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Abstract

The technical feasibility of separating mineral matter and pyrite from coal as it is transported from pulverizers to burners in pulverized coal combustion units is examined. The charge imparted on coal during pulverization and transport to pulverized coal (PC) burners in a utility boiler is quantified. In addition to field charge measurements, an existing computational model is extended to numerically simulate charged particle motion in a turbulent gas through coal transport pipes and triboelectrostatic separation zone. Results from the field tests and numerical modeling are employed in a conceptual design and a 4-40 kg/hr laboratory-scale separator is constructed and tested. This laboratory unit is used to quantify the magnitude and differential charge imparted on coals during pulverization and transport typical in utility PC units. An electrostatic separator, designed for in-line operation between pulverizers and PC boilers, will be used to clean prepulverized coals. Theoretical and experimental data are to be used in preparing a preliminary and conceptual design for a 15 ton/hr, in-line, electrostatic coal cleaning device. Finally, the economic potential for application to PC units is assessed.

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Executive Summary

The research goal was to determine whether it is technically feasible to separate mineral matter and pyrite from coal as it is transported from pulverizers to burners in pulverized coal (PC) boilers. Specific objectives were to measure particle charge in the coal transport pipe between a utility's pulverizer and the coal burner; to develop a pilot-scale separation test platform for particle charge and coal beneficiation experiments; to extend an existing computational model to numerically simulate charged particle motion in a turbulent flow; and to apply pilot-scale data, industrial expertise, and utility experience to prepare a preliminary conceptual design of a full-scale, dry coal electrostatic separation system.

The original project was scheduled for a 36 month duration. A 9 month no cost extension was granted, taking the program duration to 45 months. An additional 6 month no cost extension was granted, making the total program duration 51 months.

Charge measurements and separation experiments were performed at two utilities; one burning a low-sulfur, compliance coal and the other burning a high-sulfur, non-compliance coal. Specialized particle extraction probes were fabricated for these in situ measurements. During the on-site utility charge and separability experiments, pulverized coal was extracted from the burner pipes for further analysis and experimental work back at the laboratory. A 0.7 kg/hr batch feed analytical scale triboelectrostatic separator was used to evaluate the potential separability of the two coals. Results from these tests have been reported in the form of recovery curves. Two coals were also tested in a 4-40 kg/hr continuous feed pilot scale triboelectrostatic separator.

Concurrent with the lab testing, numerical modeling of the gas flow entering the separator was conducted by researchers at Clarkson University. The computer model first evaluated the gas flow, then the dispersion of particles in mixing and coal transport pipes immediately prior to and in the separator. These results were then used to conceptualize a full-scale triboelectric separator. They suggested that a properly designed inlet would lead to a roughly uniform concentration of particles entering the main separator.

A economic evaluation of the technology was completed. These analyses were based on a stand-alone 2 ton/hour separation system because pricing information on most of the equipment involved was readily available. The cost of an in-line unit to be installed at a utility plant was estimated to be less than the cost of a stand-alone unit because of the equipment already at a PC unit which could be used for the in-line separator.

Introduction

Wet, precombustion coal cleaning technologies are used to remove sulfur from coal before it is combusted. Establishing an efficient dry coal cleaning or beneficiation technology for precombustion removal of sulfur and mineral matter would eliminate environmental objections to the handling and disposal of byproducts created by wet processing. Because the liberation of mineral matter and pyrite relies on particle comminution, and because the first step in pulverized coal combustion is the comminution of coal to -200 mesh, the application of dry electrostatic separation in-line between coal pulverizers and burners at coal-fired power plants could improve the environmental aspects of fossil fuel usage and the overall performance of fossil powered systems. This project will be the first to establish whether charge is imparted during pulverization and whether in-line separation can be performed.

In the United States, pulverized coal (PC) boilers are the principal means for converting coal to electricity [1]. When first developed, the PC boiler demonstrated a high degree of flexibility, particularly as it related to coal type and combustion conditions. More recently, in an effort to elevate combustion efficiencies, coal firing rates and combustion temperatures have been increased, leading to more stringent coal specifications [2]. At the same time, increasing environmental controls on acid gas emissions from PC boilers have imposed further restrictions on coal composition.

With escalating demands on coal quality as a result of increased boiler efficiency and decreased acid gas emissions, fewer coals can meet specifications without some form of beneficiation. Removal of the coal mineral matter prior to combustion can have multiple benefits. Reduction of the aluminosilicate clay minerals, which typically comprise 60-90% of the of the total coal mineral matter [3], will produce a corresponding decrease in boiler erosion and fouling and will also decrease the amount of fly and bottom ash generated. Removing the pyritic minerals will decrease the SO₂ emissions and lower or eliminate flue gas scrubbing requirements.

