Electrostatic Beneficiation of Coal Fly Ash Utilizing Triboelectric Charging with Subsequent Electrostatic Separation

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A triboelectrostatic separation system for removing unburned carbon from coal fly ash is designed and evaluated. Fly ash from a coal-fired power plant is used as an accepted additive in concrete where it adds strength, sulfate resistance and reduced cost, provided acceptable levels of unburned carbon are maintained. Unfortunately, unburned carbon in coal fly ash absorbs some of other additives and reduces the concrete strength. This paper describes to investigate dry triboelectrostatic process to separate unburned carbon from coal fly ash and utilize it into economically valuable products. The laboratory-scale triboelectrostatic separation system consists of a particle feeding system, a tribocharger, a separation chamber, and collection systems. Particles of unburned carbon and fly ash can be imparted positive and negative surface charges, respectively, with a copper tribocharger due to differences in the work function values of the particles and the tribocharger, and can be separated by passing them through an external electric field. Results showed that fly ash recovery was strongly dependent on the electric field strength and the particle size. 70 wt% of fly ash containing 6.5 wt% of carbon contents could be recovered at carbon contents below 3%. The triboelectrostatic separation system showed a potential to be an effective method for removing unburned carbon from coal fly ash.

Key Words: Fly Ash, Unburned Carbon, Triboelectrostatic Separation, Work Function, Ash Recycling

1. Introduction

Fly ash is a by-product of combustion of pulverized coal in coal-fired power plants and a fine-grained material consisting mostly of spherical, glassy, and porous particles. The dust-collection systems such as electrostatic precipitators and bag filters remove fly ash, as a fine particulate residue, from combustion gases before they are discharged into atmosphere. Ash at carbon contents ranged from 4 to 15% is produced approximately 562 million tons in major coal-using countries and causes a serious environmental problem due to disposal in the ash pond (Kim et al., 1996; Malhotra et al., 1994). Fly ash from the coal-fired power plant is used as an accepted additive in concrete where it adds strength, sulfate resistance and reduced cost, provided acceptable levels of unburned carbon are maintained. Unfortunately, unburned carbon in fly ash absorbs some of other additives and reduces the concrete strength. Low NOx boiler operation can often result in unburned carbon contents of 4~15% in the ash and this unburned carbon degrades the quality of the concrete made using this coal fly ash as an additive. The unburned carbon content hence becomes an expensive disposal problem rather then a valuable combustion by-product.

Table 1 shows the requirement of fly ash for the concrete additive with ash recycling. Acceptable levels of ash recycling for the concrete additive are less than 45μm of ash size and less than 3% of unburned carbon. A dry process to segregate fly

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Table 1 Requirement of fly ash recycling for the concrete additive for ash recycling

	Fly Ash Generated	Standard Requirement for Ash Recycling[a]	Acceptable Levels
Fly Ash Size	$<200\mu m$	$<45\mu m$[b]	$<45\mu m$
Carbon Content (LOI[c])	4~15wt%	<6wt%	<3wt%

[a]ASTM Standard C618-99
[b]The amount retained when wet-sieved on 45μm sieve should be less than 34wt%
[c]LOI : Loss On Ignition

ash and unburned carbon has several advantages over a wet process like flotation or agglomeration and can overcome the problems caused by wet process, such as water treatment, product drying, corrosion, and waste disposal. Recently, dry triboelectrostatic beneficiation of coal process has been studied (Ban et al., 1993; Finseth et al., 1992; Gupta et al., 1993; Lee et al., 1999).

This paper describes to investigate a dry triboelectrostatic process separating unburned carbon from fly ash and utilize the unburned carbon into economically valuable products. The laboratory-scale triboelectrostatic separation system consists of a particle feeding system, a tribocharger to impart the charge of particles, a separation chamber, and collection systems. Separation testing is conducted as a function of particle size and electric field strength. Also the optimal conditions for maximizing the separation efficiency in the triboelectrostatic separator are investigated.

