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TECHNICAL PROGRESS REPORT

for the Fourth Quarter

(July, 1996 to September 30, 1996)

POC-SCALE TESTING OF A DRY TRIBOELECTROSTATIC SEPARATOR FOR FINE COAL CLEANING

by

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ABSTRACT

The Pittsburgh Energy Technology Center (PETC) developed a triboelectrostatic separation (TES) process which is capable of removing mineral matter from coal without using water. A distinct advantage of this dry coal cleaning process is that it does not entail costly steps of dewatering which is a common problem associated with conventional fine coal cleaning processes. It is the objective of this project to conduct a series of proof-of-concept (POC) scale tests at a throughput of 200-250 kg/hr and obtain scale-up information. Prior to the POC testing, bench-scale test work will be conducted with the objective of increasing the separation efficiency and throughput, for which changes in the basic designs for the charger and the separator may be necessary. The bench- and POC-scale test work will be carried out to evaluate various operating parameters and establish a reliable scale-up procedure. The scale-up data will be used to analyze the economic merits of the TES process.

At present, the project is at the stage of engineering design (Task 3). Work accomplished during this reporting period are summarized as follows:

i. An on-line tribocharge analyzer has been developed to study triboelectrification.

ii. The effects of aeration rate, feed rate and particle size on the tribocharging mechanisms using the on-line tribocharge analyzer.

iii. A continuous bench-scale triboelectrostatic separator has been constructed.

iv. Shakedown testing of the bench-scale triboelectrostatic separator is on-going.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Numerous advanced coal cleaning processes have been developed in recent years that are capable of substantially reducing both ash- and sulfur-forming minerals from coal. However, most of the processes involve fine grinding and use water as cleaning medium; therefore, the clean coal products must be dewatered before they can be transported and burned. Unfortunately, dewatering fine coal is costly, which makes it difficult to deploy advanced coal cleaning processes for commercial application.

As a means of avoiding problems associated with the fine coal dewatering, the Pittsburgh Energy Technology Center (PETC) developed a dry coal cleaning process, in which mineral matter is separated from coal without using water. In this process, pulverized coal is subjected to triboelectrification before being placed in an electric field for electrostatic separation. The triboelectrification is accomplished by passing a pulverized coal through an in-line mixer which is made of copper, whose work function lies in-between those of carbonaceous material (coal) and mineral matter. Thus, coal particles impinging on the copper wall loses electrons to the metal, thereby acquiring positive charges, while mineral matter impinging on the wall gains electrons to acquire negative charges. The triboelectrostatic separation (TES) process has been tested successfully on bench-scale. The results obtained at PETC showed that it is capable of removing more than 90% of the pyritic sulfur and 70% of the ash-forming minerals from a number of eastern U.S. coals. It is necessary, however, to test the process on a proof-of-concept scale so that appropriate scale-up information is obtained. Furthermore, it is necessary to increase the throughput of the TES process by improving the design for the electrostatic separation system.

The laboratory-scale batch TES unit used by PETC relied on adhering charged particles on parallel electrode surfaces and scraping them off. Therefore, its throughput will be proportional to the electrode surface area. If this laboratory device is scaled-up as is, it would suffer from low throughput capacity and high maintenance requirement. In general, surface area-based separators (e.g., shaking tables, magnetic drum separator, electrodynamic separator, etc.) have lower throughput capacities than volume-based separators (e.g., flotation cell, dense-medium bath, cyclones, etc.) by an order of magnitude. Furthermore, the electrodes of the laboratory unit need to be cleaned frequently, creating a high-degree of maintenance requirement if it is scaled-up to a commercial unit. The bench-scale continuous TES unit developed at PETC, on the other hand, separates positively and negatively charged particles by splitting the gaseous stream containing these particles in an electric field by means of a flow splitter, so that the oppositely charged particles can be directed into different compartments. This device is fundamentally different from the laboratory unit in that the former is a volume-based separator, while the latter is a surface area-based separator. The bench-scale unit is referred to as *entrained flow* separator by the in-house researchers at PETC. Thus, the entrained flow TES unit is a significant improvement over the laboratory unit with regard to throughput capacity.

In the present work, the entrained flow separator will be scaled-up to proof-of-concept POC-scale. However, the parallel plate electrodes will be replaced by a pair of circular electrodes, for which there are two advantages. First, the circular electrodes provide a non-uniform electric field (and, hence, a field gradient), which will be conducive for improving the separation of oppositely charged particles from each other. Second, the electrode will be rotated so that fresh electrode surfaces can be exposed. This new design is similar to the open-gradient magnetic separator developed by Oak Ridge National Laboratory during the early 1980s. Therefore, the new design may be referred to as *open-gradient* triobelectrostatic separator.

OBJECTIVES

It is the objective of the project to further develop the TES process developed at PETC through bench- and POC- scale test programs. The bench-scale test program is aimed at studying the charging mechanisms associated with coal and mineral matter and improving the triboelectrification process, while the POC-scale test program is aimed at obtaining scale-up information. The POC-scale tests will be conducted at a throughput of 200-250 kg/hr. It is also the objective of the project to conduct cost analysis based on the scale-up information obtained in the present work.

Specific objectives of the work conducted during this quarter were: i) to design and construct an on-line tribocharge analyzer that can be used for studying triboelectrification mechanism with an objective of maximizing separation efficiency (Task 3.1) and ii) to complete the construction of a continuous bench-scale TES unit that can process coal at a throughput of 1kg/hr (Task 3.2).

WORK DESCRIPTION

Task 3.1: Tribocharger Tests

As will be shown later in this report, separation efficiency of the TES process depends critically on the surface charges of the particles involved. In general, the larger the difference between the charges of particles to be separated, the higher the separation efficiency. It is, therefore, the objective of this subtask to design efficient charger for the triboelectrostatic separator. To meet this objective, the following R&D activities will be undertaken.

- studies of charging mechanism
- evaluation of charger design

- evaluation of charger materials
- development of design/scale-up criteria

During the current reporting period, charging mechanisms have been studied. Two different techniques were considered. One is the technique developed by Mazumder, in which charged particles are placed in an electromagnetic field, while monitoring the trajectories. The other is the method of using Faraday cages. The former may be more accurate than the latter; however, it requires a more sophisticated and costly equipment. Furthermore, this technique cannot be used for measuring the charges of particles larger than 60 μm. Although most of the TES tests were conducted on micronized coal samples at PETC, it is hoped that the POC module to be developed in the present work can be tested on coarser particles, (e.g., PC-grinds). It was, therefore, decided to use a Faraday cage to measure particle charges in the present work.

Figure 1 shows the Faraday cage used for measuring charges of particles, and Figure 2 shows how it is connected to an electrometer (Keithly Model-642) and a data acquisition system. The Faraday cage consists of inner and outer cages made of copper. The inner copper cage is electrically connected to the electrometer through a coaxial cable, while the outer cage is grounded. Both the inner and outer cups have copper lids to prevent the measurement being affected by the stray electric fields from the surroundings. This design is different from what is generally reported in the literature. Without the lids, the measurement suffered from too much noise. The particles are delivered to the inner cage through a small copper tubing, which is an extension of the inner cup. It is necessary to make the copper tubing as part of the inner cage. Otherwise, particles colliding on the inner wall of the copper tubing can acquire additional charges, causing a source of error.