While wet coal cleaning has been the predominate beneficiation technology utilized to date, dry separation technologies offer benefits which warrant increased attention. Principal among these benefits is the avoidance of coal dewatering and drying and water treatment. One of the most promising dry beneficiation technologies is triboelectrostatic separation. This process relies on frictional differential charging of finely ground coal mineral and organic matter followed by separation in an electric field. An efficient triboelectrostatic separation process requires a fine material grind - and therefore provides substantial mineral liberation, high kinetic energy for particle charging, and controlled relative humidity in the transport gas.

PC boilers typically utilize a minus 200 mesh (75 μ m) coal; hence, substantial mineral liberation is achieved in the pulverization process. If the pulverized coal were also charged, a logical location for a dry beneficiation process would be at the boiler site, in the coal preparation circuit, for example, after the pulverizers and before the burners. The process of crushing and pneumatically transporting dry particles is known to impart particle charge [4,5] in other materials. However, whether or not coal particles are charged during coal pulverization and

transport had not been measured at the beginning of this grant. The polarity of the charge, if imparted, and the presence of a bipolar charge, would also be important if triboelectrostatic principals could be employed to clean the pulverized coal as it is transported in the burner pipes. This report describes work done to quantify the magnitude and bipolarity of the charge on pulverized coal in the burner pipes at two power plants and in a laboratory separator. It also presents data on the removal of ash and sulfur from pulverized coal in experiments also performed in the power plants and in the laboratory. From these experiments and experiences, a continuous-feed, triboelectric separator was designed and tested. An estimate of the cost of constructing a in-line separator is presented.

Results and Discussion

This final report describes the work performed during the grant period. It describes the work that was planned and then presents the work accomplished in a task-by-task approach. Additional information, including papers and presentations whether in published or submitted forms, are contained at the end of the report in Appendix A.

Task 1. Charge Determinations

The predominant coal pulverization strategy for PC boilers is direct fired and includes both pressurized and suction system designs [6]. Pressurized systems incorporate a fan prior to the pulverizer, which blows prepared coal after pulverization through a classifier and into burner pipes. Suction systems utilize an exhauster fan to pull prepared coal after pulverization through a classifier and blows the coal into the burner pipes. The utilities selected for field testing incorporated these direct fired pulverization technologies.

The pressurized pulverization system field tests were conducted at the East Kentucky Power Cooperative (EKP) Spurlock Station power plant, located in Maysville, Kentucky. Tests were performed on a 50 tph B&W roll and race pulverizer which fed a 300 MW PC boiler. The second series of field tests were performed at the Tennessee Valley Authority (TVA) Widows Creek power plant, located in Stevenson, Alabama. The suction pulverization system evaluated consisted of a 30 tph CE Raymond bowl mill feeding a 500 MW tangentially fired boiler.

After initial trips to the EKP Spurlock Station and the TVA Widows Creek Station, a portable charge measurement probe was designed and constructed. This probe is shown in Figure 1. Based on the Faraday cup principal, the probe was designed to sample across the diameter of a 40 cm diameter burner pipe. The probe consists of a sample tube and filter housing, electrically connected and screened from stray electrical and magnetic signals by a grounded shield. Between the grounded shield and the copper inner wall is a PVC dielectric. Pulverized coal is either induced or flows under pressure through the sample tube and into the filter housing where it is collected in a disposable filter bag. Designed for rapid sample extraction, the filter housing has a 1 kg capacity for pulverized coal. Gas flow through the sample probe is controlled by modulating a valve on the filter housing.

A computerized data acquisition system was connected to the sampling probe. The signal from a picoammeter, connected to the probe's inner wall, was recorded by this data acquisition system. Integrating the electrical current/time data yielded a total charge for the pulverized coal

particles collected. After sample collection and data acquisition, the filter bag was removed and sealed in a plastic bag for subsequent sample analyses back at the laboratory.

The probe was modified after initial attempts at the Spurlock Station to collect charge data. It was observed that the sampling slot on the probe tip was causing excessive noise in the charge/time data. A suitable probe tip was designed and installed; subsequent charge/time data contained significantly less noise than did the data before tip modification.

A pneumatic purge and vacuum system was connected to the probe to minimize particle collection prior to the sampling period and to compensate for increasing filter pressure drop during sample collections. The system was fabricated from a light weight pneumatic eductor with full port ball valves located at its high pressure gas inlet and outlet. As the probe was inserted into the coal burner pipe, a purge flow was maintained by directing the eductor gas flow through the probe tip. When sampling was initiated, the eductor outlet valve was opened allowing high pressure gas flow through the eductor thereby establishing suction at the probe tip. Once the desired sample was collected, both eductor valves were closed and the probe was withdrawn from the pulverized coal burner pipe.

The initial results from the charge measurements of a pressurized pulverization system at the Spurlock Station power plant results have been reported [7]. Two existing sample ports, placed in a 41 cm burner pipe, were selected for the test locations (Figure 2). The first sample port was located directly above the pulverizer and the second port was located immediately before the burner.