2. Triboelectrostatic Separation

2.1 Contact charging of particles

Figure 1 shows the principle of triboelectrification by particle-to-particle impact and particle-to-wall impact. Tribocharging or frictional charging is a process whereby a charge exists on a material after partly contact of solid/solid. The magnitude of the final charge will actually be the result of two processes; the charge transfer that occurs during the contact, and the charge backflow that occurs as the materials are parted (Kelly and Spottiswood, 1989). When two materials are brought into contact, charge is transferred between them until their Fermi levels

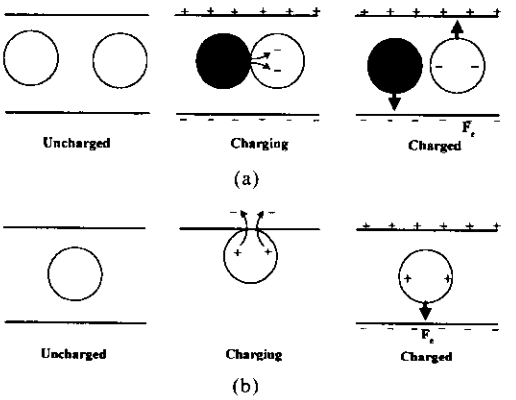


Fig. 1 The principle of the triboelectrification(Kelly and Spottiswood, 1989)(a) particle-to-particle impact, (b) particle-to-wall impact

equalize. The material having a higher work function gains electrons and is charged negatively, while the material having the lower work function loses electrons and is charged positively. The work function or contact potential is defined as the difference between the energy of an electron at the Fermi level inside the surface of the material and an electron at rest in vacuum outside, and the Fermi level is defined as the level at which the probability of finding an electron is 0.5. Therefore, the material of higher work function nas higher affinity for the electron, and gains the electron from the material of lower work function. When two materials with different work functions come into contact, electrons will flow from one of the higher work function to the other until the Fermi levels of the materials will be equilibrated (Mukherjee, 1987; Fraas, 1962).

Table 2 shows the values of work function of various compounds (Fomenko, 1972). The work function for carbon, copper, Al_2O_3 and SiO_2

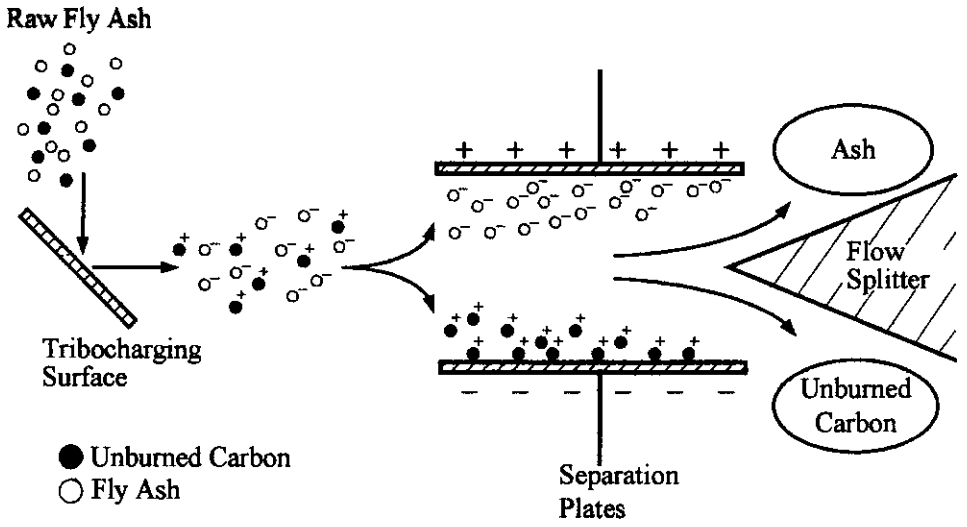


Fig. 2 The principle of the triboelectrostatic separation system

Table 2 Work functions of various compounds (Fomenko, 1972)

