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Tribo-Electrostatic Beneficiation of Fly Ash for Ash Utilization

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Abstract−The study was conducted to obtain the scale-up factor and the optimum design criteria for the development of a commercial scale electrostatic separator using a continuous, bench-scale electroseparator composed of two vertical electrode plates and an ejector-tribocharger. Tests of the charge density and separation efficiency to study the removal possibility of unburned carbon from coal fly ash were evaluated under various operating conditions. It was found that the experimental conditions for obtaining the maximum charge density were an air flow rate of 1.75 m^3/min and a feed rate of less than 50 kg/hr when operated at lower than 30% relative humidity using a SUS304 ejector tribocharger. Also, the optimum instrument conditions for recovering the clean ash with less than LOI 3% at yield over 65% when operated at above experimental conditions were found to be a diffuser slit gap of 4 mm, and a distance between diffuser slit and splitter of 15 cm. Overall, the feed rate per unit electrode surface area was about 0.074 kg/cm^2 · hr, which can be used as a scale-up factor of the electroseparator.

Key words: Fly Ash, Unburned Carbon, Electrostatic Separation, Tribocharging, Faraday Cage

INTRODUCTION

About 4.40 million tons of coal fly ash were produced from KEPCO's thermal power plants in 2000, of which only 54.6% was utilized with the remaining 45.4% being disposed of as waste. Due to the construction of new coal power plants, fly ash production in Korea will increase for next 10 years and is expected to reach up to 6.0 millions tons in 2010 [Kim and Kim, 2000]. This rapid increase in fly ash production causes serious concern over fly ash disposal amid growing awareness of environmental issues and depletion of landfill sites. Naturally, utilization of coal fly ash has received wide attention in recent years in Korea. It is well known that because of its spherical shape and pozzolanic properties, fly ash is a valuable and desirable additive to cement concrete. It also been shown to be effectively used in many other ways such as ALC (Aerated Lightweight Concrete) manufacturing, zeolite and filters material [Choi and Park, 1989; Lee et al., 2000; Shin et al., 1995; Choi et al., 1999]. However, these uses are relatively small, and potential market for high volume application lies in the cement industry. In fact, the largest application for fly ash is in cement and concrete in Korea, although the expansion of the fly ash use in this field is presently impeded by the presence of unburned carbon (LOI) in fly ash.

The Korean Standards on fly ash for use in concrete specify that the loss on ignition (LOI) is to be under 5% (KSL 5211 1992). But this level is not acceptable to concrete manufacturers who demand an LOI level of less than 3%. Therefore, it is essential to produce a consistent and uniform fly ash with less than 3.0% LOI to expand the fly ash use in the cement industry.

The fly ash beneficiation methods are generally classified as physical, chemical and biological techniques. In general, wet type froth flotation, air classification and electrostatic separation of dry type are the best known as fly ash beneficiation technology. A wet process such as froth flotation is less efficient than dry processes, such as air classification, electrostatic separation, since it does require dewatering and drying of clean ash particles. However, air classification of dry processes is not as good as expected due to the breakup of the coarse unburned carbon-rich particles caused by collisions with cyclone inner walls [Kim et al., 1998; Cho and Kim, 1999]. On the other hand, triboelectrostatic separation process was shown to give an excellent separation efficiency, which could be recovered reducing the LOI to less than 3% from high carbon fly ash samples with 9% LOI [Kim et al., 1997, 2000], yet most of the results are on lab-scale of batch-type [Ciccu et al., 1997].

In the triboelectrostatic separation of fly ash beneficiation technology, particles of two different materials are imparted positive and negative surface charges, respectively, by rubbing against each other or against a third material. The charged particles can be separated by passing them through an external electric field as shown as Fig. 1.

Currently, KEPRI (Korea Electric Power Research Institute) of

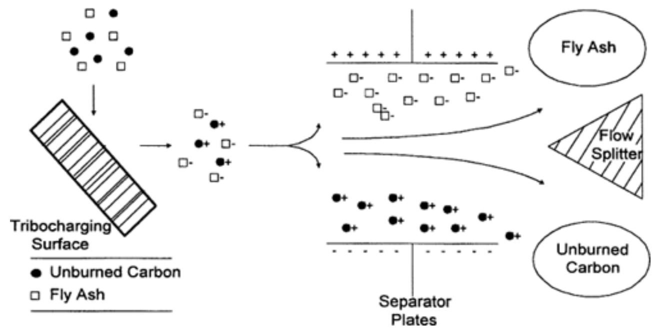

Fig. 1. The principle of triboelectrostatic separation system.