Figure 3 illustrate the mechanisms involved in the charge measurement using the Faraday cage. Consider particles touching the walls of the inner cup (Figure 3a). Let us assume that the particles are charged negatively, in which case the free electrons of the particles will flow from the particle surface to the walls, resulting in a flow of electric current from the Faraday cage to the electrometer. Consider also the case of the negatively charged particles not touching the walls (Figure 3b). In this case, the negatively charged particles will polarize the inner copper cup in such a way that the inner wall is positively charged while the outer wall is negatively charged. The free electrons will flow from the negative charge sites of the inner wall to the electrometer, causing a current. Thus, the net results are the same in both cases, i.e., the presence of negatively charged particles will result in a current flowing from the Faraday cage to the electrometer.

In order to facilitate an in-situ measurement, an on-line tribocharge analyzer has been developed as shown in Figure 4. This device consists of an in-line static mixer and an outer tube made of copper. The in-line static mixer is electrically connected to the electrometer by means of a coaxial cable, while the outer tube which served as a shield against surrounding electronic interference is connected to the ground. Figure 5 shows the entire on-line tribocharge analyzing system. It is capable of acquiring and digitizing the analog signal when particles pass through the tribocharger. The Fast Fourier Transformation (FFT) procedure has been applied to the digitized information for noise reduction.

Figure 6 shows a print out from our data acquisition system connected to the on-line tribocharge analyzer. The result was obtained with a Pittsburgh No. 8 coal sample (28 x 65 mesh). It shows that the coal particles are negatively charged and charge density increases with an increase in aeration rate. As noted in the last quarterly report, we are planning investigate the following parameters as part of the studies of charging mechanisms:

- particle size
- rank of coal

- intensity of agitation/aeration rate/feed rate
- agitation time
- coal-to-particle ratio in feed
- charger material
- temperature

All of these parameters are needed for designing efficient POC-scale TES unit.

During the current reporting period, three of these parameters have been studied, i.e. particle size, aeration rate and feed rate. At a given test condition, the measurement was repeated at least three times in order to obtain reproducible results. Table I-VII shows all of the test result. Figure 7 shows the effect of the aeration rate on the charge density for different particle sizes. In general, charge density increased with an increase in aeration rate regardless of particle sizes. For a given aeration rate, finer particles gained higher charge than coarse particles. The effect of particle feed rate on the charge density is shown in Figure 8. For coarser particle sizes, i.e. +100 mesh, the charge density increased with an increase in feed rate; however, a decrease in charge density was observed when finer coal sample, i.e. 100 x 200 mesh was used. Similar observations have been reported in the literature (Schaefer, Ban and Stencel) .

Figure 9 shows the effect of particle size on the charge density. The charge measurements were conducted at a given aeration rate and feed rate. The results given in Figures 7-9 shows the basis of the TES process, i.e., coal particles are separated from ash-forming minerals such as quartz due to the difference in particle charge. As shown in our theoretical model reported previously, maximizing the charge difference and understanding the charge behavior of particles would increase the separation efficiency.

Task 3.2 Separator Tests

The primary objectives of this subtask are i) to evaluate different bench-scale designs for the triboelectrostatic separator, and ii) to investigate the various operating parameters on separator performance. The information obtained from this task will be used for obtaining engineering guidelines for the design, manufacture, operation and optimization of the 200-250 Kg/hr POC unit. The bench-scale tests will be conducted using two different separators having nominal capacities of 1 kg/hr and 10-20 kg/hr. The performance data obtained for these units will be used to develop scale-up criteria for POC unit.

During the past quarter, a bench-scale TES separator has been constructed. Figure 10 shows a schematic representation of the separator. A coal containing mineral matter is pneumatically fed to an in-line mixer charger. When the particles exit the charger, coal particles will be charges positively while the mineral matter be charged negatively. The charged particles will pass through a collimator (flow straightner) and then through the uneven electric field created between two rotating circular electrodes. Positively charged coal particles are directed toward the negative electrode, while negatively charged mineral matter are directed toward the positive electrode. The splitter in between the two electrodes can be located in different positions to achieve some control of grade and recovery. The main advantage of this open-gradient separator concept is that the throughput is essentially proportional to the volume of the entrained flow. In addition, the rotating cylindrical electrodes are self-cleaning.

A bench-scale open-gradient TES unit has been fabricated and assembled. Figure 11 shows the original engineering design of the equipment. A power supply and control panel has been installed and hooked-up to the electrodes during the past quarter. The power supply is capable of attaining a maximum applied voltage of 100 kV across the electrodes, i.e., +/- 100 kV to the working electrode while the other electrode is connected to ground. A feeding system, which consists of an one-inch tribocharger and a distributor (Figure 12), has been installed and tested. The shakedown test work showed that without the installation of collimator (flow straightner), the disturbance of air flow within the separator resulted in a poor separation. These findings lead to the modification of the bench-scale. In this modification, a partition chamber and collimator have been installed, as shown in Figure 13, to eliminate unnecessary air disturbances in the separator when vacuum is applied. In the present work, feed samples were prepared by pulverizing coal sample in a hammer mill and feeding them by means of a screw.

Table VIII shows the shakedown test results of the TES unit. All of the tests were conducted by applying a potential of -60 kV to one of the electrode and the other grounded. Under this condition, positively charged coal particle are attracted to the negatively charged electrode, while the negatively charged ash-forming minerals (and perhaps pyrite also) bypass the electric field without being collected. It was observed that the grounded electrode did not attract significant amount of the ash-forming minerals or pyrite. The first two tests were conducted to see the effect of downward air flow velocity on the separation efficiency. When the test was conducted without vacuum, i.e., no significant downward air velocity, the separation was poor. The clean coal product assayed almost the same as the feed coal, indicating that no separation occurred when the downward air flow velocity was too low. When the test was conducted by pulling the air downward, the ash content was reduced from 17.9% to 7.04%, indicating significant separation.

The next series of shakedown tests were conducted by applying -60 kV to one of the electrode and keeping the other electrode grounded. All of the tests were conducted by creating a downward air flow by applying a vacuum at the bottom. In this test, a Pittsburgh No.8 coal assayed 20.3% ash and 4.01% sulfur was subjected initially to a rougher separation test. The clean coal product from the rougher was then subjected to a cleaner test, while the reject from the rougher was being subject to a scavenger test. The results of the rougher, cleaner and scavenger test work are given in Figure 14. As shown, the TES unit reduced the ash from 20.3% to 5.69% after one stage of cleaner operation while the sulfur content was reduced from 4.10% to 1.87%. However, the yield after the rougher and cleaner operations was low. The test results demonstrate that the TES technology provides an means of achieving a high degree of pyritic sulfur rejection, which is consistent with the results obtained by the in-house research group at PETC.

During the next quarter, we are planning to control the electrode potential such that we can obtain high BTU recoveries. This can be readily achieved by applying a positive potential to one of the electrode and keeping the other grounded. In this manner, only the impurities such as ash and pyrite will deviate from their original trajectories, which will result in high coal recoveries.

A project review meeting was held at CCMP on October 10, 1996. The meeting was attended by Dr. Michael Nowak and Dr. Richard Read. After reviewing the test results obtained in our shakedown test work and those obtained previously at PETC, there was a general agreement that the emphasis of our feature work should be placed on maximizing the BTU recovery and pyritic sulfur rejection. We believe that these objectives are achievable through further research. Drs. Nowak and Read were pleased that our new on-line tribocharge analyzer produced excellent results. Mr. Frank Knoll, president of Carpco Inc., stated that this device will be useful for studying the charging mechanism, and the result of which can be used to improve the separation efficiency of our TES unit. It is believed that the on-line tribocharge analyzer is marketable, possibly byCarpco.