Material Compounds	Work Function, eV
Plexiglass	3.50
FeO	3.85
Carbon	4.00
MoO_3	4.25
Cu	4.38
Al_2O_3	4.70
MgO	4.70
SiO_2	5.00
ZrO_2	5.80
TiO_2	6.21

compounds are 4.00, 4.38, 4.70, and 5.00eV, respectively. The carbonaceous particles acquire a positive charge when contacted with a copper surface, while the mineral matters of Al_2O_3 and SiO_2 compounds acquire a negative charge. In contrast, while in contact with a Plexiglas surface, the carbonaceous particles are charged negatively.

2.2 Triboelectrostatic beneficiation of fly ash

Electrostatic separation encompasses a number of dry separation processes which separate materials based on one or more of their electrical properties, such as dielectric constant, electrical conductivity, and work function. Typically, particles acquire a charge by some selective mechanism and an applied electric field causes relative particle movement and separation. There are three basic types of electrostatic separators based on primary particle charging processes such as electro-dynamic, electrostatic, and triboelectrostatic separators. Triboelectrostatic separators feature particle-to-particle and/or particle-to-surface contact that produces charging of the particles (Kelly and Spottiswood, 1989). Triboelectrostatic separation is a broadly applicable dry processing technique in the mineral processing industry, coal beneficiation, and recycling wastes (Ban et al., 1993; Finseth et al., 1992; Gupta et al., 1993). This process separates unburned carbon from fly ash, which is based on the difference in the surface charge of various components of the powder mixture.

Figure 2 shows the principle of triboelectrostatic separation to remove unburned carbon from fly ash. It consists essentially of triboelectric charging surface, electrostatic separation plates, and flow splitter. The work function for unburned carbon particles, copper surface, and fly ash mostly consisting of Al_2O_3 and SiO_2 components are 4.00, 4.38, and 4.70~5.00 eV, respectively. When the unburned carbon and fly ash are contacted with a copper tribocharger surface, they can be imparted positive and nega-

