FINE COAL WASHABILITY-LIBERATION ANALYSIS BY CONE-BEAM X-RAY MICROTOMOGRAPHY

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ABSTRACT

A new method based on cone-beam x-ray microtomography is described for direct determination of the three-dimensional liberation spectrum of multiphase particles 100 microns in size or less. Such a technique may provide the basis for more detailed and accurate washability analysis in fine coal characterization. Previous research has demonstrated the ability to use traditional medical x-ray CT scanners to determine the liberation spectrum of coarse coal particles of 1 cm in size (washability analysis). Now it is possible to determine fine coal (-100 mesh) washability by cone-beam microtomography. Rather than stacking a series of two-dimensional slices for volumetric imaging as is commonly done in traditional medical computed tomography, with this new microtomographic technique a three-dimensional reconstruction image array is prepared directly from the two-dimensional projections for cone beam geometry. The advantage of high spatial resolution (approximately 15 μm) with a microfocus x-ray generator combined with the benefit of direct processing of three-dimensional data, provide an excellent opportunity to overcome many of the limitations of current techniques being used for fine coal washability analysis.

INTRODUCTION

The efficiency which can be achieved by any separation technique used for coal cleaning operations depends on the nature of the mineral matter dissemination in the coal and on the extent of liberation at any particular particle size. Generally, the mineral matter dispersion gives rise to a continual variation in particle density and the entire particle population is best described by a particle density distribution, a density spectrum. The distribution is in fact the washability curve. A coal washability curve is the fundamental characteristic of a particular coal sample which shows the limits of any physical separation of mineral matter from coal.

Conventional coal washability information is generally obtained in the laboratory by the tedious sink-float analysis using halogenated organic compounds in large quantities.[1] The principle behind this procedure (sink-float) is nothing more than particle fractionation by specific gravity. Typically, the sink-float technique can be applied for coarse (plus 9.5 mm) and intermediate (9.5 x 0.5 mm) sizes of coal. The centrifugal sink-float procedure is the most commonly used technique to fractionate fine and ultrafine coal by specific gravity.[2] It should be noted that variation has been observed between different laboratories as described in a DOE interlaboratory test program.[3] Alternative methods, such as microscopic analysis of the polished sections of mounted specimens, can be used to provide the quantitative information on the compositional distribution of the coal particle population (washability curve).[4] In general, the image data is collected either from linear intercept measurements or from projected area measurements. Such an approach has obvious limitations. For example, in the most common method for determination of the volumetric grade distribution of a particle population, a set of narrow-sized particles needs to be prepared, each particle size must be mounted in resin, the resin must hardened, the mount then sectioned, polished and the linear and/or area grade distributions determined by image analysis. Next stereological correction of the data must be done to estimate the volumetric grade distribution. Furthermore, assumptions must be made either based on textural information or based on geometrical probability in order to provide the stereological correction. Finally, extension of the stereological correction for more than 2 phases is limited. In fact, a large discrepancy is observed between the results of centrifugal sink-float test and SEM-AIA analysis (without stereological correction).[4]

X-ray computed tomography (CT) had its origin in the medical services[5] and has now been applied to non-medical and industrial applications.[6,7] In general tomography refers to the cross-sectional imaging of an object from either transmission or reflection data collected by illuminating the object from many different directions.[5] Thus, the image from an x-ray CT scan is a cross-sectional representation of the x-ray attenuation during transmission through the object under examination. X-ray CT techniques have an inherent advantage in providing detailed images of the internal structures of opaque materials in a nondestructive manner. As mentioned previously, polished section techniques for the examination of the internal structure of particles are destructive and require lengthy experimental procedures. Recently the application of x-ray CT in mineral processing technology was reviewed.[8,9] For quantitative analysis of particulate systems such as coal washability analysis, a previous study[10] done at the University of Utah indicated that a conventional medical x-ray CT scanner can provide sufficient information to construct the washability curve within minutes of sample collection. In fact, it now seems possible to design an on-line washability system for the control of coarse coal cleaning circuits.[11] On this basis it is expected that x-ray microtomography can out-perform all existing stereological correction techniques based on sizing/separation and image analysis procedures. In such cases, CT techniques can be competitive with the most sophisticated microscopy techniques involving optical or electron microscopy equipped with automatic image analysis. X-ray CT analysis should be able to provide not only the volumetric grade distribution, but also a very detailed accounting for the multiphase particle population including grain size distribution, interfacial area, shape features, and textural information.

