Washability Monitor for Coal Utilizing Optical and X-Ray Analysis Techniques

Helge B. Wurst, Jan F. Bachmann, Claus C. Bachmann, Michael P. Cipold

presented by
Jan F. Bachmann
at the
17th International Coal Preparation Conference
1.-6. October 2013
Istanbul, Turkey
Washability Monitor for Coal Utilizing Optical and X-Ray Analysis Techniques

Helge B. Wurst (1), Jan F. Bachmann (2), Claus C. Bachmann(3), Michael P. Cipold (4)

(1) hwu@jcbachmann.com, J&C Bachmann GmbH, Bad Wildbad, Germany
(2) jba@jcbachmann.com, J&C Bachmann GmbH, Bad Wildbad, Germany
(3) cba@jcbachmann.com, J&C Bachmann GmbH, Bad Wildbad, Germany
(4) mci@jcbachmann.com, J&C Bachmann GmbH, Bad Wildbad, Germany

ABSTRACT

In coal washability, the objective is to establish the set of maximum possible separation performance criteria for a given coal feed. The method of choice for this has been the conventional sink-float analysis. Time, cost and safety aspects of the sink-float method have prompted the search for a new approach for establishing separation performance criteria, especially as performance levels of separator plants can be maximized if reliable information based on an analysis of washability in conjunction with particle size distribution, ash and elemental constituency becomes readily available.

The new method to establish washability and associated performance information utilizes at least two measurement technologies concurrently: x-ray transmission, image processing, and, optionally, XRF elemental analysis of each coal particle. The value of the collected data increases considerably if the washability data were additionally available in time to be considered in the control of the process plant. The incorporation of an automated washability monitor gives near real-time data that would impinge positively on the profitability of the plant operation. Tests performed with the prototype utilizing optical and X-ray analysis methods are encouraging.

KEY WORDS: WASHABILITY, DENSITY, COAL, IRON ORE, OREGON, RACCOON

1. WASHABILITY

Washability of coal or minerals is expressed by a curve or graph showing the results of a series of float-and-sink tests. Several of these curves are drawn to illustrate different conditions or variables, usually on the same axes, thus presenting the information on one sheet of paper. Washability curves are essential when designing and operating coal or mineral preparation plants.

There are four main types of washability curves: characteristic ash curve, cumulative float curve, cumulative sink curve, and densimetric or specific gravity curve [1]. The different curves are based on the relation between ash and ore grade respectively, mineral density and particle size distribution.

In determining the washability analysis, particle density is the underlying feature of all washability curves. Conventionally, the particles are separated into density fractions by immersing them in fluids of a predetermined density followed by skimming of those particles that stay afloat. The particles remaining afloat thus have a density lower than that of the fluid they were subjected to. The particles that remained at the bottom of the fluid container thus had a higher density higher than that of the fluid. By progressively increasing, for example, the density of the fluid and immersing the remaining particles so as to be able to skim the next density fraction, the particles would be fractionated into density groups. The liquids used range from aqueous solutions to organic liquids to suspensions. Unfortunately the liquids used for this separation process are often toxic and expensive. It stands to reason that a new method of determining washability is sought.

In addition to density, particle size distribution is also of importance to the topic of washability. Typically, the particle size distribution is based on sieve analyses. This technique is well introduced and proven in the laboratory. However, the size of a particle is not fully described by the mesh size of a sieve:

- sieve meshes may have different shapes (circular, hexagonal, square)
- regular particles cannot be approximated by cuboid or ellipsoidal shapes
- long but small particles may pass small meshes.

Using a model which describes the particle size by three measures (length · width · height) it can be stated that the sieve analysis characterizes the particle size by the second largest (equal to the second largest) of these measures (elongated particles can pass lengthwise so only the particle cross section bounding is critical). Although this method is a viable way for sieve analysis in the laboratory it may be logical to consider the particle volume instead of the sieve size as the best characteristic feature to describe the size distribution.
Given the issue with separation liquids used in conventional float and sink analysis as well as the need for a better volume determination of particles, this paper introduces a new method to determine washability curves suitable for continuous measurement routine that also avoids the disadvantages of the conventional float-and-sink and sieve method.

The development of a washability monitor for coal particles has to determine at least some of the following characteristics of the coal to be measured:

* washability curves
* particle size distribution
* elemental constituency
* ash content

For the development of such an analyzer to be of interest to the coal preparation industry the monitor must have certain advantages:

* It must be relatively fast, reducing the usual manual effort from weeks to hours
* It must be reliable, working with minimal intervention of personnel
* It must work in an on-line fashion, and should demonstrate a high degree of mechanical integration into the process path at the point of measurement.

In order to achieve these goals the developed washability monitor combines optical with radiometric measurement and derives all requested parameters in a nearly real-time analysis.