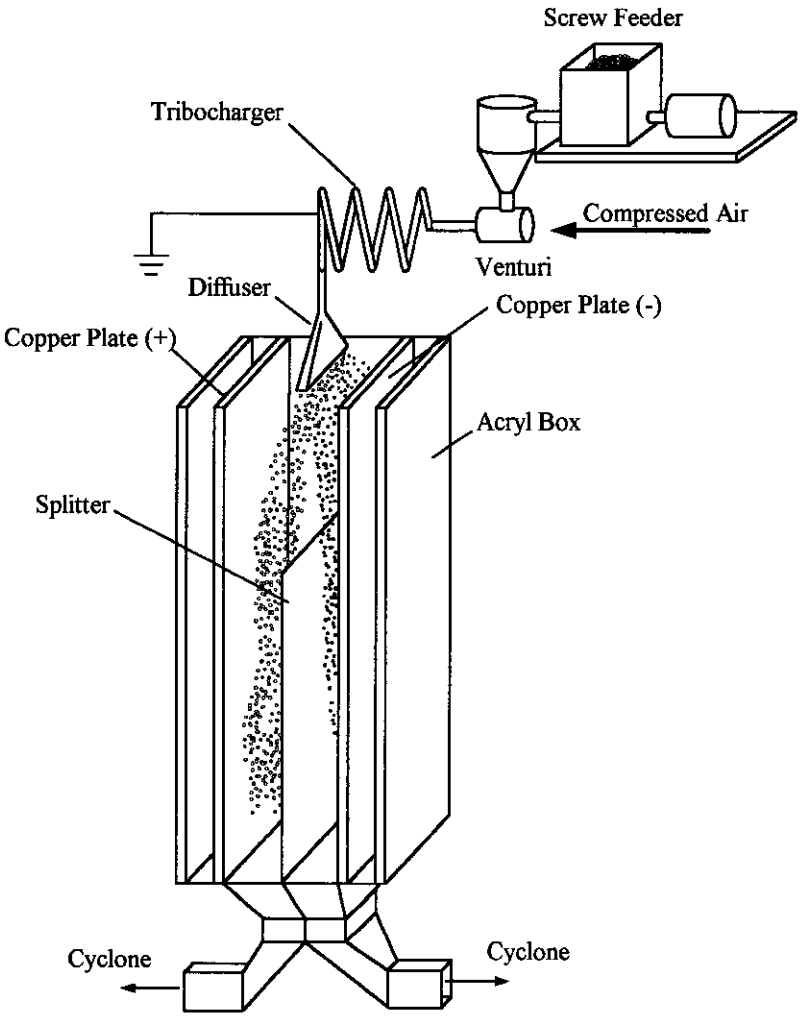


Fig. 3 A laboratory scale triboelectrostatic separation system

tive surface charges, respectively, and separated by passing them through an external electric field in the electrostatic separation plates.

3. Experimental Apparatus and Procedure

Figure 3 shows the schematic diagram of a laboratory scale triboelectrostatic separation system, which consists of a particle feeder, a tribocharger, a separation chamber, and collection systems. The tribocharger is a copper tube (8 mm in diameter) bent in spiral type shape to provide maximum particle-to-wall contact. The separation chamber contains two parallel copper plates (300 mm×800 mm) and a splitter disposed halfway between the plates for electrostatic separation of unburned carbon from fly ash. The copper plates are applied with a high voltage and disposed 100 mm apart at both sides of the separation chamber. Finally, two cyclones are placed at the bottom of the separation chamber to collect the entrained unburned carbon and purified fly ash. Fly ash is fed by the screw feeder at a constant rate, and to the tribocharger by compressed air through a venturi, and charged by particle-to-particle or particle-to-wall frictional contact. The charged particles are separated in the

Table 3 Experimental conditions for triboelectrostatic separation test

Parameters	Specification
Test Particles	Fly Ash
	• Raw ash MMD[a]=25.24μm
	LOI=7.95wt%
	• <125μm MMD=21.03μm
	LOI=6.53wt%
	• <75μm MMD=17.25μm
	LOI=4.76wt%
	• <45μm MMD=14.34μm
	LOI=3.97wt%
Electric field	0, 100, 200, 400kV/m
Inlet velocity	18m/s
Feeding rate	6g/min
Temperature	29℃
Relative humidity	65%

[a]MMD : Mass Median Diameter

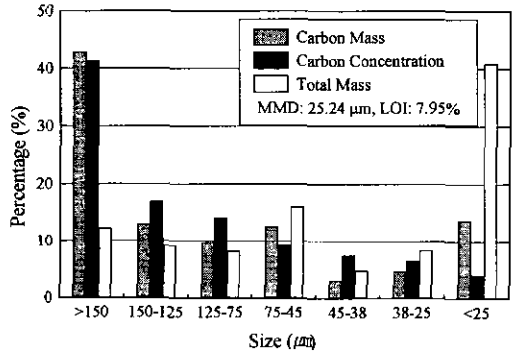


Fig. 4 Percentage of carbon mass, carbon concentration and total mass distribution in each size fraction

separation chamber by high voltage electric forces with electric field strength ranging from 0 to 400 kV/m. In the separation chamber, the purified fly ash is attached to the anode plate and the unburned carbon to the cathode plate. After triboelectrostatic separation, the particles collected on each plate and cyclones are collected in 8 parts (0-200, 200-400, 400-800 mm and cyclones), respectively. The carbon concentration is measured by the loss on ignition (LOI) method based on ASTM Standards C311-98b.

