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DEVELOPMENT OF AN ON-LINE COAL WASHABILITY ANALYZER

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Project Title

DEVELOPMENT OF AN ON-LINE COAL WASHABILITY ANALYZER

Semi-Annual Report
(04/01/1998 - 09/30/1999)

DOE award No. : DE-FG22-96PC96215

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DISCLAIMER

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ABSTRACT

Washability analysis is the basis for nearly all coal preparation plant separations. Unfortunately, there are no on-line techniques for determining this most fundamental of all coal cleaning information. In light of recent successes at the University of Utah, it now appears possible to determine coal washability on-line through the use of x-ray computed tomography (CT) analysis. The successful development of such a device is critical to the establishment of process control and automated coal blending systems. In this regard, Virginia Tech, Terra Tek Inc., and several eastern coal companies have joined with the University of Utah and agreed to undertake the development of a **x-ray CT-based on-line coal washability analyzer** with financial assistance from DOE. The three-year project will cost \$594,571, of which 33% (\$194,575) will be cost-shared by the participants. The project involves development of appropriate software and extensive testing/evaluation of well-characterized coal samples from operating coal preparation plants. Each project participant brings special expertise to the project which is expected to create a new dimension in coal cleaning technology. Finally, it should be noted that the analyzer may prove to be a universal analyzer capable of providing not only washability analysis, but also particle size distribution analysis, ash analysis and perhaps pyritic sulfur analysis.

EXECUTIVE SUMMARY

The primary objective of the proposed research program is to develop a CT-based, on-line coal washability analyzer. A secondary objective will be to demonstrate the capabilities of the analyzer by comparing efficiency data from traditional float-sink tests conducted at three preparation plant sites with efficiency data generated by the washability analyzer. The scope of the proposed research program involves several tasks including (i) the acquisition and preparation of test samples for use in testing and calibrating the analyzer, (ii) the development of appropriate hardware and software necessary to adapt a CT analyzer for use in determining coal washability, (iii) the testing and modification of the analyzer using well-characterized coal samples, (iv) the evaluation of the analyzer's performance under simulated plant conditions, and (v) an evaluation of the technical and economic feasibility of implementing the CT-based washability analyzer on a commercial basis.

Researchers from the University of Utah and Terra Tek Inc. will perform tasks related to the development, calibration and testing the analyzer, while technical personnel from Virginia Tech and Cyprus Amax will provide the required coal samples, evaluate the industrial capabilities of the analyzer, and promote system commercialization.

The main effort during this reporting period involved characterizing in detailed the full attenuation coefficient histograms of the sample composed of single-size/single-density particles and used to calibration the density scale. A methodology based on the finite mixture model and an appropriate image processing technique is being developed to analyze the mass density distribution for the coal sample.

RESULTS AND DISCUSSION (by task)

Task 1. Project Management

Two graduate students (Ataullah Mirza-Baig and Altaf Khan) at the University of Utah were assigned to the project to coordinate the CT scanning for washability analysis, and to develop software and hardware. At Virginia Tech, two additional graduate students (David Brafford and Jaisen Kohmuench) have been assigned to work part-time on this project to acquire coal samples, perform characterization tests and collect field data used to evaluate the industrial applications of the proposed technology.

Task 4. Software Development

Initially, the coal phantom was setup to be used to calibrate the density scale (see previous report) for the coal washability determination. However, an alternative density calibration method has been developed during this period to obtain a more reliable relationship between the density and the attenuation coefficient histogram. Details of this density calibration method are discussed as follows.

The x-ray computed tomography equipment used in this study produces images that are two-dimensional slices of the coal particle bed. For quantitative analysis of the mass density distributions from these tomographic images, a finite mixture model⁽¹⁾ and a special image processing technique was used to determine the coal washability curve. In this approach, physical phenomenon for the construction of coal washability curve can be described from the analysis of multimodal densities. In this regard, the problem is that of decomposing a given attenuation coefficient histogram curve into its components and mixing weights. In this case, the individual components of the curve are based on the ‘image segmentation’ of the particle surface. The detection of surface boundaries and classification of the particle population is a critical aspect of the algorithm development for the ‘image segmentation’. In this section, statistical analysis of the finite mixture distribution, based on the characteristics of tomographic data, is discussed first. Then, methodologies based on the finite mixture model and image processing techniques being developed to facilitate the segmentation and classification of particle images, are discussed in order to determine the density distribution for the packed bed of coal particles.