In view of our emphasis on pyrite rejection in the future, it is proposed that the charging mechanism of pyrite be conducted in the present work. This task was not planned originally, but the work will be conducted with no additional cost to DOE.

SUMMARY

The work performed during the current reporting period was concerned with Engineering Design (Task 3). As part of this task, tribocharging mechanism has been studied (Subtask 3.1). A major accomplishment made during the past quarter was that an on-line tribocharge has been developed. This device is equipped with a data acquisition system to achieve a high degree of accuracy and increase the speed of measurement. The advantage of using an on-line tribocharge analyzer is that in-situ charge measurement can be performed and a wide range of particle sizes can be studied. It will be useful for studying the charging mechanism and separation efficiency of our TES unit.

Three of the tribocharging parameters, i.e. particle size, aeration rate and feed rate, have been studied. Tests results showed that charge density increased with an increase in aeration rate regardless of particle sizes. For a given aeration rate, finer particles gained higher charge than coarse particles. The effect of particle feed rate on the charge density showed opposite trending when different sizes of coal sample being used. For coarser particle sizes, i.e., +100 mesh, charge density increases with an increase in feed rate; however, a decrease in charge density was observed when finer coal sample, i.e., 100 x 200 mesh, being used.

As part of the Engineering Design work, a bench-scale TES unit has been constructed (Subtask 3.2). Shakedown tests of the continuous bench-scale TES unit showed that without applying vacuum, i.e., no significant downward air velocity, the separation was poor. Test results also showed excellent sulfur rejection which is consistent with the results obtained by the in-house research group at PETC.

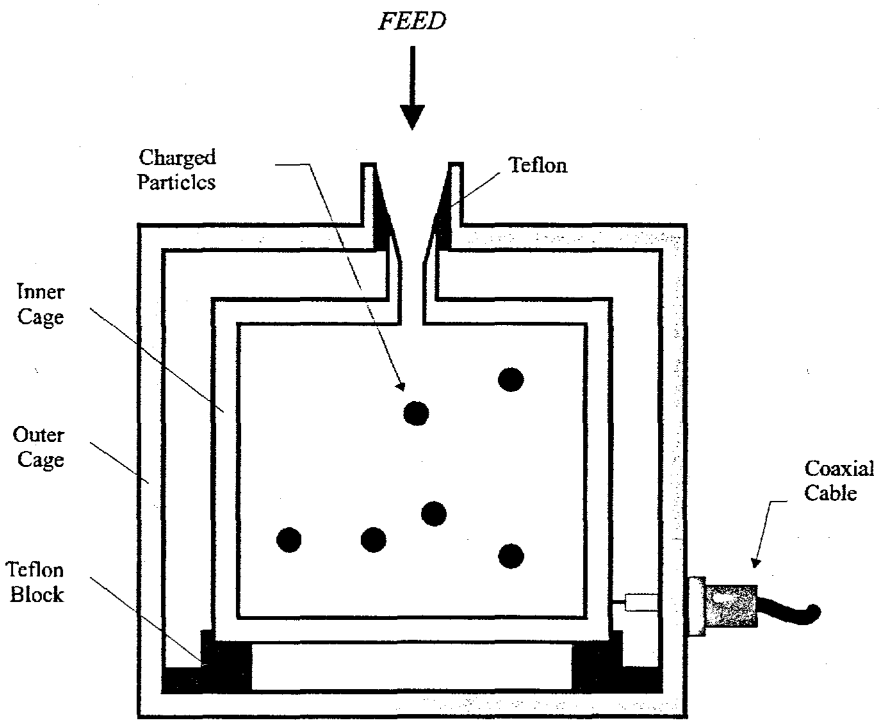

Figure 1. Schematic representation of the Faraday cage used in the present work.

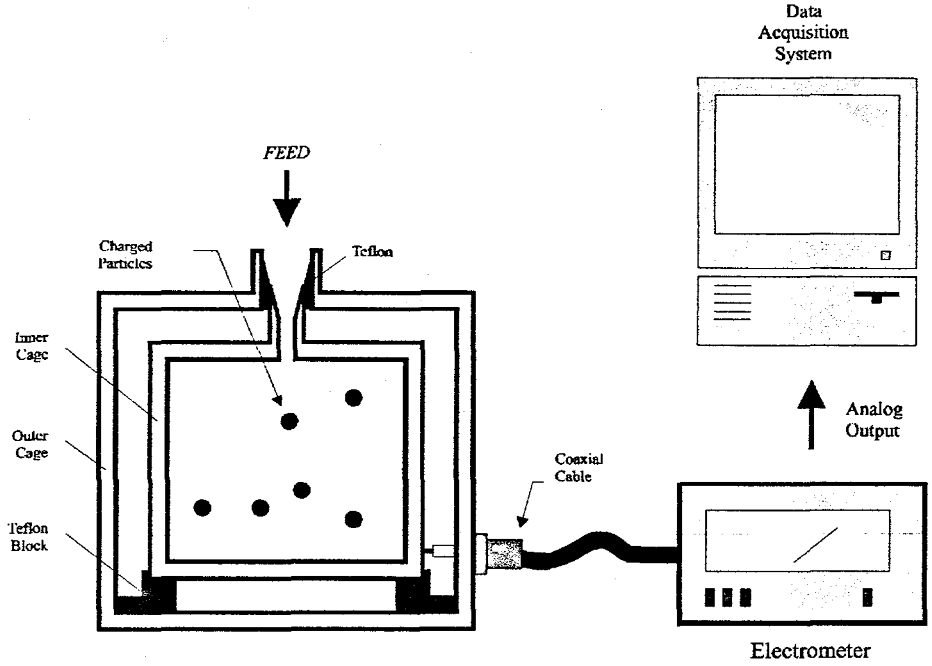

Figure 2. Instrumentation setup for the particle charge measurement using a Faraday cage.

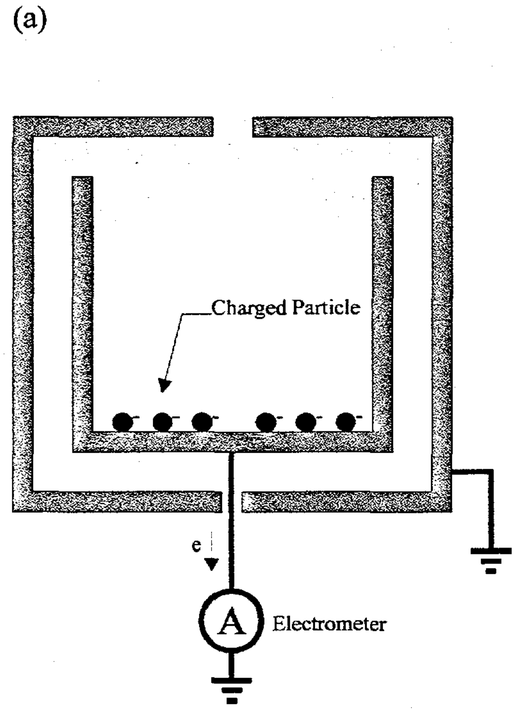

Figure 3. Schematic representation of the principles of particle charge measurement using a Faraday cage

