Electrostatic Beneficiation of Coal

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ELECTROSTATIC BENEFICIATION OF COAL
DOE PROJECT ID#: DE-FG22-93PC93203

Quarterly Technical Progress Report

October 1, 1995 to December 31, 1995

I. INTRODUCTION

This report outlines the progress made on the project during the fourth quarter of the second year, from October 1, 1995 to December 31, 1995.

II. WORK PERFORMED IN THE NINTH QUARTER

1. Charging of Small Particles by Milling

It was suggested in the proposal that small particles, due to low inertia, may not impact on the surfaces of the tribocharger. They would, thus, not receive charge and would not be beneficiated in the electrostatic separation. A milling process was proposed in which the small particles are stirred together with larger carrier beads producing the desired contact charge exchange.

A force is necessary for removing the coal particles from the carrier beads. In copying machines electrostatic force is used to pull toner particles away from iron carrier particles which are held back by magnetic force. Aerodynamic force is used in test instruments for measuring the charge to mass ratio on toners.

A similar system of milling and removal is desired for use with the small coal particles. The carrier beads need to be made of copper rather than iron. This complicates the separation process since copper is non-magnetic. We are working on coating of iron beads with a layer of copper. Dr. Robert Engleken of Arkansas State University has supplied us with several test batches of copper-coated iron in the size range of -40 +70 mesh.

We are currently testing whether the milling process used with the copper coated iron beads produces the desired charge on the coal particles. Several procedures are involved. First we compare the charge transferred to beads of pure copper, copper coated iron, and iron when

they are blown through the copper tribocharger. Initial measurements have been made, and data is given in Table 1. Very low charge is indicated by the copper - copper interactions suggesting that the copper coated iron performs much more like the copper beads than the iron, however, we believe that the results are complicated by the unequal size distributions for each of the bead types -- larger particles would be expected to show a lower charge to mass ratio. Equivalent sizes of the different bead types have been ordered to eliminate the size variable from the comparison.

Table 1. Charge to mass ratio for carrier beads passed through the copper tribocharger.

<u>Material</u>	<u>Size Range (μm)</u>	<u>Q/m ($\mu\text{C/g}$)</u>
copper	88-150	0.0013
iron	60-120	0.133
copper coated iron	210-420	0.0021

Blowoff cup -- In a second comparison each of the three types of beads is milled in a tumbler with -325 mesh coal powder. The powder is then placed in a blow-off cup. The blow-off cup functions as a Faraday cup operated in reverse -- charge leaving the cup is measured rather than charge collected in the cup. Airflow through the cup removes the coal powder while the larger carrier beads are held in place by a -325 mesh wire screen. An electrometer connected to the blowoff cup is used to measure the charge that leaves the cup. Weighing the cup before and after allows the mass of the coal that has left the cup to be determined and, thus, the net charge to mass ratio can be calculated.

For copper beads the charge to mass ratio was $-3 \mu\text{C/g}$ for freshly ground coal and $-0.5 \mu\text{C/g}$ one month after grinding. For copper coated iron, two month old coal gave a q/m of $+0.08 \mu\text{C/g}$. The quantity of coal to beads was about 1 to 1.5% by mass for these runs. It is possible that the larger beads (copper coated iron) did not provide enough surface area for adequate contact between the coal and the beads. The age of the coal also plays a role in the results. Additional tests will be made when the new bead sizes are received.

The size and charge on individual particles leaving the cup can be measured using the E-SPART analyzer. Some results were given in the last quarterly report. A magnetic brush system has also been investigated. Due to the larger size of the copper coated beads than the iron carrier beads normally used with toners, a stronger magnet than was required than the usual electro-magnet used with the magnetic brush device. Modifications to the magnetic brush device are being made.

2. Charge Distribution on the Separator Plates

It is desired to obtain information on the distribution of charge on the separator plates. The plates were removed from the separator immediately after the high-voltage was turned off, and then placed on an insulated table. An electrostatic voltmeter (Trek model EVD 320B) was used to measure the electric potential, V , at a height, d , of four millimeters above the plates. Measurements were made every five centimeters along a centerline from the top to the bottom of the plates.