Statistical Analysis of Finite Mixture Distributions from Tomographic Data

The reconstructed CT image consists of a 2-D array of x-ray attenuation coefficients, each associated with a finite-volume cube (voxel) of the sample. As mentioned previously, the attenuation coefficients are a function of the average density and composition of the material in any given voxel. A plot of the attenuation coefficient histogram is a measure of the density variation throughout the sample. Consider a 2-D x-ray tomographic slice of the packed bed of coal particles (containing single size and single density particles in this case) as shown in Figure 1(a). The distinction between the air and coal phases is not sharp due to finite volume effects and the nature of x-ray tomography. The attenuation coefficient histogram corresponding to this CT image consists of an overlapping bivariate distribution as shown in Figure 1(b). The peak with the higher attenuation coefficient value (~ 1200) is associated with the coal phase having a density between 1.30 and 1.35 g/cm³. The peak corresponding to the lower attenuation coefficient value (~ 0) is associated with the external air space surrounding the sample.

Based on the tomographic image information, the finite mixture model can be applied for the construction of the coal washability curve. Usually, attenuation coefficient histogram obtained by known density of coal particle bed, are used to provide the underlying component densities, which can then be used as a basis for estimating the mixing weights associated with the set of unknown density. The objective is that of ‘image segmentation’, which seeks to identify the area of contiguous voxels that are associated within some density range. In this regard, for quantitative analysis of the coal washability from tomographic images, it is necessary to have a well-defined, consistent method to identify each voxel as air or coal with different density scales. This approach based on image analysis involves choosing a threshold or cut-off attenuation coefficient value lying somewhere between the peaks for air and the coal phase. Any voxel with an attenuation coefficient value less than the cut-off is identified as air. Now, consider two threshold values T_0 and T_1 indicated by the gray lines in Figure 1(b). The corresponding regions defined by the two thresholds are shown Figure 1(c). To reveal more details of the resulting image, a selected square region of Figure 1(c) is enlarged as shown in

Figure 1(d). The black and white regions are distinguished as air and coal phases, respectively. It is noted that the x-ray beam of the CT scanner has a fixed beam width of about 1 to 2 mm. When the scanning beam hits the edge of the particle, the resulting attenuation coefficient value of that particular voxel is expressed as the average value for the particle and the adjacent air surrounding the particle. This creates an artificially low attenuation coefficient value for the voxels at the edges of a particle. The gray voxels that correspond to the histogram region between threshold values (T0 and T1) illustrate the problem of defining the particle surface.

As shown in Figure 1(b), a single peak for the attenuation coefficient is obtained from the coal particle population having a single size and a single density. In this regard, the attenuation coefficient histogram for the coal particle population would then show a series of spikes which identify the corresponding density scale. As expected, the attenuation coefficient histogram obtained from the packed bed of coal particles (containing one size and six density classes) is shown in Figure 2. In this example, the problem of constructing a washability curve is then to decompose curve corresponding to the attenuation coefficient histogram into different density fractions and mixing weights. To solve this problem, statistical analysis and modeling for the relationship between the distribution of x-ray linear attenuation coefficients with respected to density and size of the coal particles needs to be addressed.

X-ray CT scanning of single-size/single-density coal particle beds is a suitable method to obtain a statistical picture of the overall behavior of the attenuation coefficient with respected to density and size. In fact, Figure 1(b) is one result selected from a sequence of tests. An analysis of the peaks in the coal spectrum for six different density classes suggests that a normal distribution function can be used to model these peaks. In general form of the normal distribution function is described as

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$$

where μ and σ represent the mean and variance of the normal distribution, respectively.