To collect the data for comparison of pulverization systems, additional on-site measurements were taken at the Widows Creek site. Figure 3 shows a simplified schematic of this pulverization system. The crushed coal is pulled from the pulverizer, through the exhauster and exits via a 81 cm diameter pipe which subsequently splits into the individual burner pipes. Measurements were made in the 81 cm distribution pipe immediately downstream of the exhauster.

During coal collection, the signal from the picoammeter, connected to the probe's inner wall, was recorded by the computerized data acquisition system. Integrating the electrical current/time data yielded a total charge for the pulverized coal particles collected. After sample collection and data acquisition, the filter was removed and sealed in a plastic bag for subsequent analyses back at the laboratory. Table 1 summarizes the charge results for both sites.

While the Spurlock Station burner pipe was actually sampled at two locations, only results from the lower sample port are presented. Since this sample port was immediately above the pulverizer, it allowed for direct comparison to the Widows Creek results which were collected directly above the exhauster. At both sites, five different probe penetration distances were evaluated for particle charge. Preliminary tests were conducted at both sites to determine the optimum sample collection time. For the Spurlock Station this time turned out to be around 200 seconds while at Widows Creek samples were collected for around 60 seconds.

Both pulverization systems showed little variation in the radial profile of average charge. The absolute value of average charge was slightly lower for Spurlock Station, $32\text{-}53 \times 10^{-6}$ C/kg compared to $59\text{-}108 \times 10^{-6}$ C/kg for Widows Creek. The charge polarity for the two sites was reversed.

The average charge represents a net value, indicating that at least one component of the pulverized coal is charging. In theory, the total charge on the ash could equal the total charge on

the combustibles, yielding a net total charge of zero. In this situation, a high degree of separation may still be achievable. Many factors can affect average charge polarity including coal mineralogic and petrographic composition, charging surface composition, and charging conditions. Sampling procedures may also have an effect on average coal charge. While the polarity was reversed between the two sites, the significant result from the charge measurement experiments was that both pulverization systems produced similar absolute values of charge.

Task 2. Pilot Scale Test Rig Development

A separator, used in previous coal beneficiation work, was also used in this study. A diagram of this laboratory separator is presented in Figure 4.

The coal was placed in a container located on a vibratory feeder which was contained in a sealed tank. Pre-weighed amounts of pulverized coals were placed in this container. Coals were fed into a vertically-held funnel as it fell from the vibrating feeder, and then were transported through a feeder tube by a flow of nitrogen gas or air. This carrier gas flow, controlled and monitored by a rotameter, entrained particles through a 0.63 cm diameter stainless steel or copper tube leading to the separator. A simple tribocharger, made of 0.63 cm diameter copper or stainless steel tube loops, was used to charge particles before they exited into the separator chamber. This chamber had a cross section of 10 cm x 10 cm, with two copper plates attached to two opposite side walls of the chamber. The other two walls contained plexiglass doors for observation and sample collection.

A high DC voltage (5-30 kV) was applied across the copper plates to establish an electric field with known field strength. During the experiments, charged particles coming from the center tube deflected to and deposited onto either the negative or positive copper electrodes depending on the particle charge polarity. A filter was placed at the bottom of the chamber to capture any entrained particles not depositing on the electrodes. The exit of the separation chamber was connected to an induced draft fan.

Prior to separation tests, the coals were evaluated by proximate and ultimate analyses. The initial sample mass and the mass of collected fractions after separation were weighed. After triboelectric separation, samples were collected from predetermined locations throughout the separation chamber, and characterized by proximate analysis.

During the separation experiments, fractions of purified coal and mineral matter were deposited on opposite polarity electrodes. The depositions were long narrow ribbons of particles, starting from the near the exit of the transporting tube leading into the top of the separator and extending to the end of the copper plates. Since the coal and mineral matter content on the electrodes could be represented by a continuous distribution, it was possible to make an arbitrary split of the separated products that would satisfy desired purity requirements. However, as in any physical separation processing, higher purity products were achieved at the expense of lower yields.

For each test using this separator, a total of ten sample fractions were collected; eight from four axial regions on the two electrodes, one from the center filter, and one from the vertical plexiglass windows. These fractions along with the feed were weighed and analyzed. An

eleventh data point, which represented the particles which were not captured anywhere in the separator, was determined by performing a mass balance between the amount of coal fed during the test and the amount of product collected in the separator.

The continuous-feed triboelectrostatic separator system, shown in Figure 5, was constructed and used during testing. It used air driven particles in the delivery tubes from the eductor to the separator to effect tribocharging and transport to the separator. The electrostatic separation chamber consisted of parallel electric field plates across which a DC voltage was applied, producing an electric field strength between 100-200 kV/m. Two different lengths for the chamber were constructed; one was 23 cm and the other 61 cm. Two different widths were also constructed; one was 5 cm and the other was 10 cm. Feed rates were between 4-40 kg/hr.