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KEPCO (Korea Electric Power Corporation) has constructed a pilot-scale triboelectric separator with 3 ton/hr capacity and designed a demo-scale triboelectrostatic separator of 60 ton/hr capacity through a pilot plant experiment [Kim and Kim, 2000]. This paper discusses the experimental results of a bench-scale triboelectrostatic separator performed as a basic study to develop the pilot plant design data.

EXPERIMENTAL

1. Coal Fly Ash Sample

Fly ash sample used in this study was obtained from the Poryung coal power plant owned by KEPCO (Korea Electric Power Corporation). The size analysis of powders included both sieve and laser diffractometor analysis (Cilas, Model 1064). The subject sample was dispersed in water and was then washed through a 500 mesh (26 μm) sieve with a gentle spray of water. The fine material was recovered by filtration. Both of the −26 μm and the +26 μm fraction were oven-dried. The +26 μm fraction was then subjected to Rotap sieve analysis using a $\sqrt{2}$ progression screen starting at 100 mesh (150 μm) and extending down to the 500 mesh, followed by a pan to collect the −500 mesh particles. After sieving, the particles smaller than 500 mesh were combined with the fine fraction from the wet screening and mean size was also analyzed by the Cilas size analyzer.

Loss on ignition (LOI) tests were conducted on each size fraction and the whole sample at a temperature of 800 °C in accordance with KSL5211. Table 1 shows the chemical composition and the size distribution of the fly ash sample. It can be seen that the sample is generally less than 150 μm, but the majority (55.8%) is in the size range of −26 μm. The overall LOI of the sample is 9.6%, but in the size faction wide, a signification variation can be seen. As observed in many other studies [Kim et al., 1998, 2000], the LOI is higher for the larger sizes: the LOI of the +150 μm fractions is 46.1%, whereas that of the −26 μm fraction is less than 3.59%. In case of chemical composition, mass fractions of SiO_2+Al_2O_3+Fe_2O_3 have over 84.7%, satisfying the specifications of fly ash in Korea for cement additives (KSL 5211 1992).

Table 1. Analysis of fly ash sample (unit : wt%)

Size [μm]	Mass percentage	LOI	Chemical composition	Mass percentage
+150	1.15	46.1	SiO_2	52.8
			Al_2O_3	27.0
150-105	4.51	31.3	Fe_2O_3	4.9
			CaO	1.8
105-75	5.3	21.9	MgO	0.6
75-53	9.6	17.2	Na_2O	0.84
53-38	11.0	13.2	K_2O	0.56
38-26	12.64	11.0	TiO_2	1.3
−26	55.8	3.59	P_2O_5	0.6
Mean	32.8	9.6	LOI	9.6