2. TECHNICAL REALISATION

The washability monitor OREGON is designed for use in the laboratory and was developed by J&C Bachmann. A small conveyor belt feeds the sample through an optical and a radiometric measuring path. The sample is fed by a vibration feeder which ensures that the particles form a single layer and do not touch each other. The optical measurement determines the particle’s volume while the X-ray tube powered radiometric transmission measurement determines the mass per area of each single particle.

The first prototype was especially designed for washability analysis of iron ore and was commissioned in summer 2010. After extensive testing it is now under continuous operation (24/7).

Experience gathered with the prototype resulted in numerous improvements which were realized in the following devices.

2.1 Volume Determination

Optical distance measurement in the range of 10 – 100 cm is mostly done using lasers. This technique is available for more than ten years and is widely accepted. The basic principle can be seen in figure 1. A laser projects a well focused dot onto a surface. The laser image is then projected by using a lens onto a detector which can be a CCD line or a position sensing device to measure the distance through the lens. The lens which “sees” the dot needs to be mounted at an angle to the surface where the laser dot is projected. The position of the projected laser dot on the detector depends on the distance of the detected object to the detector and on the distance between laser and sensor.

Using the one-dimensional approach will give only very little information about each particle on a conveyor belt. In the best case we will get the length and a height profile at one single line of the particle. In the worst case a particle will not be seen at all because it is not exactly centered. If the particle is scanned a second time and the orientation does not match the previous one exactly, the measurement will show a totally different result.

![Figure 1: Principle of laser triangulation](image1)

![Figure 2: 3D display of scanned particles](image2)
recorded from a moving particle it is easy to sum up the volume of each particle. Using a standard camera module is an economic and easy way to realize the measurement.

In order to be able to maximize the amount of particles which are scanned correctly and to see the back sides of each particle a second camera is mounted in a mirrored position with the laser in between. The data of the two cameras is then correlated and combined as shown in figure 4. The upper third of the image shows the particle heights as seen by the first camera and the middle third as seen by the second camera. The lower third shows the correlated data without the errors of a single camera acquisition.

### 2.2 Weight and Density Determination

The fundamental principles of the application of x-rays for the determination of densities of materials are described by Zou et al. (2008). It is stated that x-rays have the ability to penetrate matter and interact with atomic species. The material under investigation is irradiated with x-rays of known incident energy and the attenuation is accounted for by coherent scattering, incoherent scattering and absorption. The absorption law as given in equation 1 gives the relationship between degree of x-ray transmission and the material density and thickness.

\[
I = I_0 e^{-\mu \rho d}
\]

Where

- \( I_0 \) = incident radiation
- \( I \) = transmitted radiation
- \( d \) = absorption path length
- \( \mu \) = absorption coefficient
- \( \rho \) = product density

Knowing the incident radiation and the constant absorption coefficient in the material and measuring the transmitted radiation using a x-ray line detector the weight per area \((\rho \cdot d)\) can be derived. By measuring the solid absorption path length (see optical measurement) the density is directly found by dividing the weight per area by the amount of material.

### 2.3 Mechanical Setup

The mechanical setup consists of the described optical and radiometric measuring tracks installed on a conveyor belt and a control box which contains the PLC to control the hardware and the computer to do the data analysis. The schematic setup can be seen in figure 5. The two measuring tracks can be combined to be installed at the same part of the belt which was not done in this graph to make it easy to see all components.
After being fed onto the belt by a vibrating feeder the coal particles move through the measuring tracks which are covered in the housing for optimal x-ray shielding.

As particles move through the x-ray beam, their “shadow” is recorded by the x-ray line sensor which is mounted below the belt.

Figure 6: Robotic arm for particle sorting

The calculations are performed on-the-fly so the particles can optionally be sorted directly behind the X-ray measurement by using a robotic arm which can be installed optionally.

Sorting parameters are flexible. They can be changed quickly between measurements and enable samples to be sorted by constant and variable bin widths or to collect same amounts of material per bin if required.

2.4 Determination of Washability

The software suite RACCOON running on the computer in the control box records the height lines from the optical measurement and the so called weight lines from the radiometric measurement. Subsequently, the lines are combined to an area image and single particles can be identified through segmentation. These particle data readily deliver the volume of each particle. Width, height and length and also the particle weight can easily be derived. Once particle weight and volume are established the particle density can be calculated.

A typically large set of individual particle parameters is the basis for density, mass and volume distributions such as the washability curves.

3. RESULTS AND DISCUSSION

The following section shows some results of the device gathered during intensive tests with coal samples from West Virginia in the laboratory.

Each particle is scanned and shown in the software overview. All parameters for each particle can be inspected in detail by hovering the cursor on the particle as shown in figure 7. This particle shows an optically a uniform shape.

