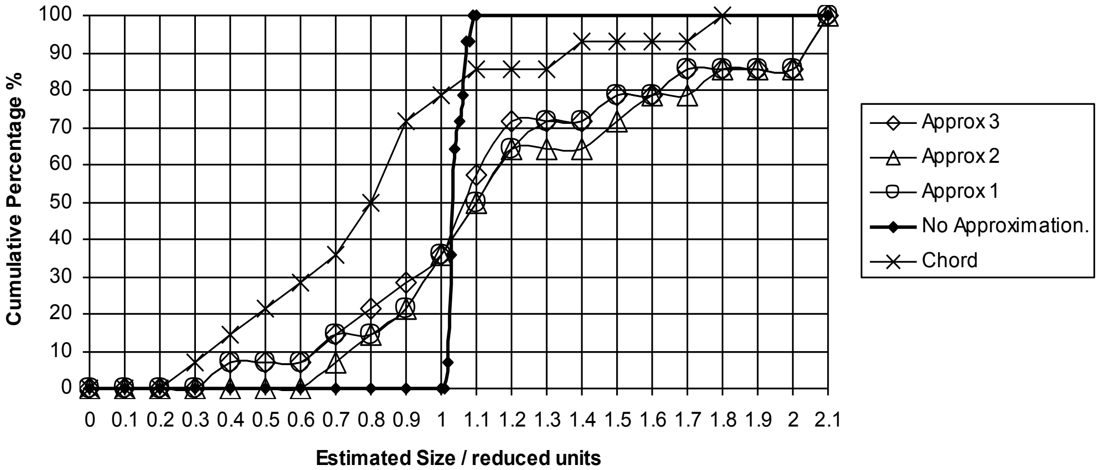

Figure 6: Size curve showing the relative performance of the reconstituted circle model, its approximations and the original chord size distribution

The unapproximated size distribution in Figure 6 shows an S_{50} (median size) of approximately 1.03 for the nominal particle size of 1.0 reduced units. This compares with similarly good estimates for all the approximations. It shows particularly good performance against the chord distribution which has $S_{50} \approx 0.8$ reduced units. There were further possibilities for refinement.

Three problems were overcome in the derivation of this size curve. Originally the curved sampling line over-estimated the maximum height dimension h_l (see Figure 7(a)). Recall that sizes obtained by the reconstituted circle method were very sensitive to the chord to height ratio. As we have already pointed out, the answer to this problem was to idealise the sampling line to a straight chord as it passed through each solid particle, but allow it to curve as it passed through the voids. A second problem was the quantization of h_l at small values. The rounding down of h_l has a disproportionate affect on chord/height ratio compared to the rounding up of h_l. A possible solution would be to ignore small particle excursions, although this has not been implemented at this stage. The third problem was that two particles may be filtered as one. Figure 7(b) illustrates two particles isolated as one particle by the sliding mean filter. The upper part of the distribution curve (Figure 5) suggests errors from this cause. A solution to the problem was to apply a more selective spatial filter.

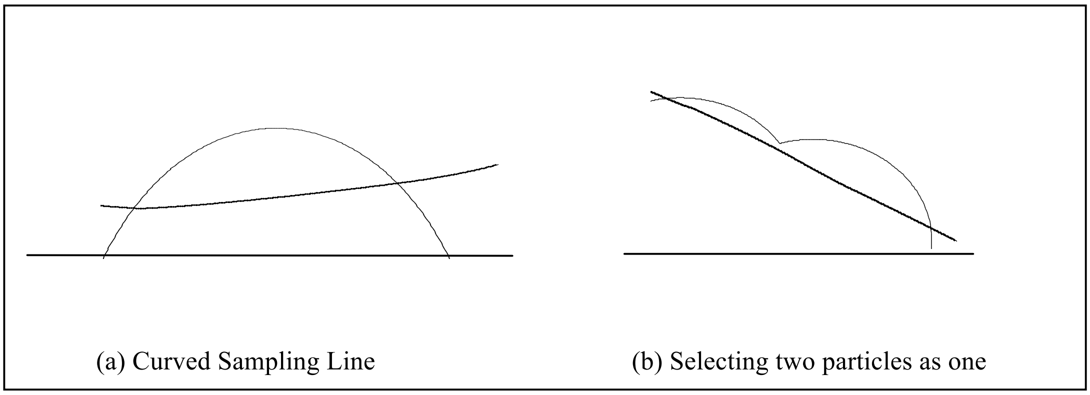

Figure 7: Errors in sampling particles in the surface

The next exercise was to analyse closely spaced particle sizes. This is analogous to a screening operation where the particle sizes lie between two nominal screen apertures. A DEM profile for a linear spread of particles between 0.9 and 1.0 reduced units was tested and the size curve is shown at Figure 8

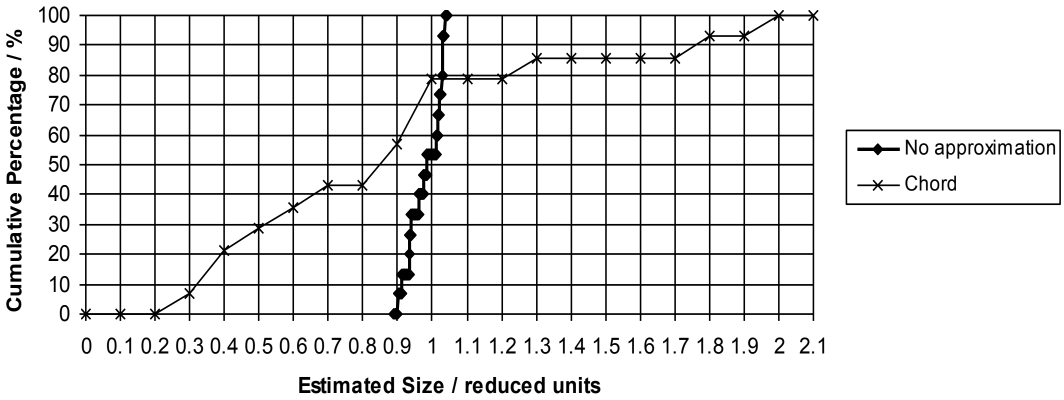

Figure 8 Size curve showing the relative performance of the reconstituted circle model, with closely-sized particles (0.9 to 1.0 reduced units)