2. Experimental Apparatus and Procedures

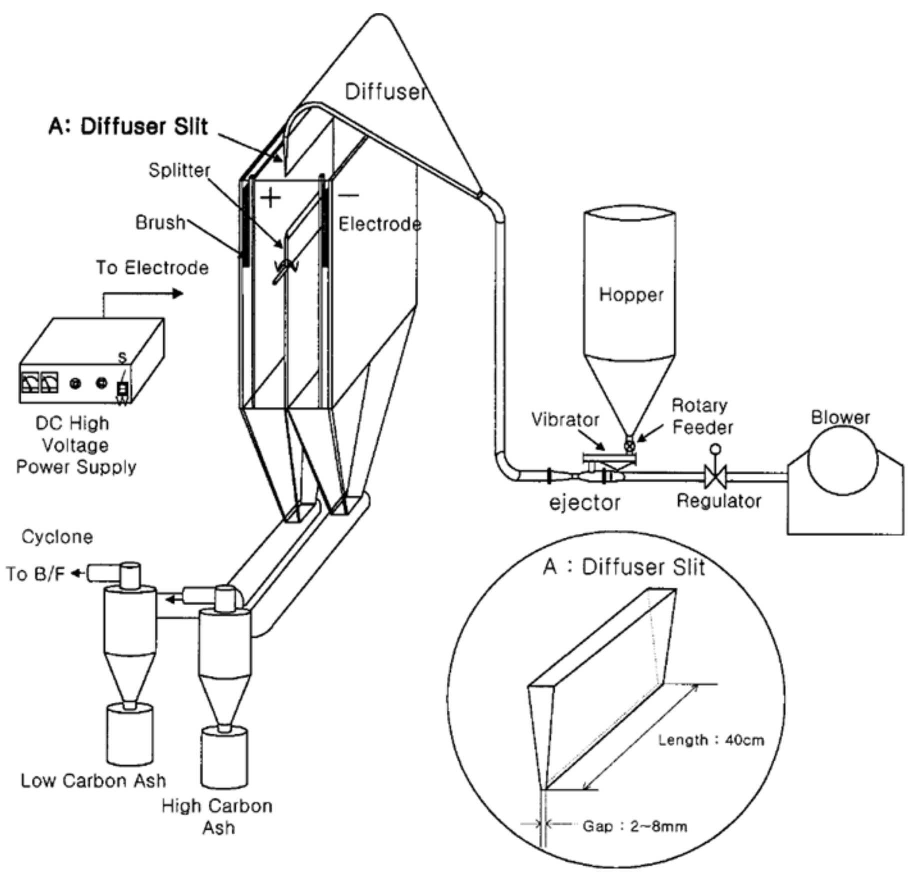


Fig. 2. Experimental system for fly ash beneficiation.

Fig. 2 shows the schematic of the pilot-scale triboelectrostatic separator, which is composed of a silo, a blower, a diffuser, two plate electrodes and two cyclones. The air supplied by the Roots blower is passed through a flow regulator. The coal fly ashes are fed to a venturi type ejector through a rotary feeder and vibrator feeder. The system has no tribocharger and the ejector itself provides the tribo-charging. The particles are charged by contact with each other or ejector inner walls at the ejector throat. The mixture of air and charged particles is injected through a diffuser to an electric field formed by two vertical plates. The electrode plates are open to the surrounding air to reduce the turbulence inside the separator formed by injection of charged particles at a high velocity through the diffuser. The plate electrodes are constructed with stainless steel of 45 cm width and 20 cm length. The two plates are spaced 10 cm apart. The electric potential difference between the two electrodes is maintained at about 50 kV, or an electric field strength of the 5 kV/cm. A splitter installed in the middle of the electric separator has a movable top, which can be rotated to split the particle streams into two streams at various proportions. The particles separated by the splitter are collected separately by two cyclones. The overflow streams at the cyclones containing very fine particles are passed through the bag filters. The particles deposited on the electrodes are removed periodically by sweeping brushes, which move on the plates horizontally from left to right. The relative humidity of the surrounding air is maintained at less than 30% through dehumidification of the incoming air. The recovery of the fly ash is based on the total amount recovered by both the cyclone and the bag filter. Fig. 3 shows a simple design for an ejector tribocharger used in this study. The motive air enters through the nozzle with 5.3 mm ID at the left (Inlet 1) and passes through the venturi nozzle at the center and out of the discharge ejector throat with 11.3 mm ID at the right. As it passes into the venturi nozzle, it develops a suction that causes some of the particles and surrounding air in the suction part with 10 mm ID (Inlet 2) to be entrained with the stream and delivered through ejector throat. Therefore, the total discharge flow rate at ejector throat is much higher than the nozzle air rate. It was found that the feed air rate of 0.34, 0.42, 0.52, 0.62, 0.7, 0.78 and 0.82 m^3/min resulted in the total air rates of 0.85, 1.197, 1.456, 1.55, 1.75, 1.95, and 2.1 m^3/min, respectively.