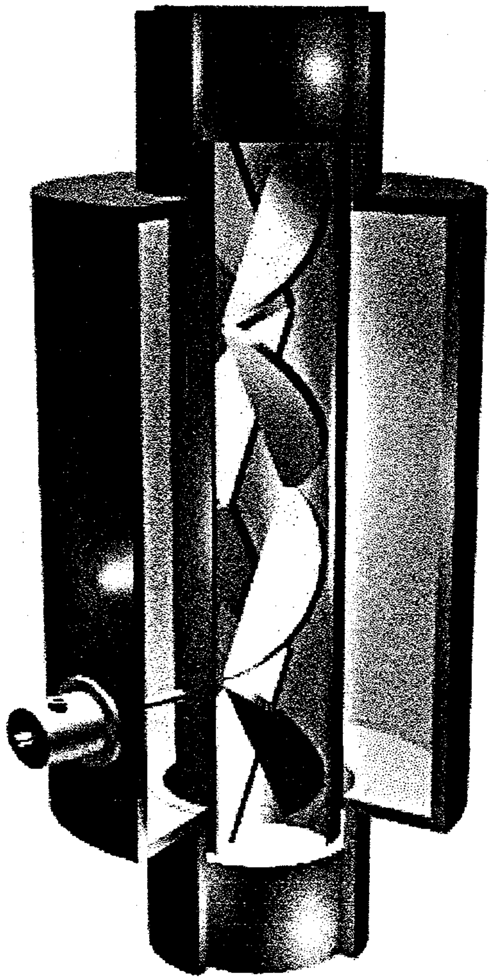

Figure 4. Schematic representation of the on-line charge measurement device for studying triboelectrification used in the present work.

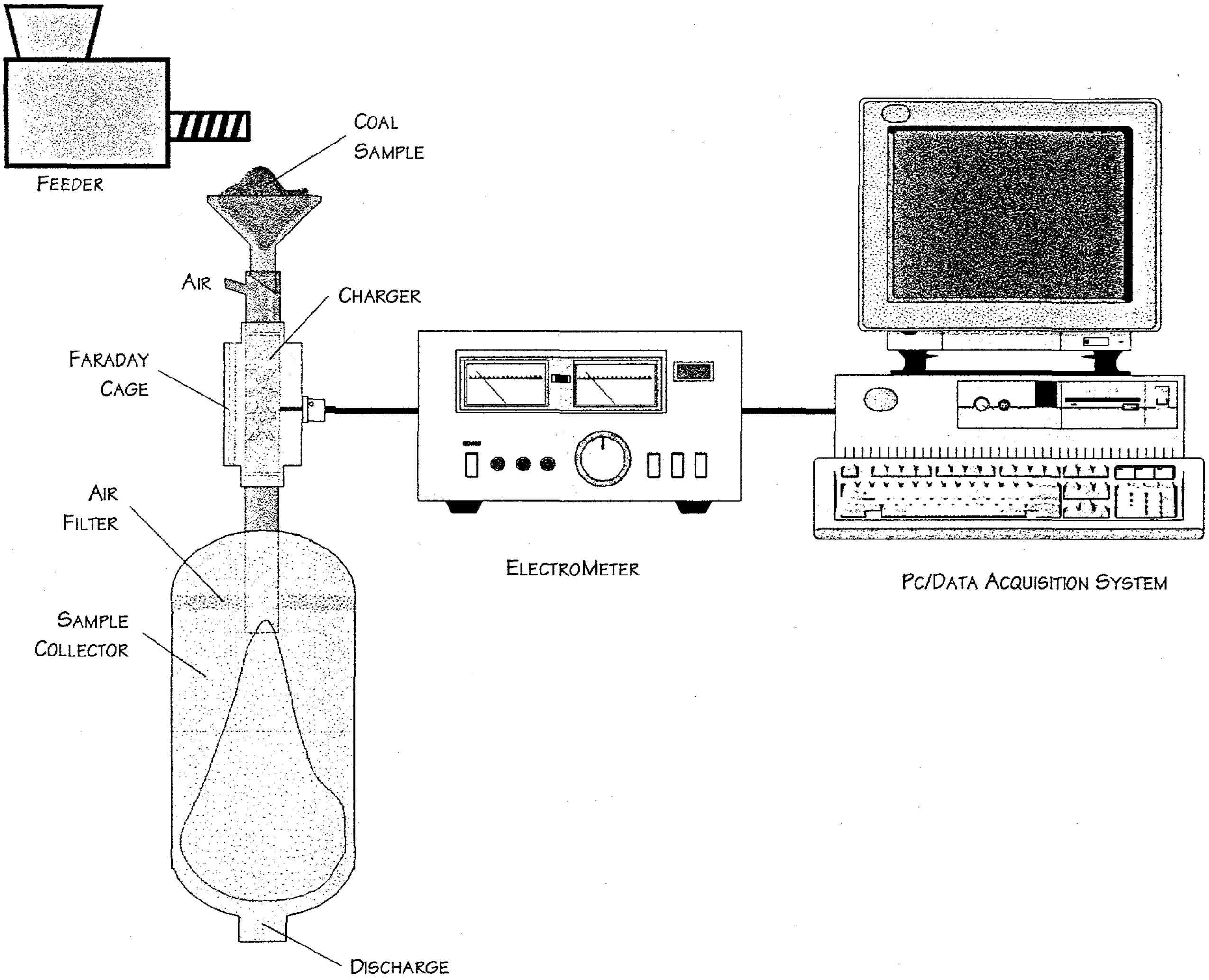

Figure 5. Schematic representation of charge measurement setup using the on-line charge measurement device.

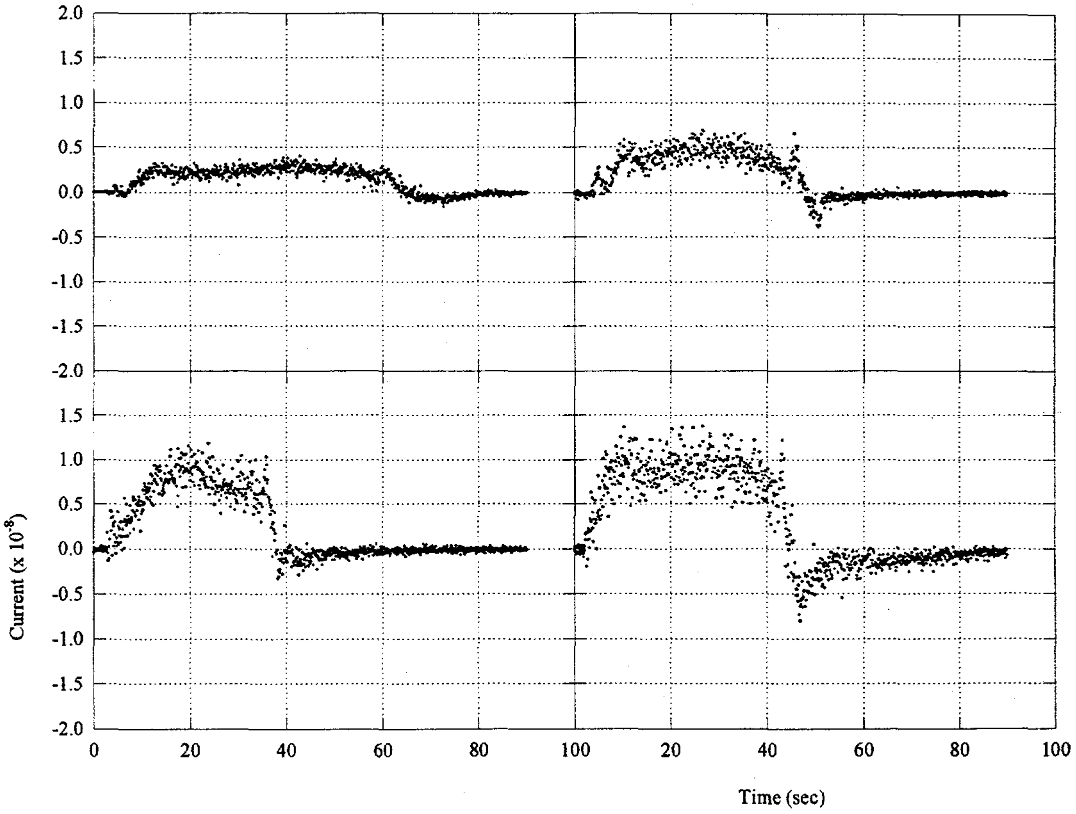

Figure 6. A printout from the data acquisition system used in conjunction with the on-line charge measurement device. The results were obtained on a Pittsburgh No. 8 coal sample (-28x 65 mesh) with different aeration rates.