Finally a size curve was obtained for the heap profile of particles for a mixture of discrete sizes 0.3 and 1 reduced unit. This is shown in Figure 9

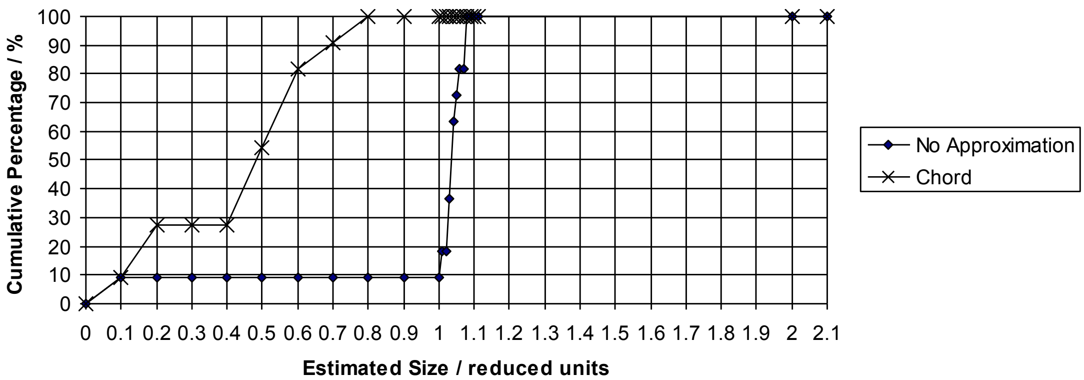

Figure 9 Size curve showing the relative performance of the reconstituted circle model, with two widely-sized particles (0.3 and 1.0 reduced units)

3. Discussion

Bulk-volume flow-rate determination was dependent on several assumptions about the loaded conveyor being measured. A constant linear belt speed has been assumed, which implies that the drum rotational speed is constant and that belt slip is a constant influence on the linear belt speed. Calibration of the image plane is an important issue. A bulk sample removed from the belt over a fixed time may change its bulk porosity during the handling process, and it will be difficult to perform the calibration in this way. The use of belt-weighers on the same stream can also be used for calibration, but there is usually no guarantee that the density of the belt burden will remain constant. Run-of-Mine coal for example will vary in size, porosity and density continuously. A combination of techniques is required to achieve a calibration acceptable to operational staff, but the calibration of the image plane must be the cornerstone of this effort.

Bulk-density determination rests on a reliable indication of belt volume flow rate. At Longannet Colliery, site tests were used to calculate the delay (Δt) between the centre of weighing and the image plane on the head drum. A further method using time series[13] had the potential for greater accuracy in the determination of Δt .

Ash content, derived from the bulk-density measurement, was the last in the chain of measurements from the pixel area of the profile. Clearly uncertainties in the determination of bulk density are carried into the determination of ash. A simple justification of the principle that Ash should be calibrated against reciprocal bulk density was given. Mined "coal" particles do not appear as independent liberated species from "shale" particles, but it was convenient to model them so. Additionally, the assumption that the bulk porosities of all the components on the belt did not change from one to another, or with time, is worthy of critical discussion, especially as adventitious moisture would be present.. The plotting of reciprocal bulk-density against ash-content from the Ram-Feed Coal Quality Monitor at Longannet showed moderately good correlation and the authors contend that with a clearer image of the belt profile the accuracy of the calibration could be improved still more. Further experimentation with this system is required.

Particle size determination from the exposed edge of a particle profile is by far the most ambitious measurement attempted. Historically, size measurements have been based on the length of chords in the exposed particle projections, using the profile method, or exposed particle area from above the belt. Simulation experiments in this paper show that the chord measure of size is both inaccurate ($S_{50} \approx 0.8$ for a single size particle heap of nominal size 1.0 reduced units) and imprecise (the tails of the single-size distribution stretch from 0.2 to 1.8 reduced units). The Reconstituted Circle Model certainly shows improvements over the chord measurement for single-size particle populations, for closely-sized particle populations and for widely-spaced particle populations. However, the results demonstrated in this paper are for spherical particles with accurately known diameters. The challenge is to apply the technique to real particles with variable shape, angularity and aspect ratio. Coal and shale for example have differing shapes and densities.

4. Conclusions

Difficult operating conditions in coal preparation plants have focussed attention on non-contact measurements. The authors have demonstrated the potential for one system of non-contact measurement using the profile of coal on the head-drum of a conveyor. Belt-volume flow rate is an important measurement in the filling of bunkers and hoppers, arguably more so than mass-flow measurements. When a belt weigher is present on the belt, bulk-density and ash can be estimated by using the two variables together. There are several reasons why a bulk-density determination of ash should be subject to error, but it is considerably less expensive than radiometric instruments to perform the same measurement. Lastly the potential for determination of particle size was shown using a new method of reconstituting each particle from its exposed part on the profile. The profile method is inexpensive, since its measurements are made with digitised images from inexpensive video cameras. This opens up the possibility of using multiple cameras to instrument several streams in a coal preparation plant for control and optimisation purposes.

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