From the foregoing discussion, it can be realized that CT has the potential to characterize the mass density spectrum or the real three-dimensional grade distribution of a particle population. However, it is noted that the quality and utility of the CT data ultimately depends on the resolution of the machine employed. Medical x-ray CT systems have a beam width of a few millimeters and an energy source of about 110 Kev x-rays. Generally such a system would not be adequate for liberation analysis, coal being an exception because of it low density. In this paper we describe a new method for the direct determination of the three-dimensional mass density spectrum of particles with a size of a few hundred microns or less. The method combines high-resolution 3-D cone-beam x-ray microtomography techniques and a classification algorithm for the determination of particle composition from three-dimensional data. Such a technique may provide the basis for more detailed and accurate coal washability-liberation analysis.

METHODS

High Resolution Three-Dimensional X-Ray Microtomography

To determine the coal washability curves for fine coal streams in a coal preparation plant, tomographic techniques which produce three-dimensional images of the internal structure of small particle samples with micrometer resolution will be required. In this regard, three-dimensional X-ray microtomography offers a unique imaging capability. In particular, accurate three-dimensional maps of density and mineral phase distribution can be measured for multiphase particles 100 microns in size or less. Spatial resolution on the order of 1 μm and 15 μm can be achieved with the use of synchrotron radiation[12] and conventional microfocus x-ray generators,[13] respectively.

Cone-beam geometry x-ray microtomograpy[14-16] is well suited for the quantitative determination of the mass density distribution of the particles with a size of less than a few hundred microns. The CT system[14] used in this study was originally designed for the detection of small structural defects in ceramic materials. Rather than rotating the x-ray source and detectors during data collection, as in medical CT technology, the specimen is rotated. Instead of generating a series of two-dimensional sliced images from one dimensional projectors, a three-dimensional reconstruction image array is created directly from two dimensional projectors.[15] Details for the description of this micro-CT system and its corresponding reconstruction algorithm can be found in the literature.[5,14] Only a short overview is provided herein.

Figure 1 shows a schematic diagram for the cone-beam geometry micro-CT system. X-rays from a microfocus x-ray generator are partially attenuated by a specimen that is made to rotate in equal steps in a full circle about a single axis close to its center. At each rotational position, the surviving x-ray photons are detected by a planar two-dimensional array (image intensifier) large enough to contain the shadow of the specimen. These two dimensional projection images are collected using conventional video technology. The video signal is then converted to a two-dimensional digital array by an image processing system. Finally, a three-dimensional image array is reconstructed from the collected set of projection images. This reconstruction

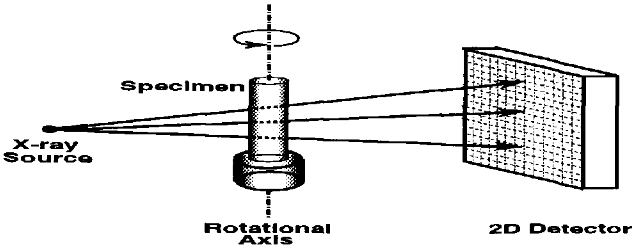


Fig. 1. Schematic diagram of the cone-beam x-ray microtomography system.

algorithm is a generalization in three dimensions of the widely used convolution-back projection method.[14]

Scanning a typical specimen takes about 45 minutes. Full three-dimensional reconstruction requires approximately 2 hours with the use of a Floating Point Systems AP-120B array processor. This time is comparable to that required for polished section analysis as discussed in the introduction. The resolution of this system is approximately 40 μm for a standard specimen. Resolution limitations largely result from the finite resolution of the image intensifier.

Analysis of Three-Dimensional Spatial Distribution of Mineral Phases in Coal Particles

In addition to the three-dimensional reconstruction algorithm, several additional algorithms are needed to properly implement the three-dimensional mass density distribution analysis for the coal particle population. These algorithms include phase segmentation, surface extraction, labeling, and particle/volumetric grade classification for the three-dimensional CT data set.[10] The principal need is to manipulate large amounts of CT data.

One of the problems faced for analysis of the three-dimensional spatial distribution of mineral phases in a multiphase particle population is the identification and separation of contacted particles. Watershed techniques commonly used in morphological analysis[17] can be used to separate these particles in contact with each other.