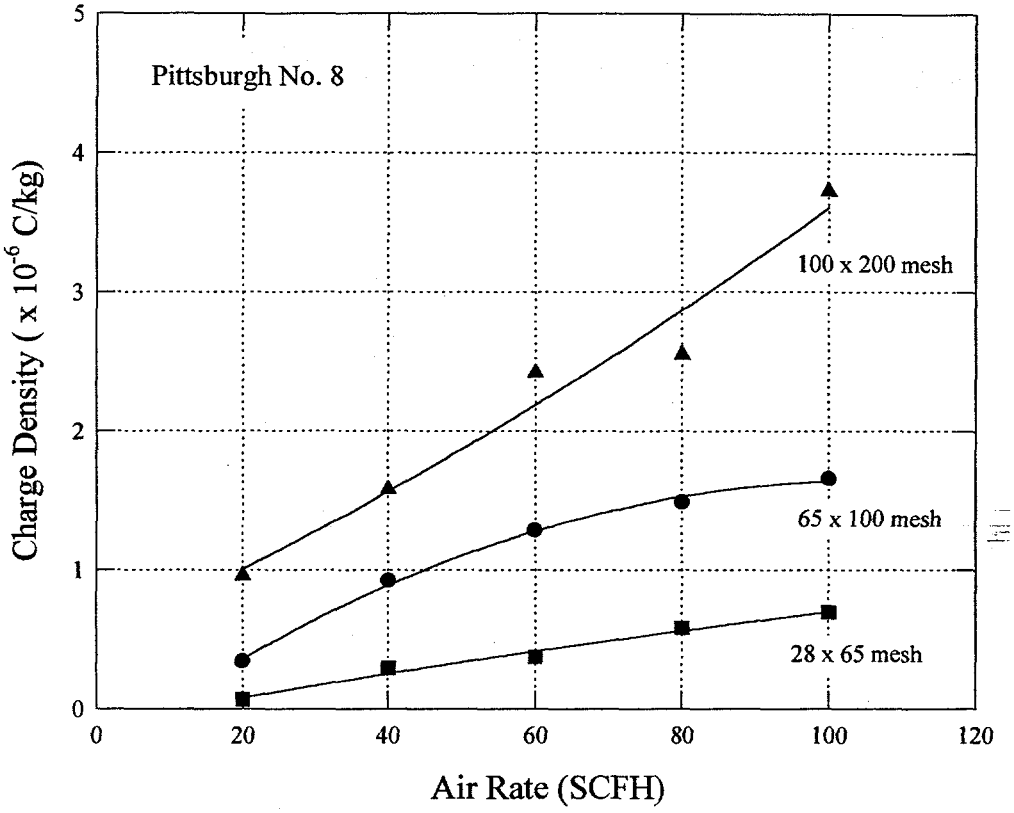

Figure 7. Effect of aeration rate on charge density. The results were obtained on Pittsburgh No. 8 coal samples with different particle size.

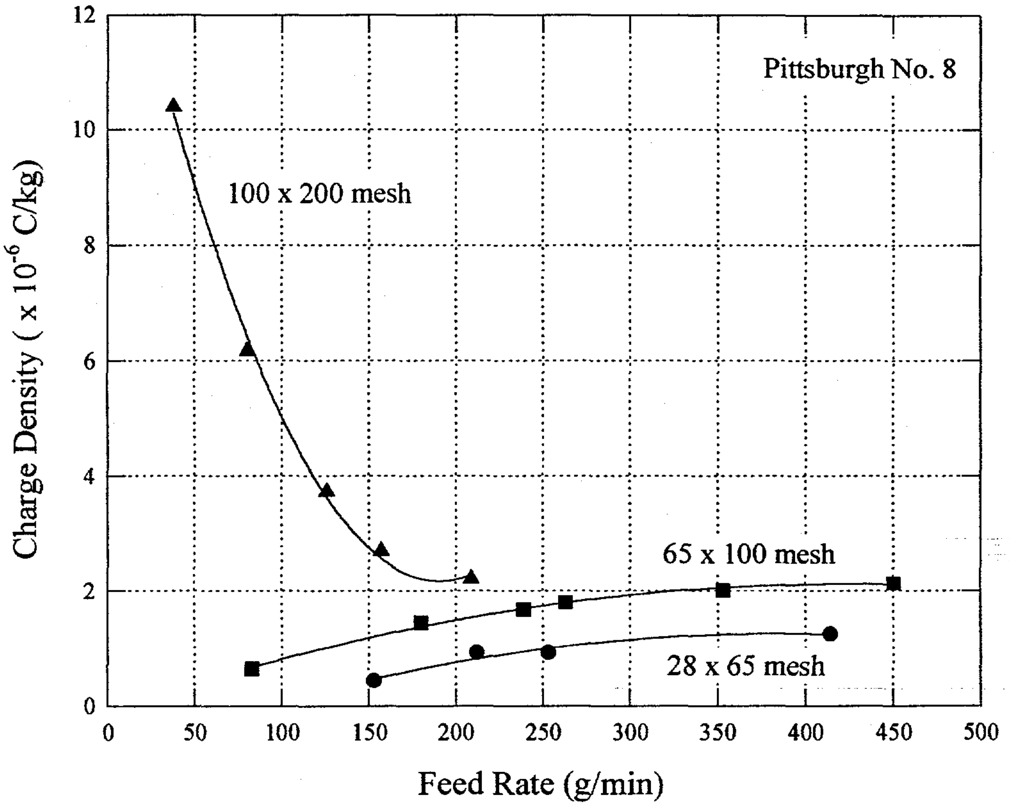

Figure 8. Effect of feed rate on charge density. The results were obtained on Pittsburgh No. 8 coal samples with different particle size.