For a plane surface with uniform charge density, Q (in C/m^2) would be given by

$$Q = \epsilon_0 V/2d, \quad (1)$$

where ϵ_0 is the permittivity of free space ($8.85E-12$ F/m). However, in the present situation we have a layer of charged particles on a conductor which creates an image charge in the conductor with polarity opposite to that on the coal particles. The net electric field due to two uniform parallel sheets of charge with equal and opposite polarity is zero in the region outside of those sheets. However, a potential reading is obtained with the electrostatic voltmeter. It may be that the presense of the probe perturbs the field due to the charges. It is expected that the charge density on the plates is approximately proportional to the measured potential so long as edge effects are minimized. Based on the net charge measured at the charger and the mass deposited on the plates it is estimated that the measured potentials were about four orders of magnitude below that expected for a single plane of the charged coal particles (i.e., without the image charge in the conducting plate).

The experimental measurements of voltage and the calculated charge densities are shown in Table 2. The mass of the 'clean' coal collected from the negative plate was 4.46 g while the

mass of 'refuse' collected on the positive plate was 2.20 g. Estimating the charge to mass ratio on the particles by this method is probably not possible. However, relative charge over the plate and the decay rate of the charge may be obtained.

Table 2. Charge measurement on the separator plates as a function of position measured from the bottom of the plate.

Position (cm)	Negative Plate		Positive Plate	
	EVD Reading (V)	Charge Density* (nC/m ²)	EVD Reading (V)	Charge Density* (nC/m ²)
5	8	17.7	-4.2	-9.3
10	8.8	19.5	-5	-11.1
15	8.9	19.7	-5.3	-11.7
20	8.7	19.2	-4.7	-10.4
25	6.4	14.2	-4.8	-10.6
30	4.6	10.2		
mean	7.57	16.8	-4.8	-1.06

* Calculation of Charge density is based on the assumption of a single plane of charge.

3. Charge Decay Measurement on the Separator Plates

Another factor affecting the measurement of the charge density is the loss of charge over time. This will depend on the charge which the particles are carrying, and the resistance of the path through which the charge can flow to earth. Therefore the charge decays fast at first, when the charge is high, and more slowly when the charge is reduced. The relationship of charge decay to time can be written as

$$q = q_0 \exp(-t/\tau), \quad (2)$$

where q is the charge at time t , q_0 is the charge at $t = 0$, and τ is the time constant for charge decay.

An electrostatic field meter (Trek model 354A) was used for these experiments. The initial trial was performed using coal powder deposited directly onto the metal separator plates.

An apparent error was observed in that the field due to each of the two plates was found to be negative. It is not possible that the particles on the two plates have the same negative charge.

The experiment was repeated using thin Teflon plates attached to the two metal plates. This would slow down the charge loss due to conduction. The results are shown in Figs. 1 and 2. The time constants, τ , for charge decay were calculated from the above equation by fitting points on the curve to equation (2). The time constant for the clean coal (negative plate) was determined to be 4.8 minutes and that for the refuse particles (positive plate) was found to be 2.6 minutes. For the clean coal particles it appears that the charge does not approach zero. This may be due to zero offset of the measuring instrument, however, it is being further investigated.

4. Particle Size Distribution On The Separator Plates

Particles were collected from the plates of the separator across 5 cm wide horizontal bands. Size distributions were measured using a Microtrac particle analyzer. The results for Illinois #6 coal are shown in Table 3. More larger particles were deposited low on the plates. While there are only small size range difference among different locations, the particles on the positive plate are smaller than those on the negative plate. Thus, larger particles are more likely to charge positively. The smaller size of particles on the positive plate may also result from the smaller sizes of most mineral inclusions which tend to charge negatively.

Fig. 1 Charge decay of the clean coal particles

Fig. 2 Charge decay of refuse coal particles

Table 3. Size distribution of coal particles as a function of position on the separator plates.