Table 3 shows the experimental conditions of triboelectrostatic separation of unburned carbon from fly ash in this study. Fly ash feeding rate to the separation chamber is 6 g/min and the carrier gas flow velocity at the exit of a nozzle is 18 m/s. The room temperature and relative humidity are 29℃ and 65%, respectively. Fly ash generated from Australia coal is sampled from the electrostatic precipitator hoppers of the coal power plant in January 1999 and contains carbon contents of 7.95%. Fly ash as test particles is classified by the wet sieving method to investigate the effect of particle size such as raw ash, <125μm, <75μm, and <45μm in diameter as shown in Table 3.

4. Results and Discussion

4.1 Carbon and mass distribution of fly ash

Figure 4 shows the percentage of carbon mass, carbon concentration, and total mass distributions in each size fractions in fly ash sampled from the electrostatic precipitator hoppers. Carbon mass describes the ratio of the mass of unburned carbon in each size fraction to total mass of unburned carbon, and total mass describes the ratio of the mass of fly ash in each size fraction to mass of raw fly ash. The carbon content and the mass median diameter (MMD) of the raw fly ash are 7.95 wt% and 25.24 μm, respectively. Results show that the carbon contents of particles over 150 μm ash size was 42 wt%, between 125 and 150 μm are 17 wt%, and under 125 μm size are 6.53 wt%. The results also

Table 4 Chemical compositions of fly ash

Component	Mass Percent, %
SiO_2	67.34
Al_2O_3	15.63
Fe_2O_3	5.33
CaO	2.17
MgO	1.02
Na_2O	0.22
K_2O	0.19
MnO	0.15
C	7.95

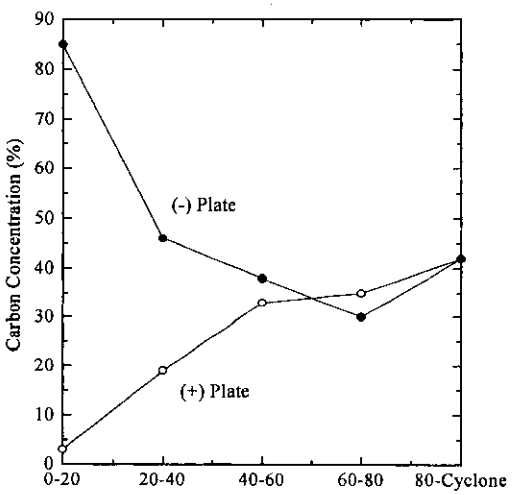


Fig. 5 Separation plate deposition profiles for the mixture of coal and SiO_2 particles

show that there is a significant amount of the ash with sizes below 25 μm.

Table 4 shows the chemical composition of fly ash, primarily consisting of SiO_2 (67.34 wt%), Al_2O_3 (15.63 wt%), Fe_2O_3 (5.33 wt%), and unburned carbon (7.95 wt%).

4.2 Separation test with model mixture

As fly ash consisted of various compounds is heterogeneous, it is not possible to determine directly the surface charge characteristics. A model system, using a mixture of coal and SiO_2 particles, was chosen to study technical feasibility of a dry triboelectrostatic process to separate mixed particles. The coal simulated the unburned carbon, while SiO_2 particles represented the mineral matter. A feed containing 50 wt% coal