Particles were fed to the tribocharging unit by using either a screw feeder or a vibratory feeder. Both feeders contained sealed environmental tanks in which the samples, about four kg, could be stored. These samples were metered into a pneumatic transport tube and then entrained in carrier air. The air-particle mixtures were then transported through a copper tube at a velocity between 10-20 m/s, exiting into the separation chamber. The particle laden flow out of the separation chamber was split into three streams: one near the positive electrode, one near the negative electrode, and one at the middle of the separator. A purified coal (or high carbon content) product was collected from near the negative electrode and an ash or mineral matter rich product was collected near the positive electrode. The middle stream from the separator was used for recycle of products which were not collected near either the positive or negative electrodes. An induced draft fan exhausted each of the three product streams from the separator through two high-efficiency cyclones mounted in series. A baghouse was used to capture any particles escaping the cyclones. The balance between feed mass and product mass in this system was always greater than 95%.

To establish a recovery curve similar to what could be accomplished with the separator shown in Figure 4, a product recycle/staged processing procedure was established. Each of the first stage primary products were again fed to the separator, from which nine products were obtained. Each of these nine had different carbon and ash contents, and in combination with the mass of each product, they could be used to plot a recovery curve that presents a cumulative data set for each sample.

Task 3. Coal Separation Determinations

Data for the coal separation tests performed in the laboratory are plotted in Figure 6 for pulverized coals obtained at the TVA and EKP utility sites. These data show that if 50% rejection of the mineral matter is targeted, the percent recovery of the purified product is about 50% of the feed. These types of results are typical to a pulverized coal grind. To attain higher recoveries with higher ash/mineral matter rejection would require a finer grind of the coal fed to the separator. Hence, it is suggested that triboelectric beneficiation may not be broadly applied within a utility setting to effect greater than 50% mineral matter or sulfur rejection unless processing or the reject stream can be used in some economical manner.

Separation tests were also performed within the burner pipes at the utility sites using a specially designed separation probe. This type of sampling and separation did not allow the

recovery curve analysis as done in Figures 6 but did enable a comparison of data from plant to laboratory. The data from the utility site separation testing are presented in Table 2.

Total sample weights for the Spurlock Station tests were somewhat erratic, possibly due to coal roping inside the transport pipe. For the Widows Creek plant, a lower percentage of material was collected on the electrodes and a correspondingly higher percentage of material was collected in the filter. Potential explanations for this finding include: insufficient particle charge; insufficient electric potential across electrodes; or inadequate separator residence time. Considering the left electrode material to be reject, and the filter and right electrode to be cleaned product, mineral matter removal ranged from 43 - 51% for Spurlock Station and 26 - 41% for Widows Creek. Combustible recovery ranged from 76 - 80% for Spurlock Station and 81 - 86% for Widows Creek. In general these results show that while the Widows Creek pulverized coal possessed a higher average charge, the separability was not as good as at Spurlock Station.

Task 4. Full-Scale Separator Design

A full-scale separator conceptualized design was carried out by assessing data from the analytical separator and from the 4-40 kg/hr continuous feed separator, by integrating flow calculations with experimental testing, and by examining conditions at and needs typical to coal-fired utility plant operation. If a in-line dry coal separator is to become viable, it would most likely be located after the pulverizer in the coal delivery burner pipes. The temperature, humidity, coal feedrate and air flow in burner pipes are controlled by plant operators. The typical mass-to-mass ratio, i.e. air:coal mass ratio, in burner pipes is near 1:1-to-2:1. These conditions are favorable for triboelectric separation of coal. Also, however, the size of the pulverized coal has to be such that mineral matter is liberated if a physical separation technique like triboelectric processing is to be effective.

The conceptual design included the use of a straight rectangular duct which formed the mixing chamber and the main body of the triboelectric separator. To improve mixing and to generate a uniform concentration in the main electrostatic separator duct, the coal entered the mixing box in the form of two opposing jets. The stress transport model of the FLUENT code was used for simulating the mean gas flow and to guide the overall design of the electrostatic coal/ash separator. A three-dimensional computational grid covered the mixing chamber with the opposing inlets and the upper part of the main separator duct. The gas flow field conditions including the directional intensities of turbulence were evaluated.

The instantaneous fluctuating velocity field was simulated by a Gaussian filtered white noise model. A recently developed computational model for Lagrangian particle tracking was used to study the transport of particles from the inlets to the main body of the separator duct. The model accounts for the drag and lift forces acting on the particle, in addition to the Brownian motion and gravitational sedimentation effects. The particles were also dispersed by the action of the high level of turbulence that was generated in the mixing chamber.

