

Evaluation of a CT-based coal washability analysis system under simulated on-line conditions

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Abstract

The appropriate software and hardware necessary to adapt an X-ray CT analyzer for the determination of coal washability was developed and successfully tested for well-characterized samples under laboratory conditions. Evaluation of the CT-based analyzer under simulated on-line conditions is also presented to verify the on-line capabilities of the newly developed X-ray CT analyzer for the control of coarse coal cleaning circuits. The investigation shows that the data obtained from CT washability analyses compare favorably with experimental sink-float data. Further, image frequency was considered to evaluate the CT-Based coal washability analyzer for simulated on-line conditions. Specifically, the number of observations (image spacing) needed for accurate sampling and the total time required to perform the calculations for a representative data set were determined.

Key words: Coal washability, Computer simulation, X-ray CT analysis

Introduction

The washability curve is the basic indicator of the coal quality and the amenability of a coal to cleaning. Thus, the washability curve determines whether the coal can be cleaned to meet the necessary product specifications or whether it needs further processing (e.g., size reduction and separation). The washability curve also provides the basis for the evaluation of the organic efficiency for a given separation process.

Washability curves are constructed by a tedious and slow method called sink-float analysis. The principle behind this analytical technique (sink-float) is nothing more than density fractionation. By its very nature and the way it is conducted, sink-float results cannot be obtained in a reasonable amount of time to provide a satisfactory feedback mechanism for control of various unit operations in a coal preparation plant.

On the other hand, the scanned sections produced by X-ray CT are maps of the density variation in the scanned volume, which can be determined in a matter of minutes. Reconstruction of the three-dimensional particle population from the scanned sections should provide sufficient information not only to construct the washability curve for the coal sample in question but also to provide information on the particle size and grain size distribution of mineral-matter grains present in each coal particle.

CT-based coal washability analysis. For quantitative analysis of particulate systems, such as coal washability analysis, a

previous study by the authors (Lin et al., 2000) indicated that X-ray CT can provide sufficient information to construct the washability curve within minutes of sample collection. A systematic procedure for the determination of coal particle density using X-ray CT was developed in this preliminary investigation. In addition, with the use of an appropriate algorithm, the construction of coal washability curves using X-ray CT analysis was successfully demonstrated by these researchers. Figure 1 shows the schematic diagram for the measurements necessary to construct a CT-based coal washability curve.

In this paper, the capabilities of the CT-based coal washability analyzer are evaluated under simulated on-line conditions by examining actual plant samples that were subjected to traditional washability (sink-float) analysis. Comparison of the data indicates that the CT analyzer offers an attractive approach for the on-line evaluation and control of coarse coal cleaning circuits.

Evaluation of CT-based coal washability analyzer under simulated on-line conditions

X-ray CT equipment and software development. The Philips Tomoscan 60/TX CT scanner (Fig. 2), located at Terra Tek Inc., was used for this study. Plastic containers were used for sample chambers. The scanner produces images that are two-dimensional slices of the coal particle bed. For quantitative analysis of the mass density distributions from these tomo-

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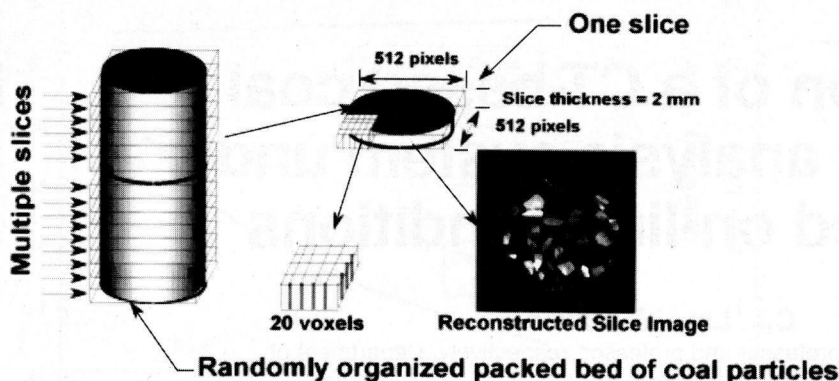


Figure 1 — Diagram of sequential X-ray CT scans of a coal sample for coal washability analysis.



Figure 2 — The Philips Tomoscan 60/TX CT scanner used for coal washability analysis.

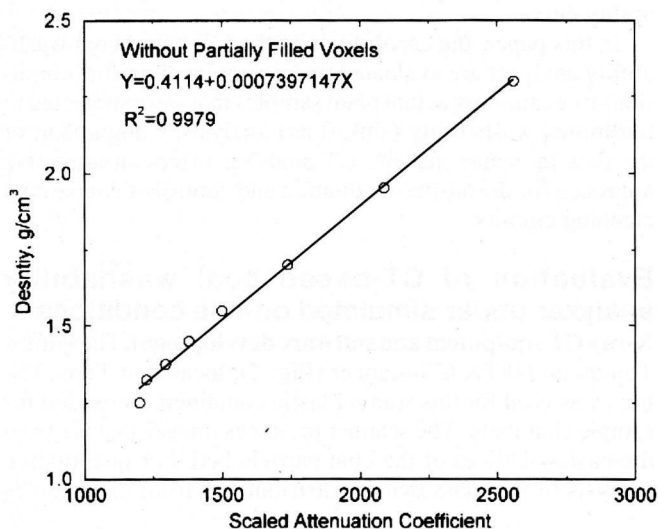


Figure 3 — Density calibration curve for X-ray CT analysis based on model fits of the normal distribution for single-size/single-density particles.

graphic images, a finite-mixture model (Titterton et al., 1985) 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 curves 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. Based on the fitted normal distribution, as indicated in the previous study, density calibration can be done considering only completely filled voxels and the actual density determined from sink-float tests. Figure 3 presents a plot of the attenuation coefficient vs. density.