Position* (cm)	Negative Plate				Positive Plate			
	mass (g)	Diameter (μm)			mass (g)	Diameter (μm)		
		10%	median	90%		10%	median	90%
5	1.05	8.4	106	247	0.39	3.2	50.0	160
10	0.58	5.0	50.6	130	0.29	3.6	47.8	120
15	0.74	6.9	68.2	150	0.30	3.1	41.1	116
20	1.02	9.3	78.6	170	0.45	2.3	26.5	103
25	1.40	9.6	72.4	143	0.45	3.6	47.9	117
30		14.8	66.1	131		4.9	53.5	120

* Top of the section relative to the bottom of the plates.

5. Coagulation of particles

During the time that particles are moving from the charger to the separator they may agglomerate to form larger particles. Among other things, this can result in mineral particles that were initially charged negatively combining with a negative maceral particle and ending up on the clean coal plate. We are beginning to look into the theoretical aspects of particle agglomeration in this region.

Coagulation of aerosols is a process whereby aerosol particles collide with one another due to a relative motion between them and adhere to form larger particles. Since the small and large particles settle at different rates, there is a relative motion between particles leading to collision and coagulation. The capture mechanisms involved are inertia, interception, and electrostatic forces. The rate of capture of small particles by a large particle can be written as :

$$n_c = \pi d_d^2 V_{TS} NE \quad (3)$$

where d_d is the diameter of the large particle, V_{TS} is the relative velocity between the large and small particle, and N the number concentrations of small particles, E is the capture efficiency. Because the rate of coagulation is proportional to N , it is rapid at high concentration, but slows as concentration reduces.

Hinds gives the time required for the number concentration to drop by half and particle size to double by the simple monodisperse coagulation. For initial concentrations at 10^{14} particles/cm³ and 10^{13} particles/cm³ the times are 20 μ s and 2 ms, respectively. In a commercial scale operation, the particle concentration inside the separator will be high so the time for particle coagulation will be short, and the frequency of interparticle collisions will be high. More precise information and analysis is being considered.

6. The Good Charging Properties of Liptinite and Amber

(Dr. David Lindquist)

Many are familiar with the ancient demonstration of static electricity, that of rubbing amber with animal fur, giving the amber an attraction for light objects such as paper scraps. Amber is chemically similar to the coal maceral liptinite, the difference being merely one of size; liptinite is typically of micron dimensions whereas amber in jewelry for example is pebble sized or larger.

A simple experiment that we have recently tried shows that liptinite, like amber, adopts a significant degree of charge. Moreover, the liptinite charge is, on average, greater than that of other coal macerals such as vitrinite. For the experiment, a small block of Illinois #6 coal was first polished perpendicular to the bed plane. Standard toner powder for a Xerox copy machine then was charged negatively using a Tesla coil and sprinkled onto the polished coal surface. It was presumed that the charged toner powder would preferentially adhere to specific macerals on the coal surface. Adhesion is dependent upon the induction of a significant positive mirror charge in the maceral when the maceral is contacted with negatively charged toner.

After the charged powder was sprinkled onto the surface, the sample was tapped repeatedly to remove excess and poorly adhering powder and then examined under fluorescing conditions in a light microscope. Many of the thickest deposits of powder were seen on top of liptinite rich veins in the coal. Although toner particles were distributed on other maceral surfaces as well, the

largest powder deposits were generally associated with liptinite. The effect was visually striking due to the strong yellow fluorescence of liptinite.

It should be mentioned that in previous quarterly reports we have noted that liptinite appeared to acquire a higher degree of positive charge than other macerals. Specifically, in particle counts of powder collected from the negative plate of the electrostatic separator there were greater quantities of liptinite than in feed powders prior to beneficiation.

Figure 3. Three orbital states for an electron pair

Fluorescence and Phosphorescence Phenomena: Possibly Related to Electrostatic Charging?

The question naturally arises as to whether the good charging properties of liptinite and amber are related to their fluorescent properties. Fluorescence phenomena in organic molecules is a complex process usually resulting from π^* electronic transitions in aromatic or conjugated olefin species. A simplified illustration of some molecular orbital electronic states are illustrated in Figure 3.