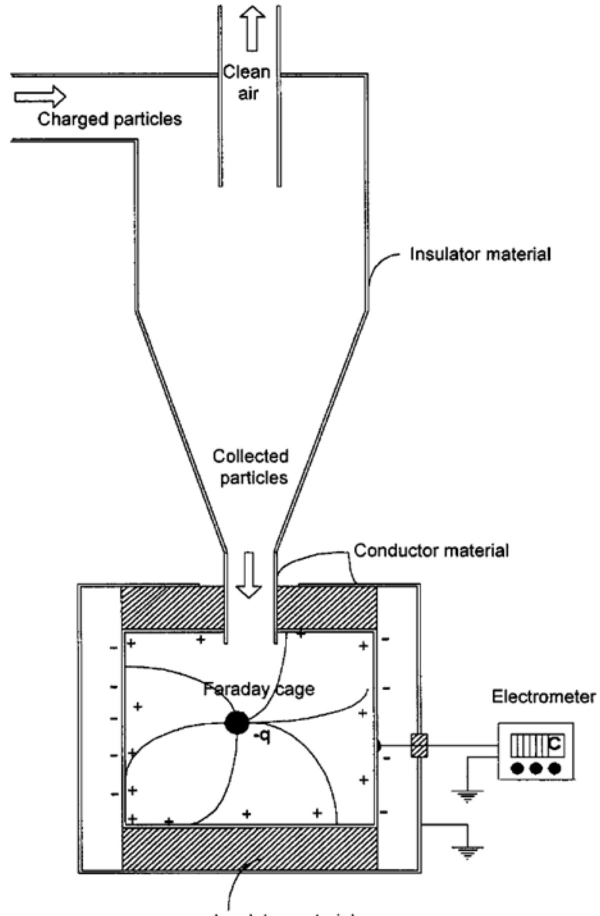


Fig. 4. Schematic diagram of the Faraday Cage system.

3. Surface Charge Measurement

The amount of surface charge acquired on the particles was measured by using a Faraday cage system coupled to a suitable monitoring circuit. Fig. 4 shows a schematic diagram of the Faraday cage system. As seen in Fig. 2, the particles discharged by the ejector-tribocharger were directly collected by a cyclone made of acryl. The Faraday cage is installed at the bottom of the cyclone, and the

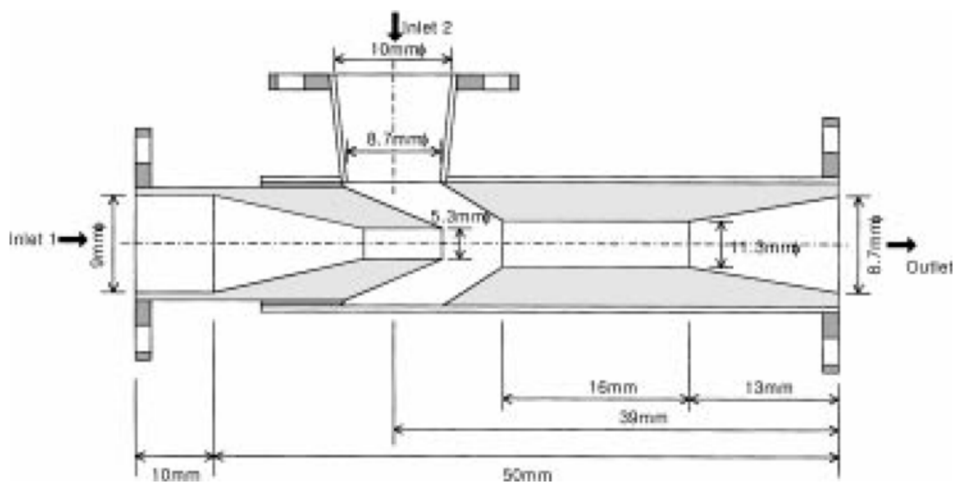


Fig. 3. Side sectional view of ejector tribocharger.

induced charge produced by the accumulation of the charged particle is measured by an electrometer (Keithly 617 HIQ, electrometer). Weight of charged particle introduced into Faraday cage was measured by the electric balance (Satorius AG) attached on the bottom of the Faraday cage. The charge density was calculated as the amount of charge divided by mass (charge-to mass ratio). A detailed discussion on the measurement of the charge using a Faraday cup is given elsewhere [Taylor et al., 1994].

RESULTS AND DISCUSSION

1. Effect of Ejector Throat Material on the Charge Density

Fly ash particles are mostly composed of silica and alumina, which has a higher function (SiO_2 : 5.0 eV, Al_2O_3 : 4.7 eV) than carbon (4.0 eV). Therefore, when they contact each other, carbon particles will charge positively and fly ash particles will charge negatively. Also, it is possible to selectively charge particles by contacting the third material, which has a work function midway between the values of materials to be separated. In order to investigate the effect of the ejector throat material on the charge density, experiments were conducted at three different materials, which included stainless steel (SUS304), steel, and ceramic. Fig. 5 shows charge densities for the three materials obtained at various air rates under conditions of a relative humidity of 30% and a feed rate of 50 kg/hr. For the ceramic ejector throat, the charge density does not change much with the air rate, whereas for the stainless and steel ejectors, the charge density increases consistently with increasing the air rate. Also, among the three materials tested, the stainless steel ejector produces the highest charge density.