Plant sample acquisition. Evaluation of the CT-based coal washability analyzer under simulated on-line conditions for the control of coarse-coal cleaning circuits started in mid-February 2000 and continued through mid-July 2000. It was decided to collect composite samples on a weekly basis. The samples were obtained from the Powellton/Cedar Grove seam and were provided by an industrial mining operation in Boone County, West Virginia. Each sample consisted of about 50 kg (110 lb) of 31.8 x 6.4-mm (1.25 x 0.25-in.) coal particles. After collection, the samples were divided into two representative splits. The first split was provided to Virginia Polytechnic Institute and State University, Blacksburg, Virginia, for analysis via traditional sink-float tests using heavy liquids. Four density fractions (i.e., 1.3, 1.5, 1.7 and 2.0 SG) were used for sink-float analysis. The other portion of the sample was shipped to the University of Utah, Salt Lake City, Utah, for comparative analysis using the X-ray CT technique.

For CT analysis, two cylindrical sample containers were used for each coal sample, 23 to 27 kg (50 to 60 lb). The size of the sample container was about 184 mm in diameter and 600 mm in length (Fig. 4). The wall of the sample container was a lightweight, nonmetallic material (0.1-mm plastic).

On-line considerations for particle segmentation, classification and mass density analysis. For the practical situation, based on image segmentation, usually only one threshold value between the air and the coal phase is set to facilitate the particle segmentation. For coal particles with a higher density, the attenuation coefficient of the partially filled surface voxels is considered as the coal phase, because the attenuation coefficient has a higher value than the threshold setting. To accurately estimate the density class of a particular coal particle, consideration of the partially filled voxels for density calibration is necessary. In this regard, a calibration methodology was developed to correct the partially filled surface voxels for accurate estimation of washability curve.

Consider a polydispersed system of irregular coal particles intersected by a plane (as from a X-ray CT scanner) with a width of about 2-mm, as shown in Fig. 5. The particle-edge effect, which generates the partially filled surface voxels, is evident. A successive subtraction process (Dehoff and Rhines, 1968) can be applied to develop the coefficients required for the calibration of various densities. The successive subtraction process is as follows. When the number of sections (or voxels) of the same density is counted, allowance must be made for the fact that some of the sections (or voxels) will be



Figure 4 — Cylindrical sample container filled with coal particles for CT analysis.

derived from partially filled surface voxels of a coal particle of higher density. The number of these latter sections (or voxels) must be subtracted from the total number to obtain those sections (or voxels) due only to coal particle of that density range. Figure 6 shows the problem involved here. The sections from particles (voxel form) in the vertical columns have the same density class (measured voxel density ρ_{s1} to ρ_{s5}), whereas the particle densities vary systematically between ρ_1 and ρ_5 . The total number of voxels of one density class, for example, the lowest density class, can be expressed as

$$N_v(1) = N_v(1,1) + N_v(1,2) + N_v(1,3) + N_v(1,4) + N_v(1,5) \quad (1)$$

This equation simply states that the total number of voxels of density ρ_{s1} consists of the sum of the separate contributions of this voxel density from coal particles of the same density and all partially filled surface voxels of coal particles with higher density. It is noted that $N_v(i)$ is the measured quantity. Similar equations can be written for other density classes.

For X-ray CT-based coal washability analysis, it is desired to calculate the number of coal particles of density $\rho_5, \rho_4, \rho_3, \rho_2, \rho_1$, etc. To do so, the number of CT sliced sections of density $\rho_{s5}, \rho_{s4}, \rho_{s3}, \rho_{s2}, \rho_{s1}$, etc., that arise only from the particle with higher density must be known. Nine gravity (density) classes were used in the X-ray CT washability tests: < 1.3 ; 1.3×1.4 ; 1.4×1.5 ; 1.5×1.6 ; 1.6×1.7 ; 1.7×1.8 ; 1.8×1.9 ; 1.9×2.0 ; and > 2.0 . From the above discussion, the corresponding symbols for each density class are: $\rho_{s1}, \rho_{s2}, \dots, \rho_{s9}$, respectively. The overall relationship between the known quantity (from sink-float test), $N_v(i)$, and the measured quantity (from CT analysis), $N_v(i,i)$, becomes

$$\begin{bmatrix} N_v(1) \\ N_v(2) \\ N_v(3) \\ N_v(4) \\ N_v(5) \\ N_v(6) \\ N_v(7) \\ N_v(8) \\ N_v(9) \end{bmatrix} = \begin{bmatrix} 1 & a_{1,2} & a_{1,3} & a_{1,4} & a_{1,5} & a_{1,6} & a_{1,7} & a_{1,8} & a_{1,9} \\ & 1 & a_{2,3} & a_{2,4} & a_{2,5} & a_{2,6} & a_{2,7} & a_{2,8} & a_{2,9} \\ & & 1 & a_{3,4} & a_{3,5} & a_{3,6} & a_{3,7} & a_{3,8} & a_{3,9} \\ & & & 1 & a_{4,5} & a_{4,6} & a_{4,7} & a_{4,8} & a_{4,9} \\ & & & & 1 & a_{5,6} & a_{5,7} & a_{5,8} & a_{5,9} \\ & & & & & 1 & a_{6,7} & a_{6,8} & a_{6,9} \\ & & & & & & 1 & a_{7,8} & a_{7,9} \\ & & & & & & & 1 & a_{8,9} \\ & & & & & & & & 1 \end{bmatrix} \times \begin{bmatrix} N_v(1,1) \\ N_v(2,2) \\ N_v(3,3) \\ N_v(4,4) \\ N_v(5,5) \\ N_v(6,6) \\ N_v(7,7) \\ N_v(8,8) \\ N_v(9,9) \end{bmatrix} \quad (2)$$