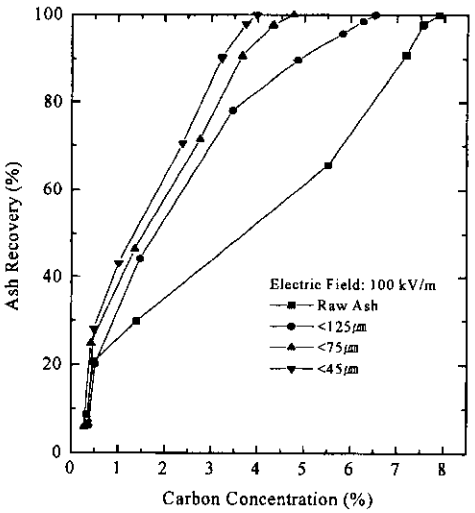


Fig. 6 Separation efficiency of fly ash as a function of particle size

particles and 50 wt% SiO_2 particles was prepared by mixing them thoroughly and this mixture was then used as a feed to the separator. Figure 5 shows the carbon content profile of both the layers deposited at the negative and positive electrode plates. These profiles indicate that the separation is essentially completed within first 20 to 40 cm for both plates. As expected, coal particles for the copper tribocharger acquire a positive charge, while SiO_2 particles are charged negatively. A layer rich in coal is deposited at the cathode plate while a SiO_2 rich layer is formed at the anode plate with separation being visually evident.

4.3 Fly ash recovery

Figure 6 shows the ash recovery of the triboelectrostatic separator as a function of particle sizes at electric field strength of 100 kV/m. Ash recovery can be defined as the percentage of fly ash recovered in the feed. For raw fly ash, the ash recovery of the particles at carbon contents less than 3 wt% was less than 50 wt%, while that was 70 wt% for fly ash under 125μm size. For fly ash of fine particles, the ash recovery was found to be higher than that of coarse particles. It is believed that the fine particle has high surface charge per unit mass due to its high specific surface area. Also because the trajectory of the

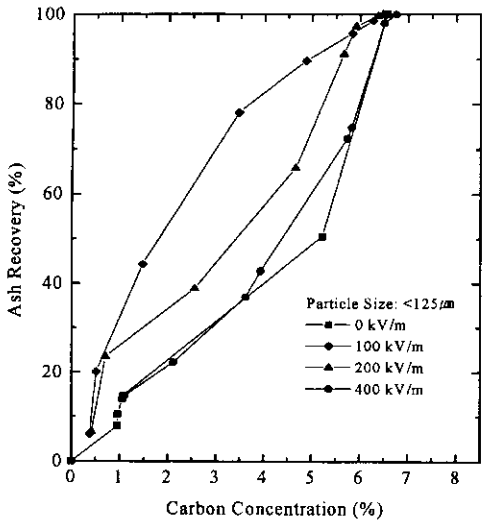


Fig. 7 Separation efficiency of fly ash as a function of electric field strength

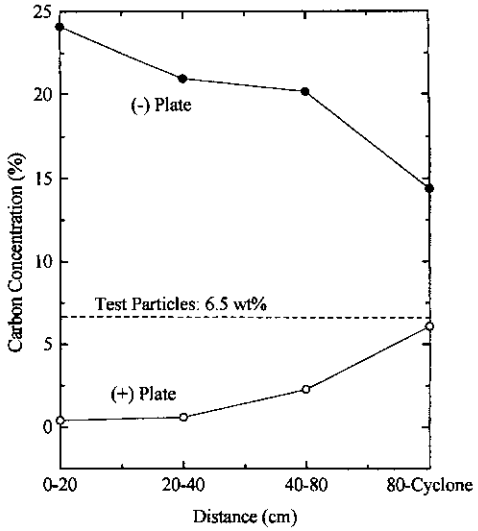


Fig. 9 Separation plate deposition profiles for fly ash and unburned carbon particles

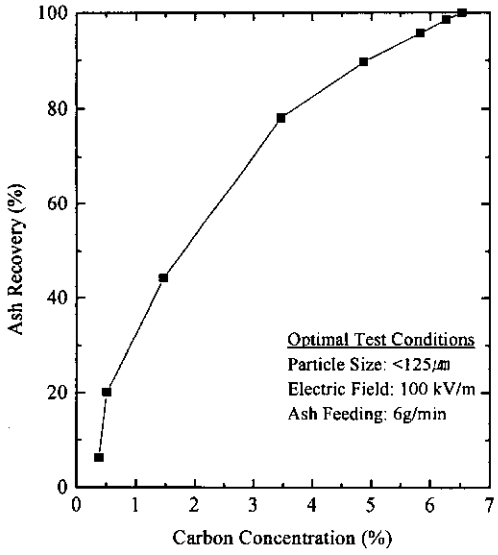


Fig. 8 Ash recovery of the triboelectrostatic separator in the optimal test conditions