Figure 3 shows the result of the model fit for a normal distribution function using the data from Figure 1(b) for a individual density class (1.30 - 1.35 g/cm³). For this specific sample, the fitted parameters, mean (μ) and variance (σ), of the normal distribution function were found to be 1225 and 0.1 respectively. The region of the histogram related to surface voxels is also shown in this figure as the shaded area.

To evaluate the effect of particle size on the attenuation coefficient histogram, two more coal samples (25.4 x 12.7 mm and multiple sizes) were prepared and subjected to x-ray CT scanning. Figure 4 illustrates the effect of particle size on the attenuation coefficient histogram. The distribution curves for these three coal samples are identical for this density scale. Of course the surface contribution (the partially filled voxels) is more significant for the sample of smaller size particles, 12.7 x 6.3 mm.

Additional tests were performed for different density classes, and the data fitted using a normal distribution function. The results are summarized in Table 1. The attenuation coefficient histogram based on the model of the fitted normal distribution is displayed in Figure 5. As indicated from the curves shown in Figure 5, the analysis of washability curves based on the overall attenuation coefficient histogram will not be an easy task due to the wide overlap between these curves. However, using an appropriate image processing technique, the area of contiguous voxels belonging to the same particle can be identified. Then, these areas of sectioned particles can be sorted based on density using the attenuation coefficient histogram. In this way, the washability curve can be constructed using tomographic imaging data.

Based on the fitted normal distribution, density calibration can be done considering only completely filled voxels and the actual density determined from sink-float tests. Figure 6 presents a plot of the attenuation coefficient (column 2, μ of Table 1) versus density (column 1 of Table 1). For the practical situation, based on image segmentation, usually only one threshold value between the air and coal phase is set to facilitate the particle segmentation. For coal particles within a higher density, the attenuation coefficient of the partially filled surface voxels is considered as coal phase due to the fact that the attenuation coefficient has a higher value than the threshold setting. In this regard, to accurately estimate the density class of a particular coal particle, consideration of the partially filled voxels for density calibration is necessitated. Figure 7 shows the density calibration curve based on filled and partially filled voxels of coal phase using a threshold value of 1000. These results were used to re-calibrate the density scale for determination of the coal washability characteristics.

Task 6. Testing/Modification

The experimental test program is in progress to evaluate the CT scanner using coal samples prepared under carefully controlled laboratory conditions. The test program is subdivided into four separate series of tests, single size/single gravity, single size/multiple gravity, multiple size/single gravity, and multiple size/multiple gravity.

As mentioned in previous report, two samples, single size/multiple density (2x1 inch and 1x1/2 inch), were prepared for washability analysis using x-ray CT techniques. Using plastic containers as the sample chamber, two sets of sequential cross sectional images (150 and 124 slices) were collected. In these experiments each 2-D CT slice is 2 mm in thickness. Washability data for these carefully prepared samples are shown in Tables 2 and 3, respectively.

Based on the 2-D CT images (slices) of these coal particle beds and using the new density calibration curve, Figures 8 and 9 illustrate the constructed specific gravity/yield curves for size fractions, 1x1/2 and 2x1 inch, respectively. The specific gravity/yield curves for both samples using sink-float tests (Table 2 and 3) are included for comparison. More accurate results are observed for both samples.

SUMMARY STATUS ASSESSMENT AND FORECAST

1. An alternative density calibration method has been developed during this period to obtain a more reliable relationship between the density and the attenuation coefficient histogram. An analysis of the peaks in the coal spectrum for six different density classes suggests that a normal distribution function can be used to model these peaks. Based on the fitted normal distribution, density calibration can be done considering on both filled and partially filled voxels of coal phase using a threshold value of 1000. These results were used to re-calibrate the density scale for determination of the coal washability characteristics.
2. For quantitative analysis of the mass density distributions from these tomographic images, a finite mixture model and a special image processing technique was used to determine the coal washability curve. In this approach, physical phenomenon for the construction of coal washability curve can be described from the analysis of multimodal densities. In this regard, the problem is that of decomposing a given attenuation coefficient histogram curve into its components and mixing weights. In this case, the individual components of the curve are based on the 'image segmentation' of the particle surface. The detection of surface boundaries and classification of the particle population is a critical aspect of the algorithm development for the 'image segmentation'.
3. Two single size/multiple density samples were prepared to evaluate the washability analysis using the x-ray CT technique. Using the algorithm for the 2-D mass density distribution analysis, the developed integrated software system and a new density calibration procedure, 150 and 124 slices of CT images were analyzed. The results indicate that the specific gravity/yield curves can be constructed using x-ray CT technique with good agreement with the data obtained from sink-float tests. More accurate results are observed compared with the use of coal phantom for density calibration.