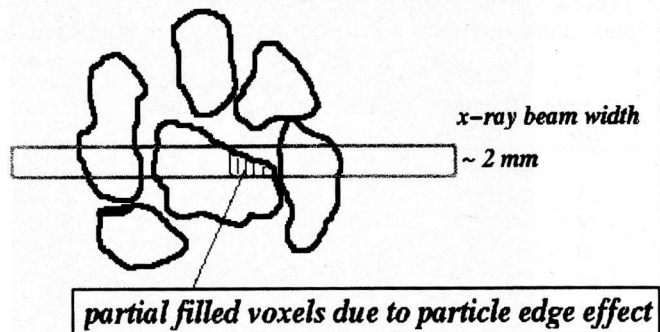


Figure 5 — Intersection of polydispersed irregularly coal particles by X-ray sliced plane with a width of about 2 mm.

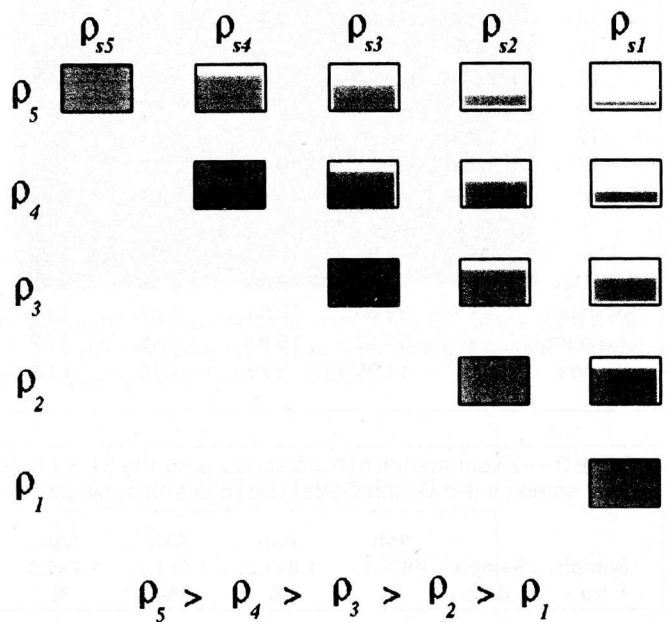


Figure 6 — Schematic illustration of the contribution of voxels with density r_1 to r_5 (horizontal row as true density) to the total number of sections with density of r_{s1} to r_{s5} (vertical column as measured density).

From Eqs. (1) and (2), it is evident that

$$N_v(1,2) = a_{1,2} \times N_v(2,2), \text{ etc.} \quad (3)$$

where

$N_v(i,j)$ is the number of voxels of density ρ_{si} obtained from particles of density ρ_j and

$a_{i,j}$ is the probability of the partially filled surface voxels of particles with density ρ_j so as to yield voxels of density ρ_{si} .

For irregularly shaped coal particles, it will be extremely difficult to derive an analytical form for $a_{i,j}$. An approximate value of $a_{i,j}$ can be determined statistically from $N_v(i,i)$ (sink-float test results) and $N_v(i)$ (CT analysis). Because nine gravity (density) classes were used for washability analysis, the mean densities of each class can be set as 1.25, 1.35, 1.45, ..., 1.95 and 2.05, respectively. The number frequency distribution, $N_v(i)$, from sink-float test (density distribution by weight) can be determined. It is reasonable to assume that $a_{8,9} = a_{7,8} = a_{5,6}$

Table 1 — Experimental mass distributions for the 31.8 x 6.3-mm (1.25 x 0.25-in.) plant samples (Powellton/Cedar Grove seam) subjected to sink-float tests.

Sample No.	Sample date	Mass Flt 1.3, %	Mass 1.3x1.5, %	Mass 1.5x1.7, %	Mass 1.7x2.0, %	Mass Snk 2.0, %	Mass feed, %
1	2/19/00	39.84	14.06	1.96	2.40	41.74	100.00
2	2/26/00	42.93	13.18	2.19	1.80	39.90	100.00
3	3/4/00	41.11	16.25	2.66	3.27	36.71	100.00
4	3/11/00	45.63	15.97	3.09	2.31	33.00	100.00
5	3/18/00	45.91	14.96	2.42	1.86	34.85	100.00
6	3/25/00	54.52	12.28	2.37	2.48	28.35	100.00
7	4/1/00	42.88	18.83	2.70	2.06	33.53	100.00
8	4/8/00	47.44	13.19	2.27	3.18	33.92	100.00
9	4/15/00	48.49	10.04	3.45	2.62	35.40	100.00
10	4/22/00	44.26	12.08	1.67	2.37	39.62	100.00
11	4/29/00	42.71	13.95	1.69	2.46	39.19	100.00
12	5/13/00	46.08	10.44	1.75	1.88	39.85	100.00
13	5/20/00	45.80	11.64	2.01	2.51	38.04	100.00
14	5/27/00	49.46	12.92	2.75	1.65	33.22	100.00
15	6/3/00	47.37	12.54	2.60	2.26	35.23	100.00
16	6/10/00	42.93	16.70	2.51	2.79	35.07	100.00
17	6/17/00	39.66	16.15	2.59	2.31	39.29	100.00
18	6/24/00	41.76	15.40	2.64	2.89	37.31	100.00
Mean	—	44.93	13.92	2.41	2.39	36.35	100.00
Std. Dev.	—	3.73	2.33	0.48	0.45	3.34	0.00
Minimum	—	39.66	10.04	1.67	1.65	28.35	100.00
Maximum	—	54.52	18.83	3.45	3.27	41.74	100.00
Range	—	14.86	8.79	1.78	1.62	13.39	0.00

Table 2 — Experimental ash distributions for the 31.8 x 6.3-mm (1.25 x 0.25-in.) plant samples (Powellton/Cedar Grove seam) subjected to sink-float tests.