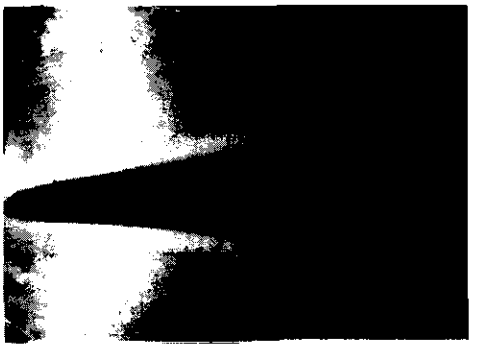
coarse particle in the separation chamber was affected by the inertial force rather than the electrostatic force, the separation efficiency of the coarse particles was lower than that of the fine particles.

Figure 7 shows the ash recovery of the triboelectrostatic separator as a function of the electric field strength at the particles size of <125 μm. For the 100 kV/m electric field strength, nearly 70 wt% of fly ash was recovered with carbon contents of <3 wt%. Ash recovery for the electric field strength of 100 kV/m was higher than that for 0 kV/m, 200 kV/m, and 400 kV/m. But the separation efficiency for the electric field strength of 400 kV/m was found to decrease dramatically due to the corona occurrence between copper plates.

Figure 8 shows the ash recovery of the triboelectrostatic separator in the optimal conditions such as fly ash of $<125\mu$m in size, the electric field strength of 100 kV/m, the inlet velocity of 18 m/s, and the feeding rate of 6 g/min. These data show that nearly 70 wt% of fly ash is recovered with carbon contents of less than 3 wt%, and 30 wt% of fly ash is recovered with carbon contents of less than 1 wt%. All fly ash collected on the anode plate contained carbon contents of 1.47 wt%, and the total recovery amount was 38.2 wt% of the feed. Fly ash of 20.7 wt% carbon contents was collected 10.3 wt% of feeding fly ash on the cathode plate. And fly ash collected on anode plate and cyclones contained the carbon contents of <3.0 wt% and the recovery percentage of 70 wt%.

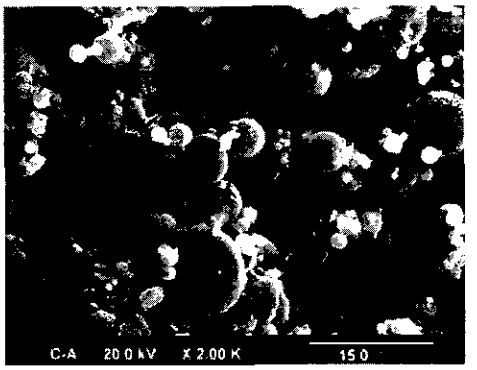
Figure 9 shows the deposition profiles of the copper plates in the optimal condition at carbon contents of 6.53 wt% as a function of collecting

(a)



(b)

Fig. 10 Photographs of fly ash deposited with the diffused shape at(+) & (−) copper plates. (a) Purified fly ash particles on the (+) plate. (b) Unburned carbon particles on the (−)plate



(a)

(b)

Fig. 11 Scanning electron micrographs of (a) purified fly ash and (b) unburned carbon particles after the triboelectrostatic separation

distance. These profiles indicate that the separation is essentially completed within first 20 to 40 cm for both copper plates. Most of the collected fly ash was deposited in the range of 0~40 cm distances and fly ash in the range of 0~20 cm distances was recovered at carbon contents below 1%.