This may probably be due to the difference of work function between the ejector throat material and fly ash. The charge density of fly ashes using ceramic made of alumina (Al_2O_3: 4.7eV) was lower than one of the fly ashes by the steel and stainless steel ejector because the difference of work function of between the ceramic material and fly ash was low. On the other hand, charging of fly ashes using stainless steel ejector made of iron (Fe : 4.5 eV) and chromium (Cr : 4.5 eV) is shown to give a higher charge density than other materials because stainless steel has a work function midway between fly ash and unburned carbon [David, 1991]. Yet the above

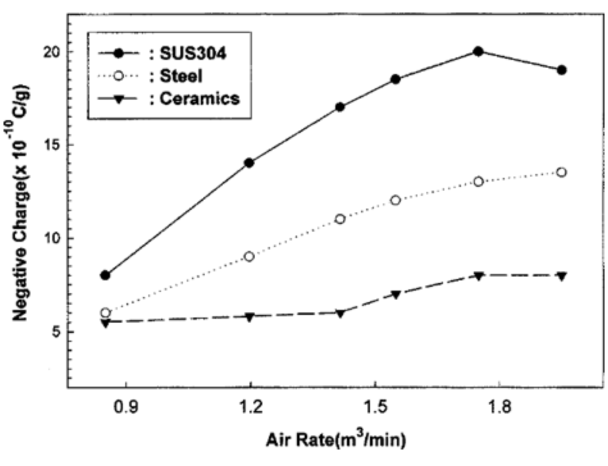


Fig. 5. Effect of the material of ejector throat on the charge density at various air rates.

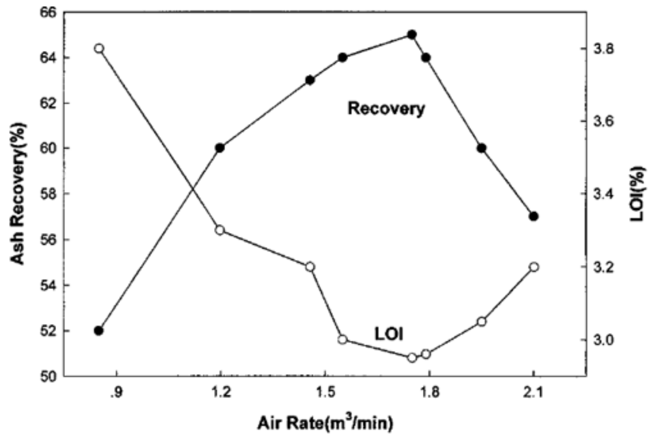


Fig. 6. Recovery and LOI of fly ash products obtained at various air rates.

results are limited on ejector throat materials such as ceramic, steel, and stainless steel, and further study is required for excellent material selection of an ejector tribocharger. Therefore, a stainless steel ejector has been used for the pilot scale unit.

2. Effect of the Ejector Air Rate on the Separation Efficiency

Tests were conducted to investigate the effect of the ejector throat air rate on the separation efficiency at seven different air injection rates of 0.85, 1.197, 1.456, 1.55, 1.75, 1.95, and 2.1 m^3/min, respectively. These air rates were achieved by controlling the pressure regulator and damper of blower as shown in Fig. 2. The corresponding air velocities at the ejector throat were calculated to be 141, 200, 243, 258, 292, 325, and 350 m/s, respectively. Fig. 6 shows the recovery and LOI of the clean fly ash streams for various air rates of an ejector throat, electric field of 5 kV/cm, and diffuser slit gap of 4 mm in electroseparator unit. It can be seen that the recovery increases with increasing the feed air rate up to 1.75 m^3/min, but when the air rate is over 1.75 m^3/min the recovery decreases. This is probably due to the fact that as the air rate increases, the particles acquire higher charges so that more particles can be recovered. However, the travel time for the particles to reach the splitter is shortened as the air flow rate increases. This adverse effect can partially offset the benefits of higher charges with higher air rate, so there is optimum air rate for the maximum recovery. Meanwhile, higher air rates charge the particle surfaces to a greater extent so that particles move by electric force in a more distinctive manner. This gives a cleaner product; i.e., the LOI of the separated fly ash reduces as the air flow rate increases. Overall, the results show that the fly ash feed of 9.6% LOI could be processed into 3.0% LOI product over a recovery of 65% when operated around 1.75 m^3/min.