Sample No.	Sample date	Ash Flt 1.3, %	Ash 1.3x1.5, %	Ash 1.5x1.7, %	Ash 1.7x2.0, %	Ash Snk 2.0, %	Ash feed, %
1	2/19/00	3.44	11.43	35.20	50.78	87.30	41.33
2	2/26/00	3.93	11.92	29.67	50.26	90.14	40.78
3	3/4/00	3.62	9.52	31.20	44.58	89.95	38.34
4	3/11/00	3.49	11.18	27.97	55.10	88.41	34.69
5	3/18/00	3.56	11.09	31.81	45.42	88.43	35.73
6	3/25/00	3.97	10.72	29.52	48.96	87.09	30.08
7	4/1/00	3.36	10.24	37.43	58.49	89.10	35.46
8	4/8/00	4.05	11.08	31.54	47.07	88.68	35.68
9	4/15/00	4.68	13.09	24.40	44.17	89.55	37.28
10	4/22/00	3.38	12.47	38.00	57.04	90.51	40.85
11	4/29/00	3.43	10.58	33.87	55.43	89.94	40.12
12	5/13/00	3.60	12.04	32.68	56.87	89.19	40.10
13	5/20/00	3.29	11.11	34.39	57.40	88.27	38.51
14	5/27/00	3.28	11.64	29.32	53.37	85.87	33.34
15	6/3/00	3.43	12.16	36.31	50.78	89.67	36.83
16	6/10/00	3.59	10.38	33.92	53.61	90.83	37.48
17	6/17/00	3.22	10.09	35.54	55.07	90.76	40.76
18	6/24/00	3.61	11.94	39.63	52.37	91.59	40.08
Mean	—	3.61	11.26	32.91	52.04	89.18	37.64
Std. Dev.	—	0.36	0.92	3.89	4.57	1.46	3.07
Minimum	—	3.22	9.52	24.40	44.17	85.87	30.08
Maximum	—	4.68	13.09	39.63	58.49	91.59	41.33
Range	—	1.46	3.57	15.23	14.32	5.72	11.24

$= \dots = a_{1,2}$ and $a_{7,9} = a_{6,8} = a_{8,9} = \dots = a_{1,3}$, etc. From the highest density class, $i=9$, $a_{9,9}$ can be calculated based on the known value of $N_v(9,9)$ and $N_v(9)$ and $a_{8,9}$ is simply determined by subtraction between known values of $N_v(i,i)$ and $N_v(i)$. This subtraction process is continued down to the lowest density class. It can be seen that each subtracted term depends on the previously calculated values of $N_v(i,i)$ and $N_v(i)$. In this manner, a kernel matrix \underline{a} can be determined. Once \underline{a} is known, the X-ray CT data for a packed bed of coal particles can be used to estimate the sink-float test results.

Based on this correction procedure for partially filled surface voxels, the washability curve can be established with the use of the scaled attenuation coefficient histogram and density calibration curve (Fig. 3). Because most of the image-processing routines for particle separation and classification are eliminated using this approach, a significant reduction in processing time is achieved. For example, to process 100 CT images, the time required for typical image-processing routines for particle separation will be about 2,500 seconds (~25 seconds per image), compared to a total time of 30 seconds with this new approach.

Simulated on-line tests. An overview of the sink-float data collected during the period between February and June, 2000 is provided in Tables 1 and 2. A total of 18 samples were evaluated from the Powellton/Cedar Grove seam. The samples were provided by an industrial mining operation in Boone County, West Virginia.

Figure 7 shows six sequential cross-sections, X-ray CT scans (5-mm/slice), of a sample taken from the Powellton/Cedar Grove seam Feb. 19, 2000. Based on the scaled attenuation coefficient histograms of the two-dimensional X-ray CT images (slices) for these coal samples, the density/yield curves for these samples were constructed as shown in Figs. 8(a), 8(b) and 8(c). The density/yield curves for these samples using sink-float tests (Table 1) are included for comparison. As shown, the results indicate that the density/yield curves constructed using X-ray CT technique are in good agreement with the data obtained from independent sink-float tests.

As mentioned above, for washability analysis using X-ray CT, two cylindrical sample containers were used for each coal sample to evaluate the effect

of sample weight required for analysis. Washability measurements were made for each container separately for image distances of 5-mm/slice. Figure 9 illustrates the constructed density/yield curves for both containers. As expected, a large variation (about 5%) is observed for an insufficient amount of sample (~12 kg).

Image frequency must be considered to evaluate the CT-based coal washability analyzer under the dynamic case (on-line condition). At what rate should CT slices be taken? What is the appropriate number of CT slices per unit of length? In this regard, image frequency, the number of CT slices needed to represent the entire coal-particle population, was analyzed in detail. In this regard, two samples, 25.4 x 12.7 mm and 50.8 x 25.4 mm, were prepared for washability analysis by X-ray CT. Two sets of sequential cross-sectional images (150 and 124 slices) were collected. In these experiments, each two-dimensional CT slice was 2 mm in thickness. In this way, the total coal-particle population is scanned. CT washability measurements were made for image sample spacing of 4, 6, 8, 10, 20 and 30 mm for the total coal-particle population. Thus, of the total 150 slices for the 50- x 25-mm (2- x 1-in.) sample, an image sample spacing of 6 mm means that one out of every three images is analyzed.