To test the effectiveness of the three-dimensional cone-beam CT measurement of coal washability, coal particles from Pittsburgh #8 seam were selected for this preliminary study. Several coal particles (0.7 to 1.0 mm) from three specific gravity fractions (1.25 x 1.27, 1.39 x 1.50, and > 1.60) were taken and sent to the University of Michigan for CT analysis. The reconstructed three-dimensional image arrays were sent back to the University of Utah for volumetric grade distribution analysis.

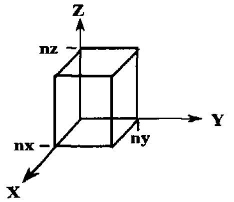
RESULTS AND DISCUSSION

Since this study represents the first attempt to directly measure the three dimensional grade distribution of coal particles, only preliminary data are presented to illustrate the potential of cone beam microtomography. More detailed results will be presented in subsequent contributions to demonstrate the reliability of the technique and confirmation of previous estimates of volumetric grade distribution from microscopic polished section analysis.

The three-dimensional reconstruction region for this study is a volume of 0.603 by 0.603 by 1.101 cm. The reconstruction set consists of 201 x 201 x 367 voxels (volume elements) with each voxel being 30 microns on a side. Figure 2 illustrates the coordinate system for the coal sample.

To fully test the effectiveness of three-dimensional cone-beam x-ray microtomography for the determination of the specific gravity of individual coal particles, a sample was prepared by mixing three kinds of coal particles with a size range of 0.7 to 1.0 mm from three specific gravity's (1.25 x 1.27, 1.39 x 1.50, and > 1.60).

Coordinate System for the Coal Sample



Reconstruction Size

X : nx = 201 units. 0.603 cm
Y : ny = 201 units. 0.603 cm
Z : nz = 367 units, 1.101 cm

Fig. 2. Coordinate system for the sample of coal particles.

Figure 3 displays two sequences of four cross sections (from a total of 367 sections) along the z-direction as established from the three-dimensional reconstruction of the sample. It should be noted that these sections are taken from the three dimensional image and not used as such to construct the three dimensional image. As shown in Figure 2, the image elements in the reconstruction are cubic, so the spacing between planes equals the resolution which in the z-direction corresponds to 30 μm. Here the gray scale levels of the images indicate the relative attenuation coefficient present in the bulk of the sample. The white features represent the mineral phase which has the higher mass absorbance. The gray regions in these planar images represent the coal phase which has a relatively lower mass absorbance. Reconstruction noise from plastic wrap material (specific gravity 0.9-0.92) is also present in these images as a cloud of tiny dots with a relatively lower gray level than the coal phase.

Systematic shift in measured density from measurement to measurement can arise if the characteristics of the x-ray beam are not precisely reproduced.[15] For quantitative analysis, such as coal washability, calibration is required for the compensation of systematic shifts by periodic scanning and reconstruction of a portion of a reference object.

Beam hardening is a potential complication in CT when the x-ray source is polychromatic. For application in coal washability analysis which covers a wide range of densities a beam hardening correction will likely be required. For this study, the 3-D image is reconstructed without beam hardening correction. In fact, a lower density than expected is observed for the coal material. At present, no quantitative density measurement is made for this image data set, the unreconstructed data set is saved and will be processed for beam hardening correction in the future.

Volume visualization of the three-dimensional image data is a rapid growing field in the area of computer graphics. Three major approaches for volumetric visualization have been developed in the last decade. These techniques include surface-based, binary voxel, and semitransparent volume rendering methods. Details of these techniques can be found in the literature.[18] Volume visualization using the semi-transparent volume rendering technique is characterized by allowing a color and a partial opacity to be assigned to each voxel. Images are formed from the resulting colored semi-transparent volume by blending together voxels projecting to the same pixel on the picture plane. Based on the volume rendering technique, four surface rendered particle images at a different angle of rotation along the Y-direction were generated using the VolPack volume renderer[19] from the reconstructed three-dimensional image array as shown in Figure 4.