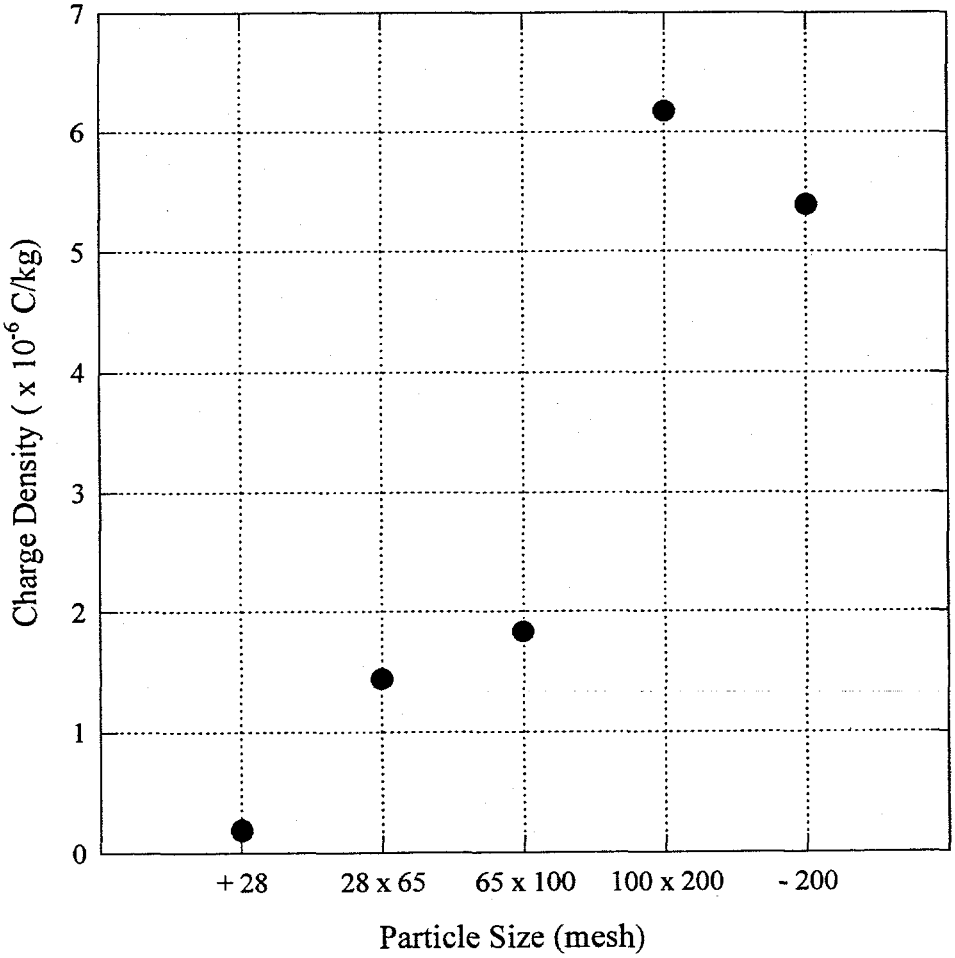

Figure 9. Effect of particle size on charge density. The results were obtained on Pittsburgh No. 8 coal samples with a 150 g/min feed rate.

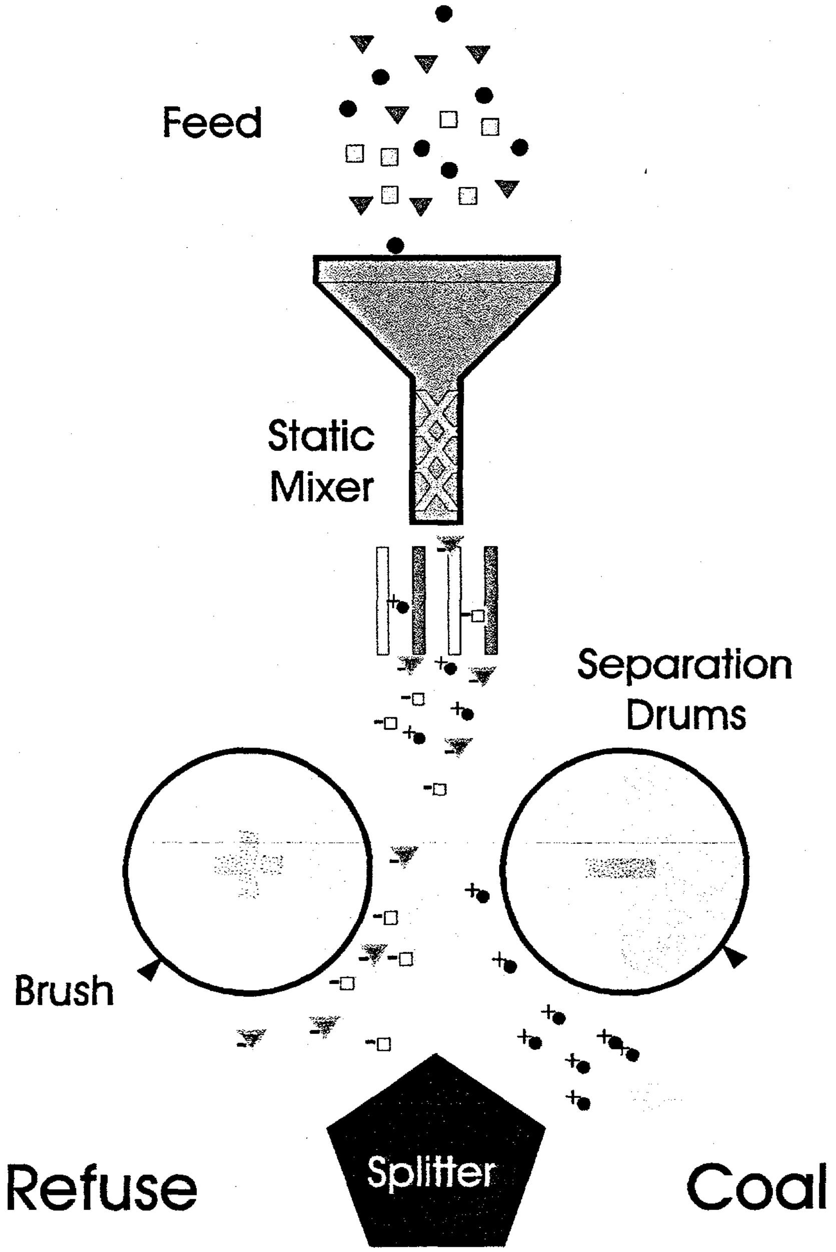

Figure 10. Schematic representation of the open-gradient triboelectrostatic separator used in the present work.