Table 1. Summary of the normal function fit for different density classes.

Density (g/cm ³)	Parameters for Fitted Normal Distribution	
	μ	σ
< 1.30	1220	0.08
1.30x1.35	1225	0.10
1.35x1.40	1295	0.20
1.40x1.50	1380	0.25
1.50x1.60	1500	0.40
1.60x1.80	1740	0.40
1.80x2.10	2090	0.40
>2.10	2560	0.50

Table 2. Sink-float analyses for the Stockton coal sample 2 (25.4 x 12.7 mm).

Specific Gravity		Individual Basis			Cumulative Basis		
Sink	Float	Mass (%)	Ash (%)	Unit	Mass(%)	unit	Ash(%)
	1.30	26.40	3.14	82.9	26.40	82.9	3.14
1.30	1.40	21.10	10.10	213.1	47.50	296.0	6.23
1.40	1.50	15.83	23.16	366.6	63.33	662.6	11.46
1.50	1.60	6.59	29.06	191.5	69.92	854.1	12.22
1.60	1.80	1.85	42.32	78.3	71.77	932.5	12.99
1.80	2.10	1.85	59.09	109.3	73.62	1041.7	14.15
2.10		26.38	86.48	2281.3	100.00	3223.1	33.23
		100.00					

Table 3. Sink-float analyses for the Stockton coal sample 3 (50.8 x 25.4 mm).

Specific Gravity		Individual Basis			Cumulative Basis		
Sink	Float	Mass (%)	Ash (%)	Unit	Mass(%)	unit	Ash(%)
	1.30	21.61	2.89	62.4	21.61	62.4	2.89
1.30	1.40	19.46	10.73	208.8	41.07	271.2	6.60
1.40	1.50	17.78	21.55	383.2	58.85	654.4	11.12
1.50	1.60	5.39	28.32	152.6	64.24	807.1	12.56
1.60	1.80	3.23	41.27	133.3	67.47	940.4	13.93
2.10		32.54	84.11	2736.9	100.00	3677.3	36.77
		100.00

Figure 1. (a) A 2-D x-ray CT slice obtained from a packed bed of coal particles. (b) The x-ray attenuation coefficient histogram for the entire sample. (c) A priori identification of the image region: coal (white), air (black), particle surface containing both coal and air (gray) based on the thresholds T0 and T1 shown in (b). (d) An enlarged view of the square region identified in the image presented in (c).

Figure 2. Attenuation coefficient histogram for a coal particle sample (single size/multiple density) showing peaks corresponding to the different density components.

Figure 3. Model fitted normal curve for the attenuation coefficient distribution as obtained for a single-density/single-size sample.

Figure 4. Effect of particle size on model fitted normal curve of attenuation coefficient distribution.

Figure 5. Fitted normal distribution of attenuation coefficients for coal samples of different density classes.

Figure 6. Density calibration curve for x-ray CT based on model fits of the normal distribution for single-size/single-density particles as indicated in Figure 5.

Figure 7. X-ray CT density calibration curve for single-size/single-density coal particles (packed bed) based on filled and partially filled voxels.

Figure 8. Comparison of specific gravity/yield curve for sample 2 as determined by sink-float test with the results from x-ray CT analysis.

Figure 9. Comparison of specific gravity/yield curve for sample 3 as determined by sink-float test with the results from x-ray CT analysis.