Figure. 10 shows the photograph of the fly ash deposited on the plates for the optimal condition test. The deposited profile looks like a diffused shape. The gray part of the anode plate was the purified fly ash, and the dark part of the cathode plate was fly ash containing a high amount of unburned carbon.

Figure. 11 is the scanning electron micrographs image of products after triboelectrostatic separation of fly ash. Figure 11(a) is the purified fly ash attached on the positive plate, and Fig. 11(b) is the unburned carbon particle on the negative plate. As shown in the figure, the purified fly ash is the spherical and fine particle, on the other hand unburned carbon is the heterogeneous coarse particle.

5. Conclusions

The separation system for the unburned carbon from fly ash has been evaluated, and the separation tests have been conducted to find the optimal separation conditions. Results showed that fly ash recovery was strongly dependent on the electric field strength and fly ash size. Considering ash recovery, the optimal conditions for the triboelectrostatic separator were found out fly ash

of $<125\mu m$ in diameter and the electric field of 100 kV/m. 70 wt% of fly ash containing 6.5 wt% carbon contents could be recovered at the carbon contents below 3 wt%. The system of the triboelectrostatic separator showed a potential to be an effective method for removing unburned carbon from fly ash.

Acknowledgements

This work was supported by the Institute for Environmental Technology and Industry (IETI), Pusan National University, Korea, by R&D Management Center for Energy and Resources, Korea Energy Management Corporation, and by the Brain Korea 21 Project.

References

ASTM Standard C311-98b, 1998, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete.

ASTM Standard C618-99, 1999, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolans for Use as a Mineral Admixture in Concrete.

Ban, H., Schaefer, J. L., and Stencel, J. M., 1993, "Size and Velocity Effects on Coal Particle Triboelectrification and Separation Efficiency," *Proceedings of 10th Annual International Pittsburgh Conference,* University of Pittsburgh, Pittsburgh, pp. 138~143.

Finseth, D., Newby, T., and Elstrodt, R., 1992, "Triboelectrostatic Beneficia-tion of Fine Coal," *Proceeding of the 9th Korea-U. S. A Joint Workshop on Coal Utilization Technology,* pp. 221~230.

Fomenko, V.S., 1972, *Emission Properties of Materials*, NTIS-JPRS-56579, U. S. Department of Commerce.

Fraas, F., 1962, *Electrostatic Separation of Granular Materials*, Bulletin 603, Bureau of Mines, United States Department of the Interior.

Gupta, R., 1990, *Dry Electrostatic Beneficiation of Illinois Coal and Eastern Oil Shales*, Ph. D. Dissertation, Illinois Institute of Technology.

Gupta, R., Gidaspow, D., and Wasan, D. T., 1993, "Electrostatic Separation of Powder Mixtures Based on the Work Functions of Its Constituents," *Powder Technology*, Vol. 75, pp. 79~87.

Kelly, E.G., and Spottiswood, D.J., 1989, "The Theory of Electrostatic Separations: A Review Part II. Particle Charging," *Minerals Engineering*. Vol. 2, pp. 193~205.

Kim, N.H., Lee, Y.P., Yoon, Y.S., and Jung, J. S., 1996, "A Study on the Pressure Loss, Heat Transfer Enhancement and Fouling Control in a Vertical Particulate Flow," *KSME International*, Vol. 10, No. 4, pp. 450~457 (in Korea).

Lee, J. K., Kim, S. C., Kim, D. H., Lee, J. E., and Ku, J. H., 1999, "Development of Centrifugal and Triboelectrostatic Separation System for the Removal of Unburned Carbon from Fly Ash," *Project No. 96C-CC02-P-05*, R&D Management Center for Energy and Resources.

Malhotra, V.M., and Ramezanianpour, A.A., 1994, *Fly Ash in Concrete*. Minister of Supply and Services.

Mukherjee, A., 1987, *Characterization and Separation of Charged Particles*, Ph. D. Dissertation, Illinois Institute of Technology.