Figure 7: Analyzed coal particle with calculated parameters

Figure 8 shows the corresponding X-ray image of the same particle which illustrates the weight per area (originally in false colors). The grayscale image impressively visualizes the layered structure of this specimen where light gray areas correspond to lower area mass and darker shades of gray correspond to higher area mass respectively.

Looking at the smooth surface obtained optically in figure 7 it is evident that the spatially resolved density will have the same structure as the x-ray image.
3.1 Measurement Stability and Dynamic Range
An important criterion for an automated device is the dynamic range of the measurement.

The analyzer was consecutively fed samples of different densities. This was done with coal and iron ore samples in order to test the dynamic range of the instrument. The difference between shelf and iron ore density is much higher than the difference between coal and sandstone density. Therefore the linearity of the measurement can be evaluated over a wide density range using iron ore.

![Graph](image)

Figure 9: Practical example of two data sets produced by measuring high grade coal (#2 - black crosses) and an ore sample (#1 - gray circles). Broadening of the distribution reflects the quality of the sample preparation and is not caused by systematic errors during the OREGON analysis.

![Graph](image)

Figure 10: Enlarged area of Fig. 9 showing data sets of two distinct samples as point clouds. A set of density iso lines is shown as a density minor grid. In the double logarithmic representation slopes of lines going through the origin translate into offsets between parallel lines.

Figure 9 shows the mass vs. volume scatter diagram for two samples of distinct densities while figure 10 shows a zoom of the selected area of figure 9 to further highlight the internal structures of the distributions and to motivate and explain the type of graph that was chosen. Each particle is represented by a point in the diagram.

Tilted lines in figure 10 define regions of constant density (implicitly there is an underlying linear density gradient in a direction orthogonal to these lines. The logarithmic diagrams show that the immediate measured values have a linear dependency with little broadening over a wide density range which directly relates to the good homogeneity of the unpartitioned bulk material.

Samples taken from material with a coarse internal granular structure and associated larger heterogenous density distribution are expected to show significant broadening when comparing the smaller to the larger particle density sub-distributions because lumped grains of different density produce a mean per-particle density while they tend to exhibit their individual densities when broken up and inspected individually.

3.2 Statistical Analysis and Visualization
Figure 11, 12 and 13 show graphs for an Australian coal sample which was analyzed in the laboratory (coarse steps with box-shaped point symbols) and with the washability monitor OREGON (fine steps and bars). The results obtained with RACCOON software are compared to the lab values.

![Graph](image)

Figure 11: Comparison of washability analyses as performed by standard laboratory procedures vs. data obtained with the OREGON analyzer. Sample has a nominal particle size of 4..16 mm.

Figure 11 shows a typical washability curve (an accumulated representation of the mass fraction in each density bin) as obtained by the lab and the OREGON washability monitor respectively. Three different particle classes were analyzed.

The comparison shows good correlation between the laboratory and the washability monitor results. Due to the ease of use and high particle throughput the OREGON analyzer data sets could be made much larger in a fraction of the time of a standard laboratory analysis.
By virtue of the sink-float analysis there is a trade-off between settling time for each fraction and the total time it takes for one sample to be processed. Additionally, the boundary bins contain all particles below (lowest bin) and above (highest bin) a certain value, rescaling the bins in between to less than 100%. This also produces a discontinuity that can be observed in all standard laboratory measurements. The OREGON analyzer does not suffer from this effect.

In figure 11 through 13 the advantage in resolution between the OREGON analyzer and the standard lab procedure is evident. With a small spread of the density distribution around 1.35 g/cm³ the main feature of the washability curve is obscured by the low resolution of 0.1 g/cm³ of the standard measurement.

One of the major advantages of the OREGON analyzer is that all information is stored in a database with sub-particle resolution. Therefore data can be re-evaluated easily under different aspects. Since the number of particles is limited, it is always possible to achieve the optimum trade-off between resolution in density and the degree of statistical fluctuations.

4. CONCLUSIONS

The washability monitor OREGON was developed as a laboratory device to derive washability curves of ores or coal. Tests with coal of different origin show good comparison between laboratory analyses.

Obviously OREGON delivers a more detailed analysis than the laboratory method. Density class limits can be set dynamically. The fact that the results are stored in a database offers the possibility to re-evaluate entire data sets under different aspects which cannot be done with the lab results.

Besides the fact that no hazardous chemicals are required the operation of the analyzer only requires a pre-screening step of the particles in order to remove the very fine contents (˂1 mm). This enables fast sample processing which in turn allows to return results after short time. Therefore process control using the analyzer’s results can be done which can improve coal preparation strongly.

The analyzer also opens up opportunities for further in-depth analysis of particle compositions and associated physical and chemical properties. These in turn may supplement the understanding of feed properties and process performance metrics and improve process control.

References


Miller, J. D.; Lin, C. L.; Luttrell, G. H.; Adel G.T.; 1999; development of an on-line coal washability analyzer; University of Utah, Department of Metallurgical Engineering.