Based on the above procedure, it is reasonable to use both the sink-float washability data and

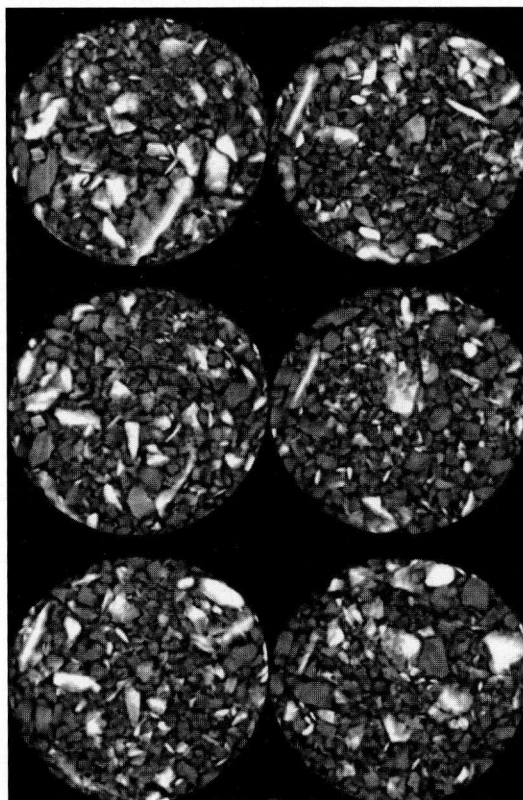


Figure 7 — Sequential cross sections from X-ray CT scans for a 31.8- x 6.3-mm (1.25 x 0.25 in.) coal sample at 5-mm/slice (Powellton/Cedar Grove seam, sampling date: Feb. 19, 2000).

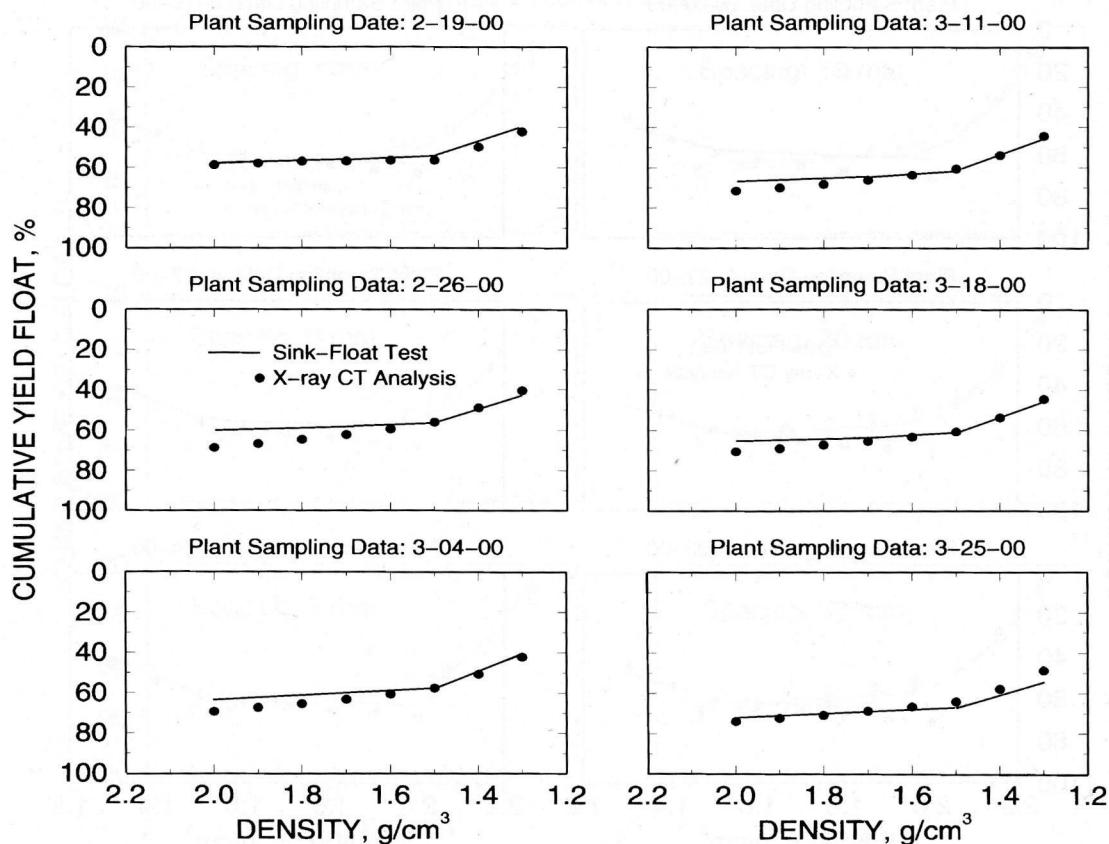


Figure 8(a) — Comparisons of density/yield curves for coal samples (sampling data between 2/19 and 3/25) as determined by sink-float test with the results from X-ray CT analysis (31.8- x 6.3-mm, ~24-kg sample weight).