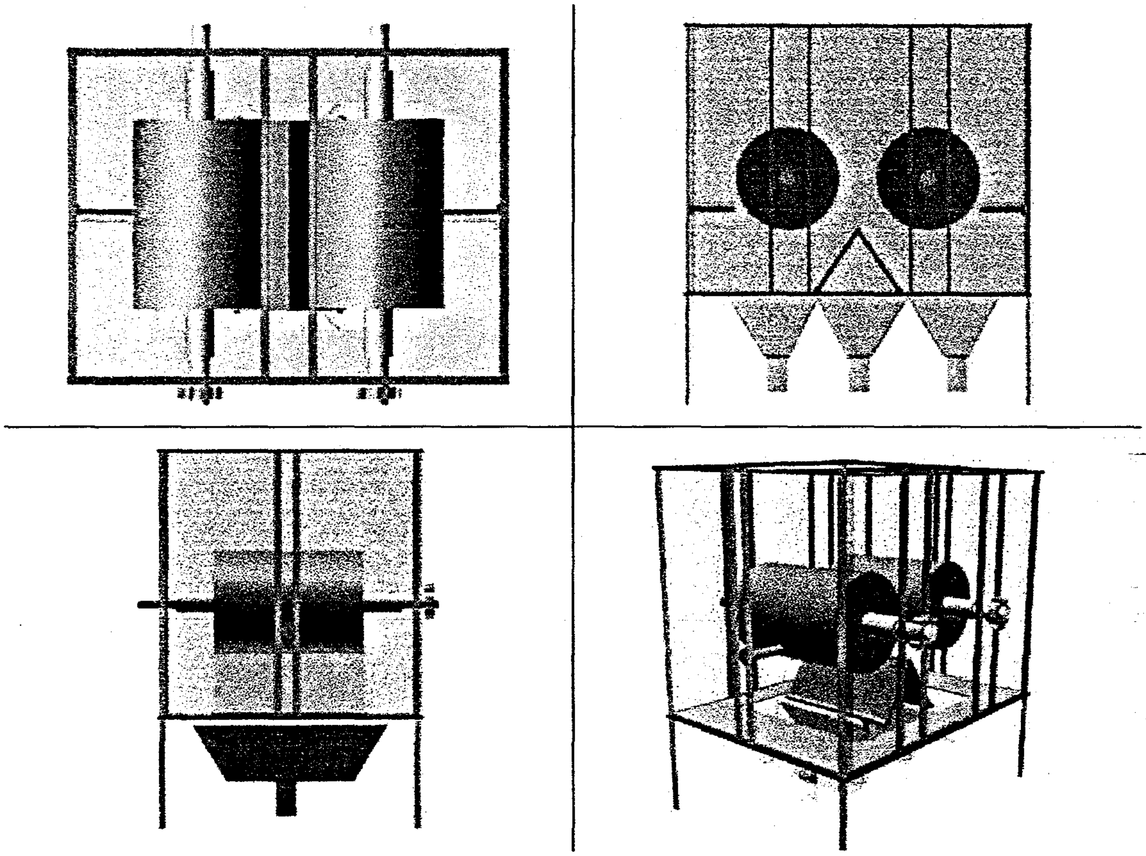

Figure 11. Schematic representation of the original engineering design of the open-gradient triboelectrostatic separator.

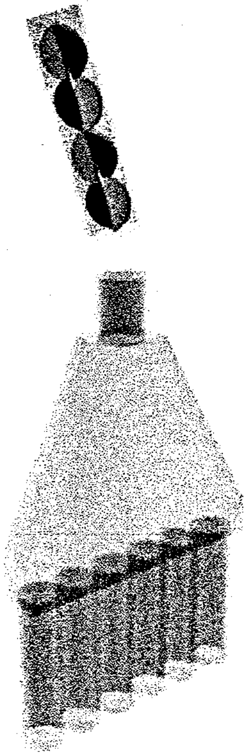

Figure 12. Schematic representation of the tribocharger and feed distribution system used in the present work.

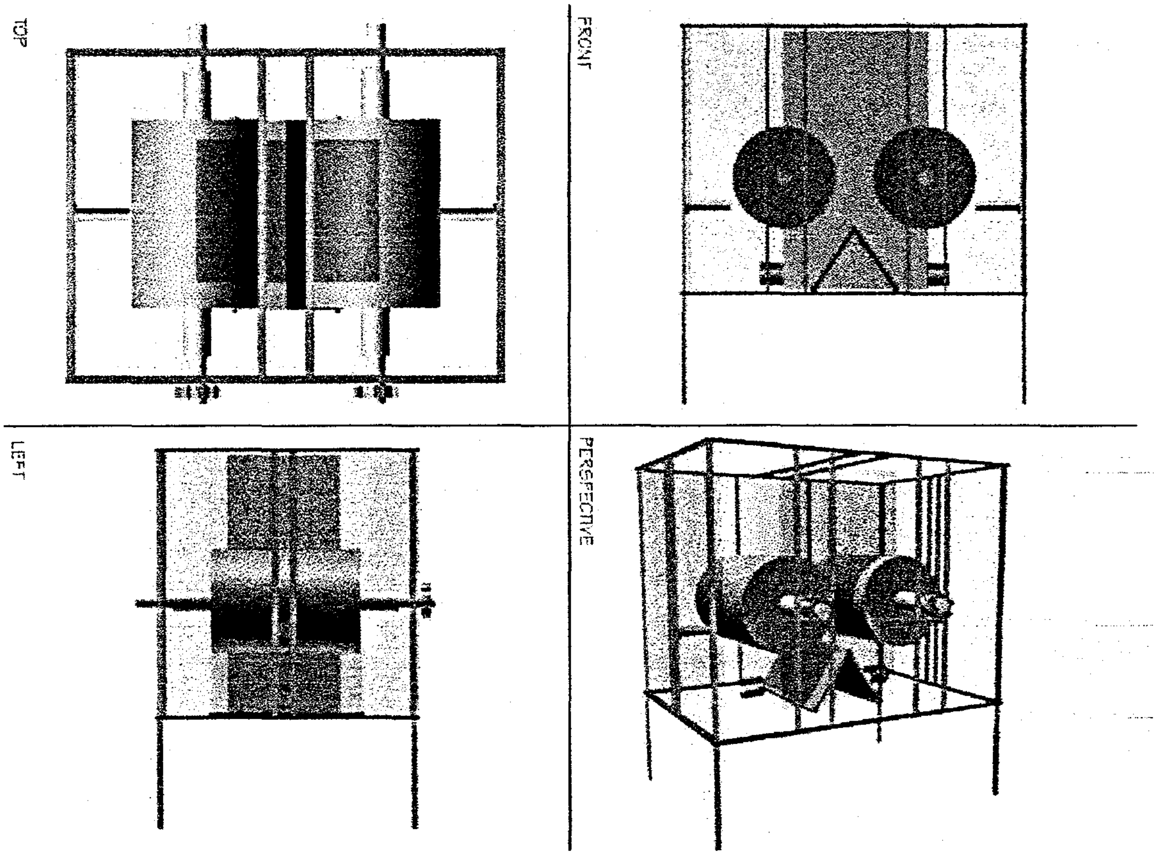

Figure 13. Schematic representation of the modified engineering design of the open-gradient triboelectrostatic separator used in the present work