The proposed system is composed of a rectangular cross section duct which forms the mixing chamber and the main body of the triboelectric separator. To promote mixing, the mixture of pulverized coal and/or exhausting ash is introduced into the mixing chamber through two opposing high speed inlet jets. The coal/ash and other minerals are charged differently (with opposing sign) through the process of tribocharging as they pass through the inlet ducts. The

mixture will then flow down the main separator duct in which a strong electric field is imposed across the section. The coal, ash and other minerals are charged differently and with opposing sign by particle-particle contacts and collisions. As a result, these particles are deflected by the electrostatic forces to various degrees in different directions and can be physically separated.

Based on the design requirement, in the present work, a 3D grid for the separator intake was generated. The FLUENT code was used for simulating the mean gas flow condition. The Reynolds stress transport (RST) model of the code was activated to account for the effects of turbulence on the gas flow in the separator. Design modifications were performed and the computation was repeated until the desired flow pattern was obtained. Particles of different sizes were introduced at the inlet with a uniform distributions and their trajectories were also evaluated. Variations of the mean gas flow velocity and turbulence properties in the separator were studied.

Particle distributions at different planes across the triboelectric separator were evaluated. The results showed that the particle concentration became gradually more uniform with distance from the inlet region. Furthermore, the larger (100 μm) particles were more uniformly distributed at the exit when compared with the smaller (40 μm) particles.

To study of the effect of electric field on the performance of the separator and to conceptualize a separator design, a series of computer simulations were performed. The particles were assumed to carry a specific amount of charge that was typically observed in a comparable experimental setup. Trajectories of charged particles in the triboelectric separator were evaluated and statistically analyzed.

The new design of the separator which is suitable for scale-up for use in utility power plants was conceptualized. The separator consisted of a 50 cm x 12.25 cm rectangular cross section duct. The upper part of the duct formed a mixing chamber, which was connected to the main separator section. The gas-solid mixture entered the mixing chamber in the form of two opposing jets from the side walls. The opposing inlet duct were located at 4.3 cm away from the top wall. The cross sections area of the inlet ducts was 12.7 x 1.6 cm. An upper part of the duct with a length of 91.4 cm, and includes an inlet, a mixing chamber and the upper part of the triboelectric separator, was assessed.

A series of computer simulations were performed and the air flow conditions generated by the inlet opposing jets in the upper part of the separator was studied. The particle trajectories were also evaluated and their distribution at various sections was analyzed. The Coulomb force due to the imposed electric field E , given as $F = qE$, where, $q = ne$ is the total charge carried by a particle, n is the number of units of charge, and $e = 1.6 \times 10^{-19}$ Coulombs is the unit electrical charge. The other components of the electrical forces (such as image, dielectrophoretic and dipole-dipole forces) are comparatively small and were neglected in this study. It should be emphasized that with the use of the instantaneous fluid velocity field in our equations, the effect of local turbulence on particles was taken into account.

As noted before, the FLUENT Code was used for flow simulations. A grid of 20 x 12 x 80 was generated to describe the upper part of the separator. The grid spacing was roughly uniform, except for being finer in the region near the inlets. This is because significant variations of the flow in this region is expected.

The gas physical properties were assumed to be the same as air at 20°C and atmospheric pressure. The velocity boundary conditions were specified at the inlets. Accordingly, the gas

velocity at the inlets to the mixing chamber was 18.3m/s, and the intensity of turbulence was taken to be 20 percent.

It took about 8000 iterations for the computation to meet the convergence criteria. It was observed that the velocity was very high near the inlets, but reduced significantly inside the vessel. The velocity was also nonuniform in the upper part of the duct, but it became relatively uniform near the outlet. The velocity magnitude contours at different sections indicated that the velocity magnitude varied significantly across the vessel in the upper regions and, in particular, near the inlets. The flow, however, became quite uniform in the lower part of the duct.

Calculations using opposing inlet gas/particles flows showed that strong opposing jets were formed in the upper part of the duct, that bend into a vertical downward stream. The interaction of these jets generated two large recirculation regions which extended roughly about 10 cm into the tank. It was noted that the velocity field became relatively uniform in the lower part of the vessel. The results indicated that the new mixing chamber/separator design led to a roughly uniform axial velocity in the main body of the triboelectric separator.

The variation of the mean pressure field in the duct was somewhat low at the inlet region due to the high speed jet formation, but became quite high in the central part of the vessel near the top. The pressure inside the main body of the vessel was roughly constant and varied only slightly with the downstream distance.

The variation of turbulence kinetic energy in the duct at the planes of symmetry was quite high in the upper part of the mixing chamber at the level of inlet ducts. The high level of turbulence intensity provided a good mixing condition. The turbulence intensity then decreased rapidly along the separator duct and became quite low in the lower part of the duct. This new design, therefore, was expected to provide a uniform velocity field with relatively low level of turbulence in the electrostatic separator section.

The variation of turbulent shear stress in the plane of symmetry of the duct was rather large near the inlet mixing jet regions and decreased with distance along the duct. The contours indicated that the magnitude of the stress became very small in the lower third of the separator duct that was modeled.