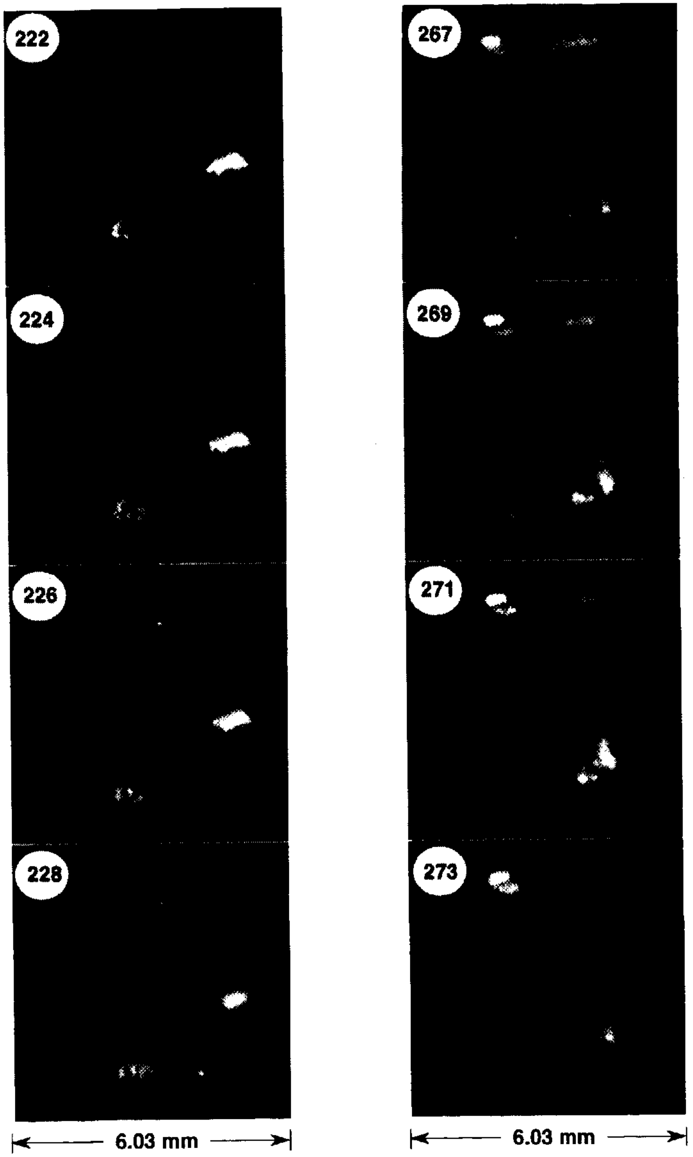


Fig. 3. Two sequences of cross sectional images from the three dimensional x-ray microtomography reconstruction of the coal particles. Numbers indicate the position of the cross sectional image taken along z-direction according to the coordinate system shown in Fig. 2.

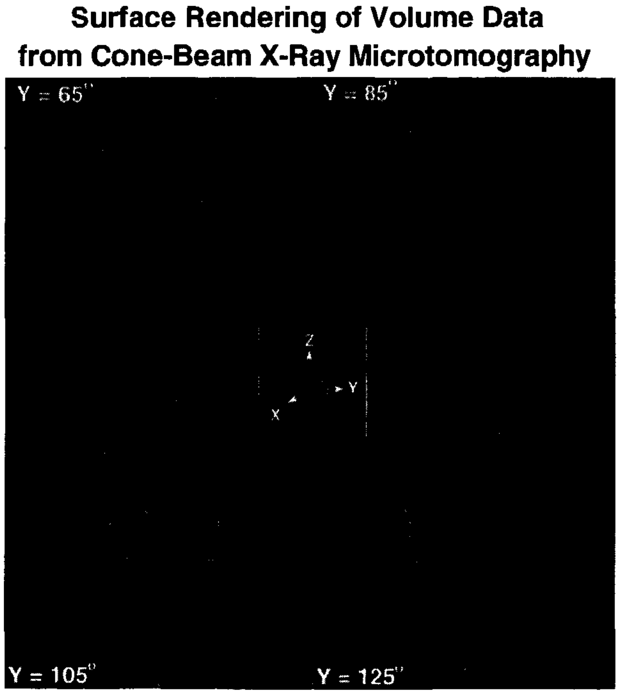


Fig. 4. Four views of 3-D surface rendered images of the coal particles around the Y-axis from cone-beam microtomography using the VolPack[19] volume rendering software.

SUMMARY AND CONCLUSIONS

For detailed coal washability analysis of fine coal particles, the volumetric grade distribution of coal particles, 100 microns in size or less, can be measured directly by cone-beam x-ray microtomgraphy as described in this study. High spatial resolution (in this study 30 μm) and the direct processing of raw volumetric data are the two important benefits offered by this new method. Three dimensional liberation analysis by microtomography provides an excellent opportunity to overcome many of the limitations of currently used polished section techniques. Although only preliminary results are reported, it is expected that this analytical approach will provide the basis for more accurate detailed coal washability analysis in the 21st century. With the advanced system, complete accounting of the spatial distribution of mineral phases in each particle is possible, including grain size distribution, interfacial area, shape features and textual information.