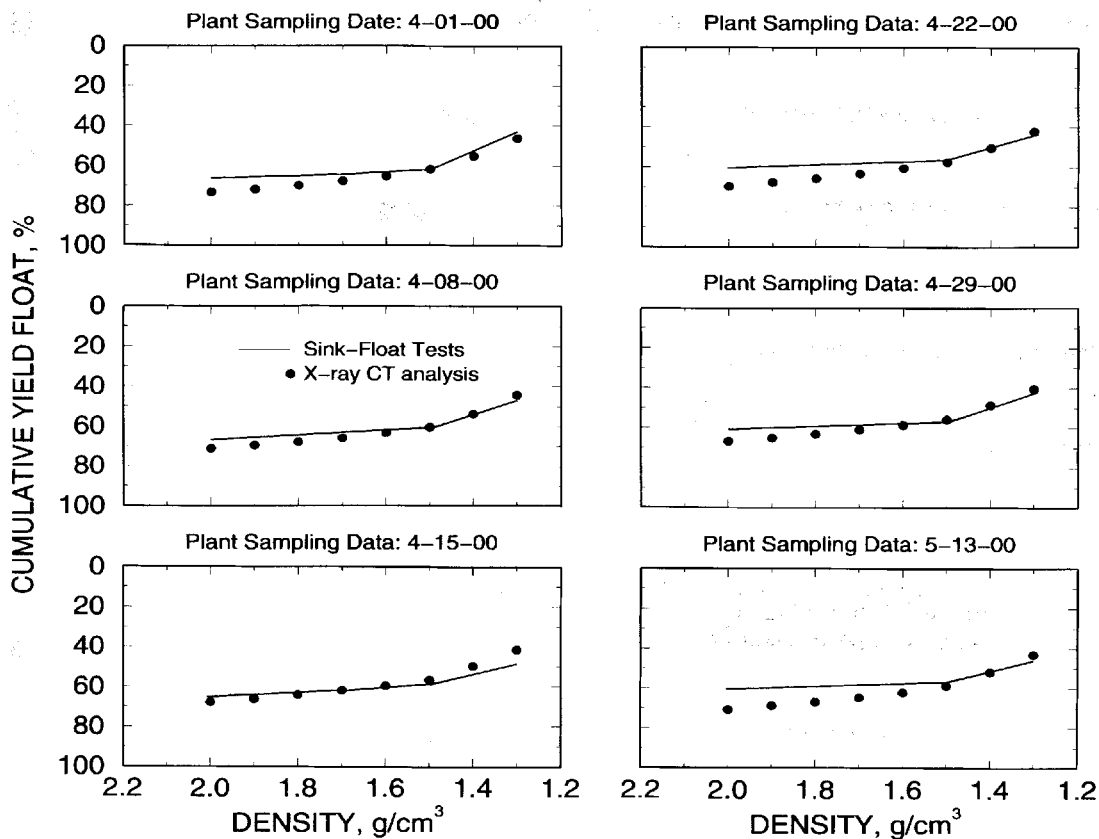


Figure 8(b) — Comparisons of density/yield curves for coal samples (sampling data between 4/01 and 5/13) as determined by sink-float test with the results from X-ray CT analysis (31.8- x 6.3-mm, ~24-kg sample weight).

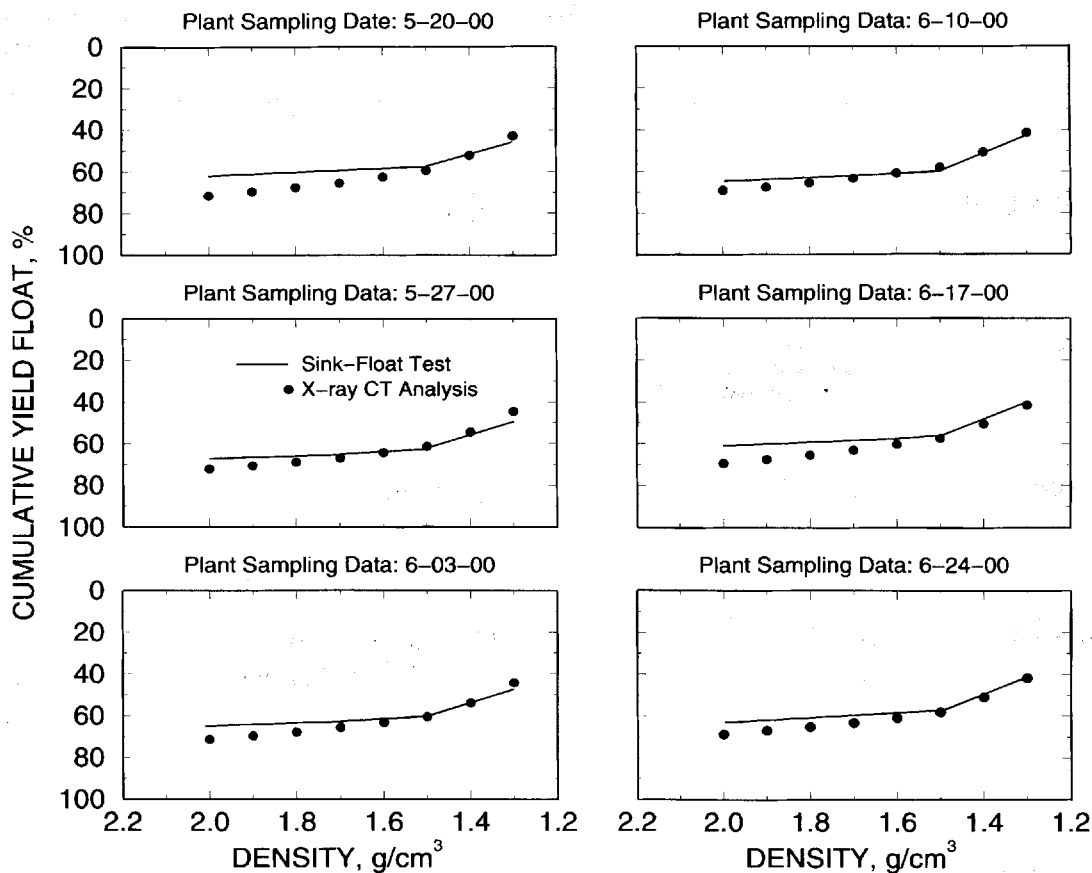


Figure 8(c) — Comparisons of density/yield curves for coal samples (sampling data between 5/20 and 6/24) as determined by sink-float test with the results from X-ray CT analysis (31.8- x 6.3-mm, ~24 kg sample weight).

the CT measurement of the total population (image spacing of 2 mm), as references to evaluate the number of scans required for analysis. Based on the two-dimensional CT images (slices) of these coal particle beds, Figs. 10 and 11 illustrate the constructed density/yield curves for different image spacing for both the 25.4 x 12.7-mm and 50.8 x 25.4-mm samples, respectively. Clearly, the deviations for an image sample spacing of less than 10 mm are not large, but larger variations for 20- and 30-mm spacings are observed as shown in Figs. 10 and 11.