Sample trajectories for particles under the action of mean flow field was studied. Twenty four 100 μm particles were uniformly introduced at one of the inlets to the mixing chamber and their trajectories were evaluated. The FLUENT code was used for evaluating these mean particle paths. Since the flow was symmetric, and also to avoid cluttering of data, the particles were introduced only in one side. The corresponding mean particle trajectories were calculated with the inclusion of the effect of gravity; however, the effect of turbulence was ignored. It was observed that particles were captured by the strong jet flows in the inlet region. The particles then followed the gas jet as it turned downward near the centerline. About half of the particles spread around as they moved downstream. The other half stayed roughly close to the centerline. One reason for the skewed particle concentration was that the effect of turbulence dispersion was neglected in this analysis.

Simulations were also performed using the added turbulence effects. In this case, 100 particles with diameters of 40 μm and 100 μm were released uniformly from the inlets. The calculations showed that particles enter the separator following the strong inlet opposing jet flows, and then turned downward following the mean flow streamlines. It was also noticed that particles were dispersed significantly by the action of turbulent fluctuating gas velocity. Some

particles were captured by the recirculation flows, a few deposited on the vessel walls, and most of the particles spread around as they are transported downstream. Near the outlet, however, the 100 μm particles had a somewhat more uniform distribution when compared with the 40 μm ones. It was noticed that particle trajectories under mean flow condition (when turbulence effect was ignored) had significant differences with the case when turbulence dispersion was included. Clearly turbulence played an important role in particle dispersion and transport processes in the separator.

To provide an understanding of the particle concentration distribution in the vessel, the locations of particles as they crossed different planes along the duct were also recorded. In this case, 4000 particles with diameters of 40 μm and 100 μm were released uniformly from the inlets. It was observed that the particles tended to concentrate near the centerline in the upper part of the triboelectric separator. The concentration, however, became more uniform near the outlet. It was also noted that the average concentration of 40 μm particles at the vessel exit varied between 1-to-5 particles/ cm^2 .

The concentration of 100 μm particles at a distance of 0.1 m from the top of the vessel was highly nonuniform with the peak concentration occurring in the central region of the vessel. As the particles penetrated deeper into the tank, the concentration became more uniform. The averaged concentration profile showed that the 100 μm particles had a roughly uniform concentration of about 5 particle/ cm^2 at the exit of the vessel. Only very near the wall, the concentration increased to about 20 particles/ cm^2 .

To study the effect of electrostatic forces on charged particle transport, 4000 charged particles with the same diameters were released uniformly from the inlets. The average charge carried by each 100 μm and each 40 μm particle was, respectively, assumed to be 2×10^{-13} Coulombs/particle and 1×10^{-13} Coulombs/particle. These values were based on the charge measurements performed in the laboratory. A constant electric field of 200 kV/m perpendicular to the flow direction across the separator for $Z > 0.4\text{m}$ was considered (Z was the distance from the top of the separator).

It was observed that the charged particles moved towards one side of the duct in the lower part of the triboelectric separator under the action of the electrostatic forces. Thus, particles with a positive charge were separated from particles with the opposing charge.

The averaged concentration profiles at different sections in the lower part of the vessel for the charged 100 μm particles became highly asymmetric. Near the outlet, there was a high concentration in a narrow band close to one side of the vessel wall. These calculations showed that the electrostatic forces played a significant role on charged particle transport: therefore, the proposed design for triboelectric separator has the potential to separate coal and ash particles that carry different charges.

To study the effect of manufacturing imperfections of the separator on particle transport in the triboelectric separator, the case that there was a slight asymmetry in the geometry of the inlets was also studied. The computational grids for the separator geometry was obtained with nonsymmetric inlet locations, where it was assumed that the opposing inlets were not in the same level in Z direction due to manufacturing error. One inlet was slightly (about 4 mm) lower than the other inlet, and both inlets were about 14 mm closer to one side of the duct wall, i.e. the inlets were slightly misplaced in both Y and Z directions.

The velocity magnitude contours in the XZ-plane of symmetry of the separator and at several YZ sections along the duct showed asymmetry in the X direction whereas the corresponding velocity vector plots in the separator showed two large recirculation flow regions generated by the inlet jet flows due to the asymmetry. The recirculation flow near the inlet that was somewhat lower penetrates deeper into the tank than the other one. The flow, however, near the inlet that was somewhat lower penetrated deeper into the lower part of the duct beyond $Z > 0.7\text{m}$.

Particle trajectories and concentration were also evaluated for the case with imperfectly manufactured inlets. The concentration of $100\text{ }\mu\text{m}$ particles at a distance of 5.5 cm from the top of the vessel was clearly nonsymmetric and nonuniform. While near the exit of the vessel, the concentration became quite uniform. This resulting exit concentration was similar to the case of perfectly symmetric inlets. These results indicated that particle concentration near the outlet of the separator was not sensitive to slight manufacturing imperfections.