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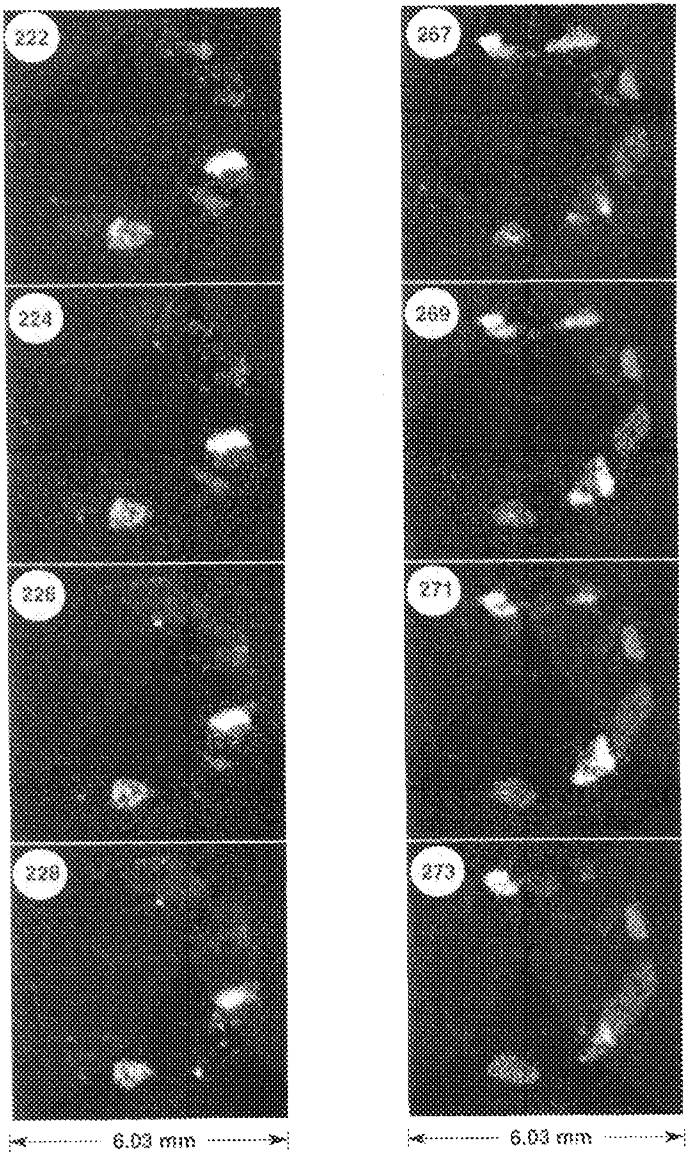

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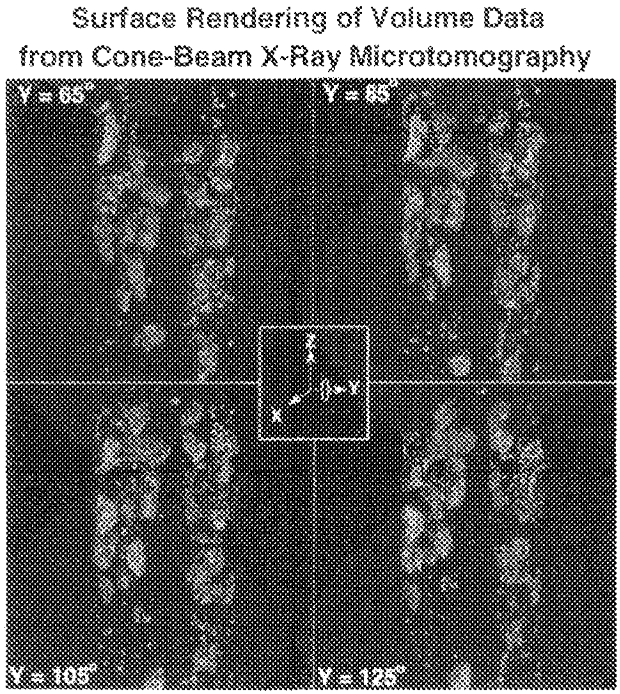
Surface Rendering of Volume Data
from Cone-Beam X-Ray Microtomography

Fig. 4 Four views of 3-D surface rendered images of the coal particles around the Y-axis from cone-beam microtomography using the VolPack[19] volume rendering software.

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