Figure 12 illustrates the constructed density/yield curves for image spacing of 10 mm for one of the samples to simulate on-line tests. Clearly, the deviations for an image distance of 10-mm/slice are not large compared with the effect of sample weight as shown in Fig. 10.

Summary and conclusions

A methodology based on the finite mixture model and an appropriate successive subtraction technique is discussed for development of the X-ray CT-based coal washability analyzer. In summary, full attenuation coefficient histograms of the coal sample from X-ray CT analysis are used to calibrate the density scale and to obtain the mass density distribution for the coal sample.

Performance of the on-line washability analyzer has been evaluated and plant data were collected to assess the accuracy of the unit for washability analysis. Composite samples were collected on a weekly basis starting mid February 2000 and running through mid July 2000. Plant site samples were prepared to evaluate the washability analysis using the X-ray

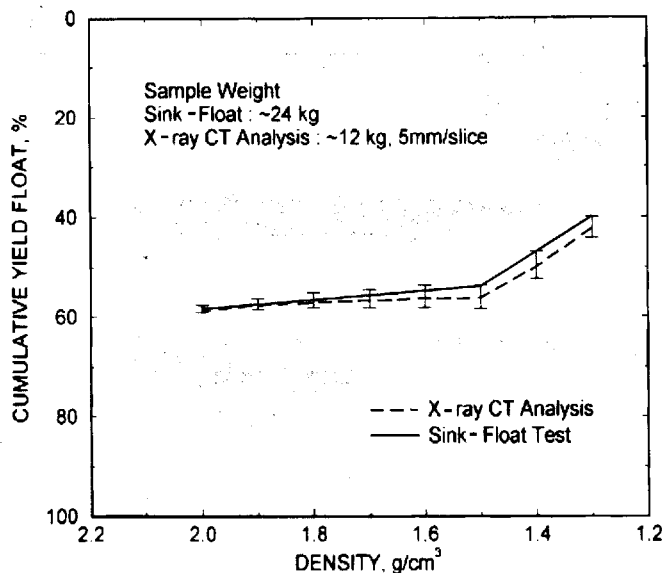


Figure 9 — Effect of sample weight (~12 kg) on density/yield curves for coal sample (2-19-00). Sink-float result (solid line) is included for comparison.

CT technique. Using the newly developed methodology for the mass density distribution analysis, scaled attenuation coefficient histograms of the two-dimensional CT images of these samples were analyzed. The results indicate that density/yield curves can be constructed using the X-ray

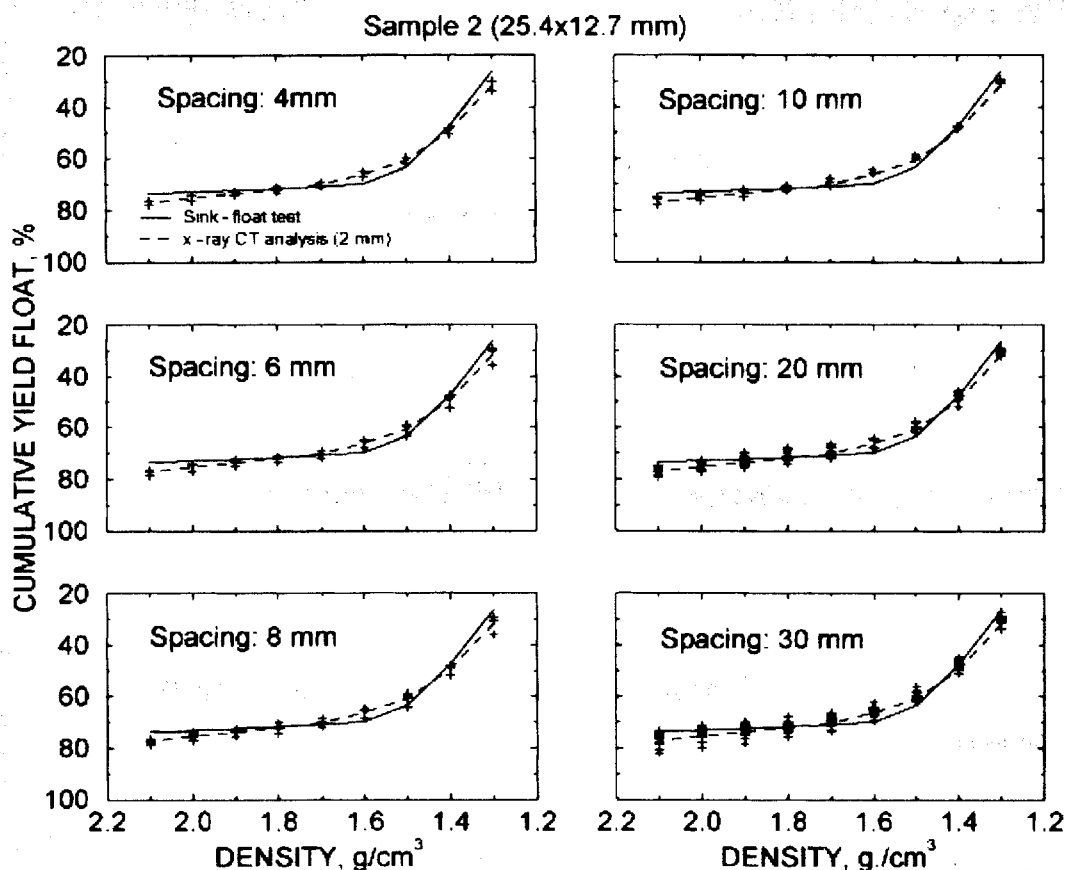


Figure 10 — Comparisons of density/yield curves for Sample 2 (25.4 x 12.7 mm) for different image spacings. Sink-float results (solid line) and complete CT measurements at 2 mm (dash line) are included for comparison.