Task 5. Economic Evaluation

An economic evaluation of the technology was performed. These analyses were based on a stand-alone 2 ton/hour separation system because pricing information on most of the equipment involved was readily available. The cost of an in-line coal cleaning system is expected to cost substantially less, on a per-ton-of-coal processed basis, due to an approximate 80% reduction in equipment needs, i.e. a majority of the equipment needed for in-line coal cleaning would already be in use at the utility site.

For a 2 ton/hour *stand-alone* system, the major equipment components are storage silos, feeders, baghouse filters, piping, and the separator. Most of the equipment would be off-the-shelf components that are designed for pneumatic particle transport and collection. Only the separator would be custom built. The estimation begins at the airlock feeders, where the coal is fed to the system, and ends at the baghouses where separated solids fractions are captured. A forced-draft fan will generate pneumatic power to deliver the coal particles to the separator.

The economic analysis included the cost of major equipment, operation and labor. The equipment and operation cost estimation was based on the 2 ton/hour system; however, the labor costs were based on a 20 ton/hour system. Table 1 shows the major equipment cost and useful life, and the cost/ton of ash processed based on a linear depreciation rate and no salvage value.

Labor cost, based on a 20 ton/hr system and system operation by one trained worker at 20 \$/hr salary, was approximately \$1/ton. Electricity costs for a 2 ton/hr system would be less than \$0.28/ton, based on a rate of 0.07 \$/KW-hour.

Therefore, the total cost-per-ton of coal processed for a *stand-alone system* would be near \$2.62/ton. If a 15% contingency is added to the estimation, the cost becomes nearly \$3/ton. It must be remembered that this cost is for a stand-alone facility, not for an in-line separator which would be built and used for coal cleaning within a utility burner pipe. The labor and equipment costs would be substantially less than this estimate, leading to an overall cost of about \$1.50/ton of coal cleaned for an in-line system.

Task 6. Reporting/Publications

See Appendix 1.

Conclusions

The pulverization of coal within PC power plants imparts bipolar charge on the coal particles which could be taken advantage of in an in-line triboelectrostatic separation system that rejects mineral matter and pyrite from pulverized coal streams. The extent to which the cleaned coal can be recovered would depend on the coal grind. As a consequence of tests performed in the laboratory and at two power stations, it is suggested that the extent to which coal is rejected with the mineral matter may limit the broad applicability of an in-line, triboelectric beneficiation technology. However, if the coal is very-well pulverized to smaller than 200 mesh, it is possible that the triboelectrostatic technology could be efficiently applied.

The modeling of particle flow in a conceptual separator suggested a potential and rather simple design for a in-line system. The cost for a new, stand-alone system was estimated to be less than \$3/ton whereas incorporating an in-line separator in an existing plant was estimated to cost near \$1.50/ton.

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Figure 1: Charge measurement probe used at the Spurlock and Widows Creek PC power stations.

Figure 2: Location of sampling ports in the Spurlock Station, pressurized pulverization system.

Figure 3. Coal sample port used in the Widows Creek pulverization system.

Figure 4. Laboratory triboelectrostatic separator used in pulverized coal beneficiation studies

Figure 5. Schematic of continuous 4-40 kg/hr separator.

Figure 3. Laboratory separation results for pulverized coal obtained at the partner power stations.

Distance from port wall (cm)	Sample Weight (g)	Sample Time (s)	Sample Flowrate (g/s)	Average Current (nA)	Average Charge (10^{-6} C/kg)
Spurlock Station					
5.1	53.50	163	.33	18	53
10.2	57.30	169	.34	15	44
15.2	51.70	196	.26	14	53
20.3	74.96	194	.39	15	38
25.4	78.15	227	.34	11	32
Widows Creek					
5.0	111.40	78	1.43	-84	-59
7.5	79.01	52	1.52	-139	-92
10	71.95	50	1.44	-155	-108
12.5	80.40	69	1.17	-119	-102

Table 1. Charge measurement data summary obtained at the coal fired power plants.