3. Effect of the Feed Rate, Electric Field on the Electroseparation Efficiency

Fig. 7 shows the variation of the charge density as a function of the feed rate ranging from 29 kg/hr to 103 kg/hr at the ejector throat air rate of 1.75 m^3/min and the relative humidity of 30%. It can be seen that charge density is about 15×10^{-9} C/g at a feed rate of 50 kg/hr, but decreases continuously as the feed rate increases, and it is reduced to 0.8×10^{-9} C/g as the feed rate reaches up to 103 kg/hr. The magnitude of the charge density obtained in this study is one order less than that obtained for the batch, lab-scale separator [Kim

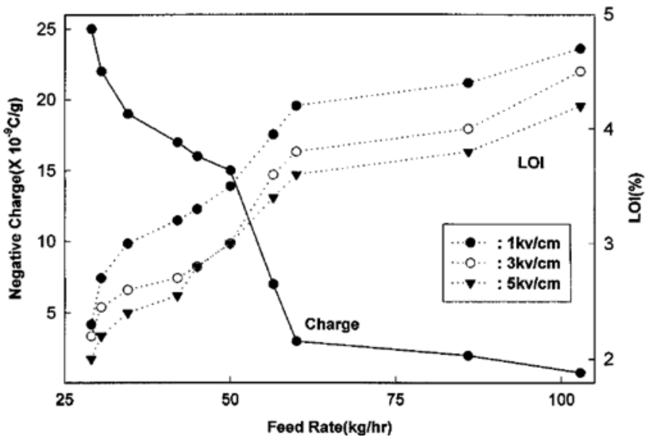


Fig. 7. Effect of the feed rate on the charge density and LOI of fly ash products [basis : ash recovery 65%].

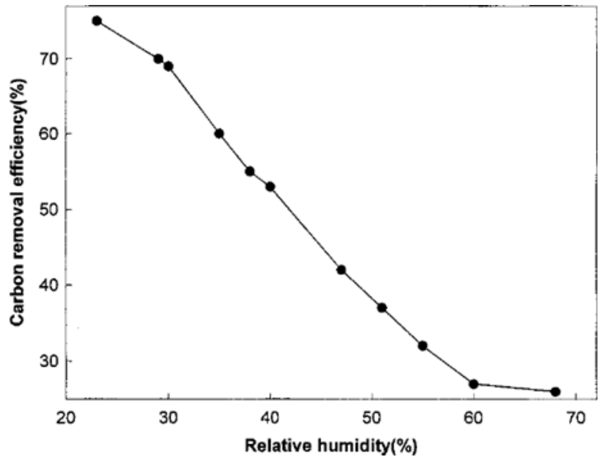


Fig. 8. Effect of relative humidity of surrounding air on the carbon removal efficiency.

et al., 2000]. However, for conversion from feed rate to solids loading, this continuous bench-scale separator was operated at solid loading of 476 g/m^3 (feed rate of 50 kg/hr, air rate of 1.75 m^3/min), whereas the batch lab-scale unit was operated at the lower solids loading (below 290 g/m^3). Obviously, as the feed rate increases, there is a less chance of particles to contact with the metal surface and in turn, the overall charge reduces.

The feed rate (or solids loading) is an important design parameter because it is directly related to the capacity of the separator. Fig. 7 shows also the LOI of the products for various feed rates at the relative humidity of 30%, and the ejector throat air rate of 1.75 m^3/min. It can be seen that as the feed rate increases, the LOI of the product fly ash also increases. This phenomenon can be attributed to the effect of the feed rate on the charge density: the higher the feed rate, the lower the charge density. Therefore, in order to obtain a product of less than 3% LOI at an electric field of 5 kv/cm, the feed rate should not be increased over 50 kg/hr. This result was about 1.5 times higher than the optimum solids loading for the batch, lab-scale electroseparator. For the batch, lab-scale electroseparator, the particles deposited on the plates were not removed, whereas for the continuous separator, the deposited particles were periodically removed by operating the insulation brushes. When particles are deposited with an appreciable thickness, the strength of electric field is reduced and, therefore, the electrical force acting on the particles is reduced.