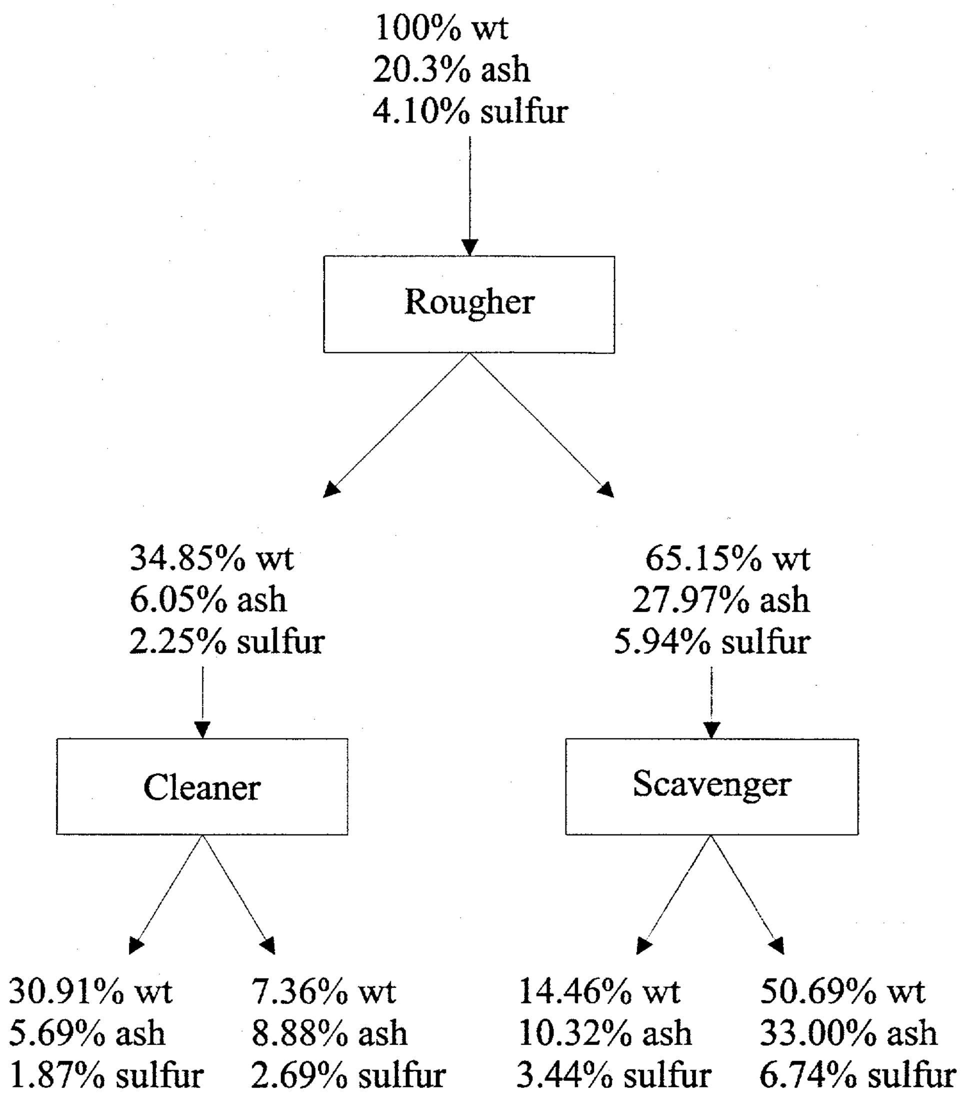

Figure 14. Rougher, cleaner and scavenger test results of the continuous bench-scale triboelectrostatic separator

Table I Charge measurement test results of 28 x 65 mesh Pittsburgh No. 8 coal sample.

Weight (g)	Time (sec)	Feed Rate$_{ave}$ (g/min)	Charge Density, σ (x 10^{-7} C/Kg)	$\sigma_{average}$ (x 10^{-7} C/Kg)
400.1	36	686	2.97	4.42
400.2	35		4.40	
400.1	34		5.89	
400.0	42	571	4.49	4.56
400.0	41		4.73	
400.0	44		4.47	
400.2	57	414	12.1	12.5
400.1	57		11.8	
400.1	57		13.0	
400.0	62		12.5	
400.3	57		13.3	
400.2	95	253	9.33	9.29
400.3	95		9.24	
400.3	112	212	8.55	9.22
400.2	115		9.88	
400.3	150	157	4.52	4.41
400.3	155		5.39	
400.0	165		3.32	

Table II Charge measurement test results of 65 x 100 mesh Pittsburgh No. 8 coal sample.

Weight (g)	Time (sec)	Feed Rate$_{ave}$ (g/min)	Charge Density, σ ($\times 10^{-7}$ C/Kg)	$\sigma_{average}$ ($\times 10^{-7}$ C/Kg)
300.1	32	581	16.9	17.2
300.0	30		17.4	
300.1	40	450	22.1	21.4
300.0	40		19.9	
300.0	40		20.8	
300.1	40		22.6	
300.1	48	353	21.7	20.1
300.1	53		18.7	
300.3	53		20.0	
300.0	67	263	16.6	18.0
300.1	70		19.4	
300.1	76	239	16.9	16.8
300.3	75		18.0	
300.0	75		19.2	
300.1	75		12.9	
300.0	101	180	17.1	14.5
300.0	100		19.6	
300.2	100		18.3	
300.1	101		15.7	
300.0	98		10.6	
300.2	210	83	5.6	6.46
300.1	220		6.8	
300.2	220		7.0	

Table III Charge measurement test results of 100 x 200 mesh Pittsburgh No. 8 coal sample.

Weight (g)	Time (sec)	Feed Rate$_{ave}$ (g/min)	Charge Density, σ (x 10^{-7} C/Kg)	$\sigma_{average}$ (x 10^{-7} C/Kg)
300.0	86	209	23.6	22.2
300.1	86		20.7	
300.1	117	157	28.2	27.0
300.0	113		27.5	
300.1	115		25.2	
300.1	143	126	40.6	37.3
300.0	142		40.8	
300.0	144		30.6	
300.1	225	80	61.2	61.7
300.1	225		60.1	
300.0	225		59.9	
300.1	225		65.5	
300.0	475	38	103	104
300.0	475		96.2	
300.0	475		113	

Table IV Charge measurement test results of 28 x 65 mesh Pittsburgh No. 8 coal sample at a constant feed rate of 436 g/min.

Weight (g)	Air Rate (SCFH)	Charge Density, σ (x 10^{-7} C/Kg)	$\sigma_{average}$ (x 10^{-7} C/Kg)
400.0	20	0.62	0.68
400.2	20	0.75	
400.1	20	0.66	
400.0	40	2.55	2.93
400.2	40	3.14	
400.2	40	3.00	
400.0	40	3.02	
400.2	60	3.90	3.72
400.0	60	3.93	
400.2	60	3.34	
400.0	60	3.72	
400.0	80	6.78	5.82
400.1	80	5.46	
400.1	80	5.81	
400.1	80	5.21	
400.2	100	6.80	6.95
400.2	100	7.11	
400.0	100	6.94	

Table V Charge measurement test results of 65 x 100 mesh Pittsburgh No. 8 coal sample at a constant feed rate of 180 g/min.

Weight (g)	Air Rate (SCFH)	Charge Density, σ (x 10^{-7} C/Kg)	$\sigma_{average}$ (x 10^{-7} C/Kg)
300.2	20	5.12	3.41
300.1	20	2.94	
300.0	20	2.16	
300.0	40	8.47	9.22
300.0	40	10.1	
300.0	40	9.09	
300.0	60	16.4	12.9
300.0	60	10.8	
299.9	60	11.5	
300.1	80	15.5	14.9
299.2	80	18.7	
299.9	80	10.4	
300.0	100	14.1	16.6
300.1	100	18.6	
300.0	100	17.1	

Table VI Charge measurement test results of 100 x 200 mesh Pittsburgh No. 8 coal sample at a constant feed rate of 126 g/min.

Weight (g)	Air Rate (SCFH)	Charge Density, σ ($\times 10^{-7}$ C/Kg)	$\sigma_{average}$ ($\times 10^{-7}$ C/Kg)
300.0	20	9.75	9.6
300.0	20	9.12	
300.1	20	9.94	
300.1	40	15.9	15.8
300.0	40	15.8	
299.7	40	15.8	
300.1	60	24.1	24.2
300.1	60	24.5	
300.2	60	24.0	
300.0	80	24.8	25.5
300.1	80	25.9	
300.1	80	25.8	
300.0	100	30.6	37.3
300.1	100	40.6	
300.0	100	40.8	

Table VII Charge measurement test results of Pittsburgh No. 8 coal sample with different particle sizes.

Size (mesh)	Charge Density, σ (x 10^{-7} C/Kg)	$\sigma_{average}$ (x 10^{-7} C/Kg)
+28	1.66 2.90 1.12	1.89
-28 x 65	15.5 14.5 13.3	14.4
-65 x 100	16.9 17.6 18.9 19.9	18.3
-100 x 200	61.2 60.1 59.9 65.6	61.7
-200	45.4 62.3	5.39

Table VIII Shakedown test results of the continuous bench-scale triboelectrostatic separator

Test Conditions	Streams							
	Feed (%)		Clean Coal (%)			Refuse (%)		
	Ash	Sulfur	Ash	Sulfur	Yield	Ash	Sulfur	Yield
-60 kV w/o vacuum	17.58	-	15.13	-	42.47	17.90	-	57.53
-60 w/ vacuum	17.90	-	7.04	-	38.26	25.12	-	61.74