Voltage		25 kV			15 kV			7.5 kV			0 kV		
sample	feed	left	filter	right	left	filter	right	left	filter	right	left	filter	right
Spurlock Station													
avg. wt. (g)		15.05	19.35	25.14	6.60	7.03	10.38	6.93	12.79	10.18	0.79	46.05	1.74
weight %	100	25.3	32.5	42.2	27.5	29.3	43.2	23.2	42.8	34.0	1.6	94.8	3.6
ash	11.57	22.70	13.29	6.32	22.22	11.94	5.32	22.00	11.38	5.76	12.09	11.63	12.37
moisture	1.58	2.06	1.61	1.71	1.75	1.58	1.83	1.91	1.72	1.79	1.70	1.71	1.64
volatiles	31.97	26.82	32.25	33.32	27.45	32.49	33.63	27.69	32.28	33.27	30.97	31.99	31.08
carbon	54.9	48.4	52.8	58.6	48.6	54.0	59.2	48.4	54.6	59.2	55.2	54.7	54.9
Ash Removal		45%			51%			43%			2%		
Combust. Recovery		78%			76%			80%			98%		
Widows Creek		30 kV			20 kV			15 kV			7 kV		
avg. wt. (g)		21.63	40.76	34.07	21.95	46.32	31.64	20.69	48.98	28.74	14.83	59.94	19.82
weight %	100	22.4	42.3	35.3	22.0	46.3	31.7	21.0	49.8	29.2	15.7	63.3	21.0
ash	12.21	20.97	13.41	7.75	22.80	13.59	6.79	22.82	13.41	8.00	20.54	12.28	8.08
moisture	1.41	1.25	1.44	1.42	1.37	1.83	1.96	1.53	1.38	1.42	1.32	1.53	1.89
volatiles	35.49	31.31	35.52	36.59	31.44	35.45	36.60	32.00	35.26	36.00	32.09	35.69	37.43
carbon	50.90	46.47	49.63	54.24	44.40	49.13	54.64	43.65	49.96	54.58	46.05	50.51	55.73
Ash Removal		39%			41%			39%			26%		
Combust. Recovery		80%			81%			82%			86%		

Table 2. Electrostatic separation results obtained at the power stations.

Table 1: Equipment cost for a 2 ton/hr *stand-alone* dry coal separator (An in-line system is estimated to cost less than ½ this value).

Item	cost \$	life	cost/ton
Fan and motor:	50K	10 years	0.29
Feeder	2.4K	6 month	0.28
Separator	100K	10 years	0.58
High Voltage	3K	10 years	0.02
Baghouses	10K	10 years	0.06
Pipes	2K	1 year	0.11
	164.4K		1.34

Appendix 1.

List of Publications and Presentations

H. Ban, J.L. Schaefer and J.M. Stencel, *Process and Material Dependencies for Dry Electrostatic Coal Cleaning*, Workshop, Dry Separation Technology Development, 3/14/95, Lexington, KY

J.L. Schaefer, H. Ban, K. Saito and J.M. Stencel, *Quantifying Pulverizer Induced Charge in a Utility Boiler*, Twelfth Annual International Pittsburgh Coal Conference, Pittsburgh, PA, 9/11-15, 1995.

J.M. Stencel, H. Ban, J.L. Schaefer and J.C. Hower, *Partitioning and Behavior of Coal Macerals during Dry Coal Cleaning*, Proc., 8th International Conf. Coal Science (ICCS), 9/10-15/95, Oviedo, Spain, Vol. 2, pp. 1549-1552.

J.Hower, H. Ban, J.L. Schaefer and J.M. Stencel, *Macerial/Microlithotype Partioning Through Triboelectristatic Dry Coal Cleaning*, Soc. Org. Petrologists, Houston, TX, 8/28-29/95.

H. Ban, T.-X. Li, J.L. Schaefer and J.M. Stencel, *Dry Triboelectrostatic Beneficiation of Coal and Fly Ash Using Recovery Analysis*, 13th Annual International Pittsburgh Coal Conf., Pittsburgh, PA, Sept. 3-7, 1996.

J.L. Schaefer, H. Ban, K. Saito and J.M. Stencel, *Pulverizer Induced Charge: Comparison of Separate Utility Pulverizer Configurations*, 13th Annual International Pittsburgh Coal Conference, Pittsburgh, PA, 9/3-7/96.

J.M. Stencel, T.-X. Li, J.K. Neathery, J.L. Schaefer and H. Ban, *Fundamentals of Triboelectrostatic Separation: A Discussion on Particle Charge, Particle Size and Separation*, 1997 SME Annual Meeting & Exhibit, Denver, Colorado, 3/1-4/97.

J.M. Stencel, J.L. Schaefer, J.K. Neathery, H. Ban and T.-X. Li, *In-line Coal Cleaning: Triboelectrostatic Separation of Coal and Mineral Matter*, 9th International Conf. Coal Science, Essen, Germany, 9/7-12/97.

J.M. Stencel, J.L. Schaefer, H. Ban, T.-X. Li and J.K. Neathery, *Triboelectrostatic Cleaning of Coal In-line between Pulverizers and Burners at Utilities*, 9th International Conf. Coal Science, Essen, Germany, 9/7-12/97

J.M. Stencel, J.L. Schaefer, H. Ban, T.-X. Li and J.K. Neathery, *Mineral Matter Rejection In-line Between Pulverizers and Burners at a Utility*, Engineering Foundation Conf., Impact of Mineral Impurities in Solid Fuel Combustion, Kona, Hawaii, 11/2-7/97.

J.Hower, H. Ban, J.L. Schaefer and J.M. Stencel, *Maceral/Microlithotype Partioning Through Triboelectristatic Dry Coal Cleaning*, International Journal Coal Geology, 34(1997)277-286.

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