Fig. 7 shows the effect of the electric field strength on the separation efficiency. It can be seen that cleaner products are obtained for the higher electric field strength for the whole range of the feed rate. At 1 kv/cm of electric field strength, the feed rate should be less than 34.5 kg/hr (that is, the solids loading of 328 g/m^3 at ejector outlet air rate of 1.75 m^3/min) to produce a clean fly ash of less than 3% LOI. However, at 5 kv/cm, the feed rate loading can be increased about 1.5 times higher than at 1 kv/cm to obtain a product of the same grade.

Although the charge density of fly ash is high at high feed rate, the electrostatic separation efficiency decreased because many charged particles were interfering to move to each other polarity in the electric fields. Therefore, feed rate per unit electrode surface area to obtain a product with less than 3.0% LOI was about 0.074 kg/cm^2·hr at ejector outlet air rate of 1.75 m^3/min, electric field of 5 kv/cm (feed rate of 50 kg/hr, surface area of positive electrode with 675 cm^2; 45 cm L×15 cm H), which can be used as a scale-up factor of the electroseparator. That is, feed rate per unit electrode surface area means the maximum feed rate of charged particles treated by the surface area of one positive electrode at the optimal conditions.

4. Effect of Relative Humidity of Surrounding Air

Carbon removal efficiency is defined as a percentage of the carbon recovered in the waste ash stream to the carbon in raw fly ashes. Fig. 8 shows the effect of relative humidity of surrounding air on the carbon removal efficiency at the feed rate of 50 kg/hr and the electric field strength of 5 kV/cm. It can be seen that the carbon removal efficiency is significantly reduced as the relative humidity of the surrounding air increases. This trend is consistent with that observed for the batch, lab-scale separator [Kim et al., 2000], which is ascribed to the change of surface properties and the increase of electrical conductivity by the adsorption of moisture on the surface of fly ash. When the relative humidity was higher than 50%, it was observed that the fly ash particles agglomerated, which could severely interfere with selective charging and movement of the fly ash particles under the electric field. In case of feed LOI 9.6%, carbon removal efficiency should be more than 68.75% to recover the clean ash with less than 3% LOI. From Fig. 8, it can be seen that this requirement can be met only when the relative humidity of surrounding air is less than 30%.

5. Effect of the Width of the Diffuser Slit

It was found that the width of the diffuser slit affected the separation efficiency. Therefore, tests were conducted to investigate the effect of diffuser slit gaps on the electrostatic separation by using four different diffuser slits having width of 2, 4, 6 and 8 mm at a feed rate of 50 kg/hr. However, to maintain the discharge velocity of about 18.2 m/s at the diffuser slit as shown in Fig. 6, the ejector air rates were adjusted to about 0.87, 1.75, 2.62, and 3.5 m^3/min for gaps of 2, 4, 6 and 8 mm, respectively. Fig. 9 shows the curves of the recovery versus LOI obtained at an electric field of 5 kV/cm.

The result shows that as the diffuser silt gets wider, the LOI of clean ashes increases at the same ash recovery. This means that the separation efficiency is higher for the smaller diffuser slit gaps. However, with the 2 mm diffuser slit, problems of plugging and coating

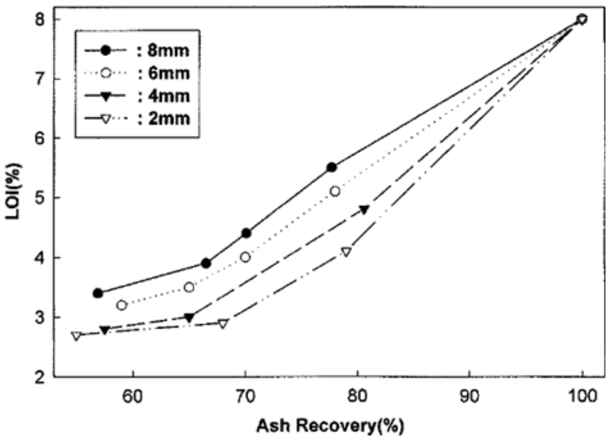


Fig. 9. Recovery and LOI of fly ash products obtained at various diffuser slit gaps.