In the most rudimentary description of fluorescence, a metastable excited state singlet [Figure 3 (middle)] is first produced by light stimulation. The π^* electron then returns to the ground state and light is emitted with the decrease in energy of the system. The lifetime of the excited singlet is on the order of 10^{-8} seconds.

A process related to the fluorescence observed in liptinite and amber is that of phosphorescence. Phosphorescence results from decay of the triplet state shown in Figure 3. The triplet state producing phosphorescence is longer lived than the excited state singlet of

fluorescence since return to the ground state is spin forbidden in the triplet case. The lifetime of the triplet ranges from approximately 10^{-3} seconds to 10 seconds. Formation of the triplet is a multistep process. The electron in the ground state is first promoted to an excited singlet energy followed by a change in the electron spin. It should be noted that phosphorescence is less common in nature than is fluorescence.

Most coal electrostatic studies, including our own, indicate that coal macerals prefer to lose electrons and adopt a positive rather than negative electrostatic charge. Perhaps the metastable excited electronic states which produce fluorescence in liptinite, are the same electronic states which provide a means for transfer of electrons out of the maceral during tribocharging. In this scenario, a small proportion of the outer π^* orbitals of the maceral would be populated with electrons. And since the lifetimes of these states are relatively long lived, it would be possible to remove these electrons when the maceral is contacted with an electron acceptor such as the grounded copper plate used for electrostatic beneficiation. Only a very small number of electrons must be transferred during tribocharging in order to develop a significant charge useful for the beneficiation process.

If this model has any validity, then it should be possible to enhance charge beneficiation by promoting fluorescence. For example, fluorescent agents could be added to coal powder prior to charging in order to enhance the charging of other macerals such as vitrinite and inertinite. A quick means of screening potential agents would be to repeat the toner experiment described above using a polished coal surface treated with a fluorescent compound to note any changes in where the toner sticks to the surface. Another approach would be to use blue or ultraviolet light illumination at the copper plate during tribocharging to promote formation of excited electronic states, thus encouraging electron transfer. Phosphorescence might be a better aid to charge transfer than fluorescence since the triplet excited state is longer lived than the excited singlet. However, phosphorescence is not a natural property of coal macerals and would have to be induced by additives.

The Chemistry of Macerals and Fluorescence

Why do the intensity and wavelength of fluorescence vary greatly among the different macerals in coal? These questions of course have already been thoroughly addressed by others and this knowledge may be helpful in understanding electrostatic beneficiation. As stated above, the general requirements for fluorescence in organic compounds are accessible and metastable π^* excited states. The stability of the excited π^* state is dependent upon this molecular orbital being delocalized over several atoms. If however delocalization involves too many atoms, then the band gap between the π and π^* is narrow and the stability of the excited state collapses. This is what occurs for example in the maceral vitrinite, which has extensive aromatic structure and therefore no fluorescence. In the case of liptinite, the requisite aromatic and olefinic character is present, but the larger percentage of hydrogen and hence aliphatic carbon present in liptinite restricts the delocalization to say between 10 and 20 carbon atoms. Liptinite fluorescence is quite intense in bituminous and subbituminous coals. As coal rank increases however, liptinite fluorescence shifts to longer wavelengths and diminishes in intensity. This observation is consistent with the increasing aromatization of the liptinite with increasing rank. In anthracite the pseudographitic structure is highly developed.

Other atoms besides carbon influence the energies of conjugated systems and hence their fluorescence behavior. For example oxygen and nitrogen are structural components of many fluorescent molecules. Quinoline, a nitrogen containing heterocycle, exhibits intense fluorescence. Coals of the Eastern United States, prime candidates for electrostatic beneficiation because of their high pyrite content, contain large quantities of nitrogen for the same reason that they have large pyrite, namely bacteria. Eastern U.S. coals originated in river delta salt marsh environments conducive to bacterial growth. Sulfur bacteria in the ancient marshes were the source of the fine pyrites found in these coals and the relatively high nitrogen content of these coals arose from the bacterial proteins.