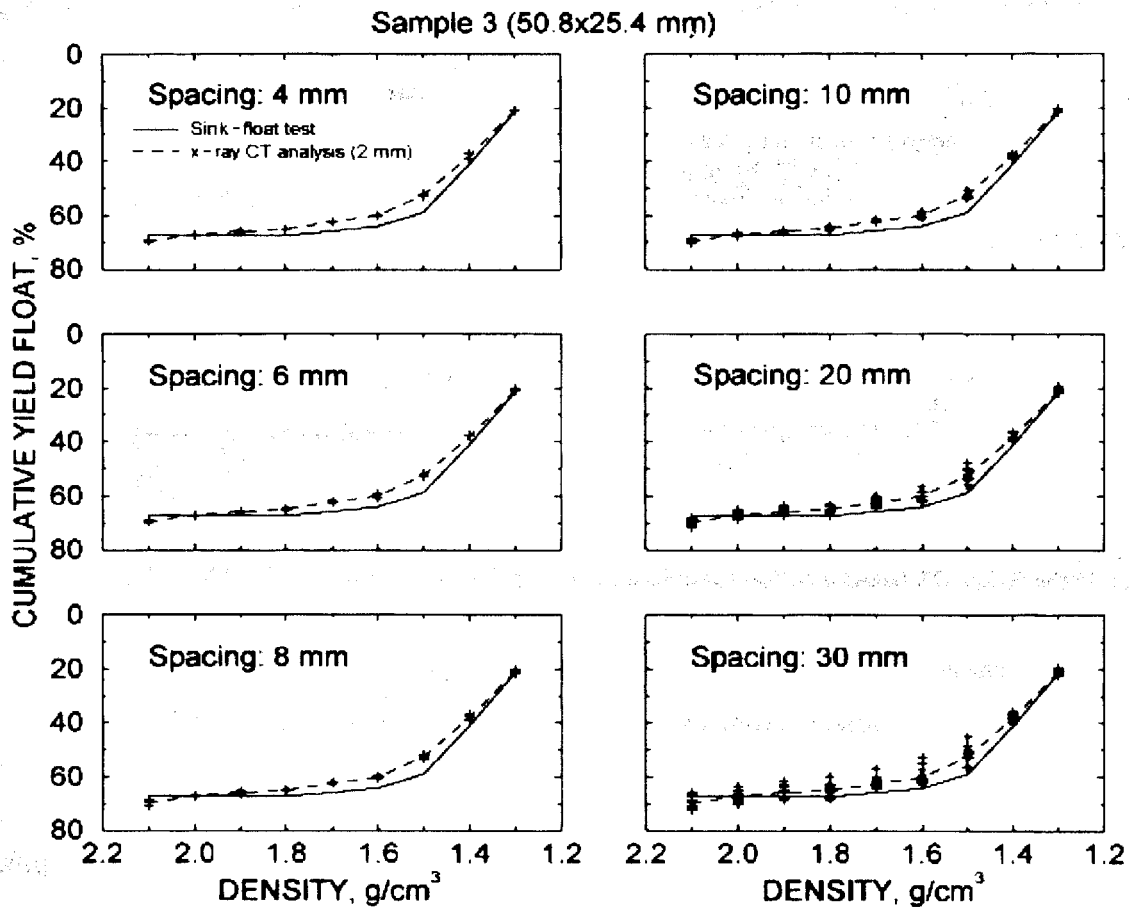


Figure 11 — Comparisons of density/yield curves for sample 3 (50.8 x 25.4 mm) for different image spacings. Sink-float results (solid line) and complete CT measurements at 2 mm (dash line) are included for comparison.

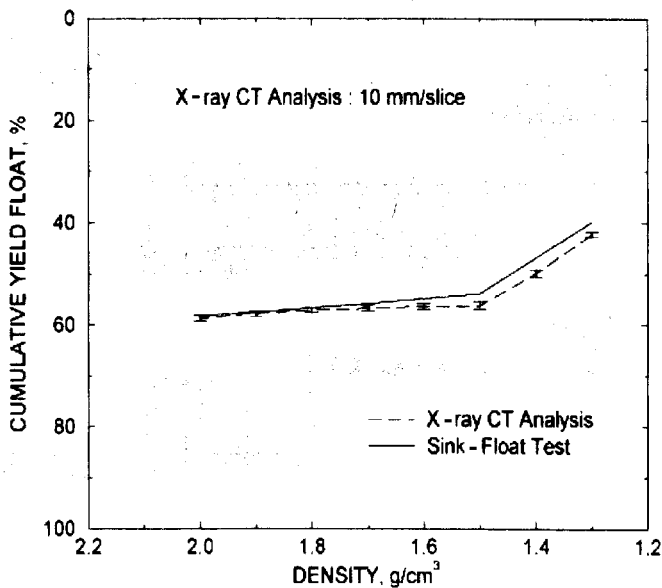


Figure 12 — Effect of image spacing at 10 mm on density/yield curves for coal sample (2-19-00). Sink-float result (solid line) is included for comparison (~24-kg sample weight).

technique and that these results are in good agreement (within 5% to 10%) with the data obtained from independent sink-float tests.

Further, image frequency was considered to evaluate the CT-Based coal washability analyzer for on-line conditions. Specifically the number of observations (image spacing) needed for accurate sampling was determined, and the time necessary for the washability analysis was found to be 15 min. On this basis, it appears that on-line coal washability should be possible using X-ray CT methodology.

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