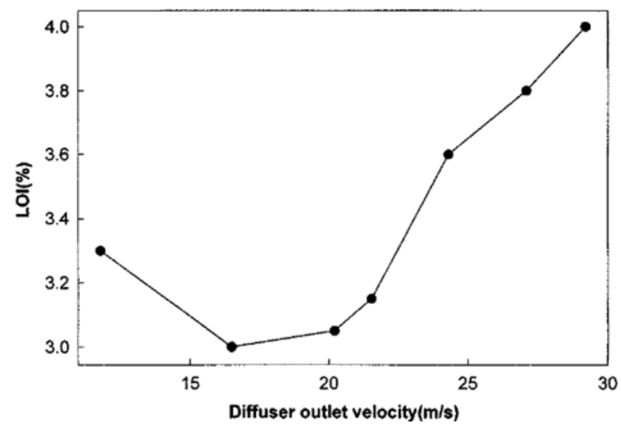


Fig. 11. Effect of the air velocities in electric field on the LOI of clean ashes.

inside the diffuser slit occurred; therefore, a 4 mm diffuser slit was used.

6. Effect of the Distance between the Diffuser Slit and the Splitter

The splitter is located some distance below the diffuser slit, and it divides the particle streams into two streams: clean ash stream and high carbon ash streams. Particles entering the electrical field move laterally due to the electrical force as they move downward. Therefore, the position of the splitter determines how far particles travel before partitioning of the particle stream occurs. If the distance between the diffuser and the splitter is too short, there is not enough time for particles to move horizontally, so that particle partitioning would not be efficient.

Fig. 10 shows the test results for the three different distances (10 cm, 15 cm, and 20 cm) between diffuser slit and splitter. Tests were conducted at the diffuser slit gap of 4 mm, ejector air rate of 1.75 m^3/min, feed rate of 50 kg/hr and the electric field of 5 kv/cm. It can be seen that when the distance is increased from 10 cm to 15 cm, the LOI is lower for a given ash recovery, i.e., a cleaner product for the same ash recovery. However, when the distance is increased further to 20 cm, the LOI rather increased. It is often observed that when the particles of high unburned carbon content touch

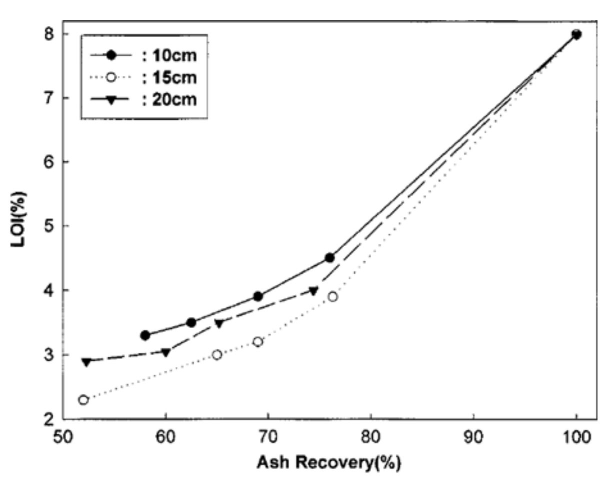


Fig. 10. Effect of the distance between diffuser slit and splitter on the electroseparation efficiency.

the negative electrode, they bounce back into the center of the stream. High carbon particles possess some conductivity so that the charge dissipates through the particle to the electrode plate. When this occurs, the particles are no longer attracted to the electrode, and fly back towards the air stream. Therefore, if the distance becomes too long, the separation efficiency deteriorates because more high carbon particles touch the plate and are re-entrained by the air stream.

7. Effect of the Air Velocities in Electric Field

The air velocities in the electric field and the air velocity at the diffuser outlet are different because more air is introduced through the top open ends between the electrode plates. In order to investigate the effect of the total air rates in electric field on the separation efficiency, tests were conducted at several different air flow rates of 3.28, 5.98, 6.79, 11.94, 13.27, and 15.37 m^3/min. It was found that these air flow rates correspond to air velocities of 1.8, 2.8, 3.1, 4.9, 5.5 and 6.28 m/s in the electric field. Suction air rates were controlled by the pressure regulator of the I.D. Fan damper.

Fig. 11 shows the effect of the air velocities in the electric field on the LOI of clean ashes. It can be seen that the LOI of clean ashes decreases as the air velocity increases, and reaches minimum at 3.1 m/s, but starts to increase as the air velocity increases further. It seems that when the air velocity in the electric field is too low, the particle stream entering the electric field is disturbed by turbulence due to the velocity unbalance between the injected particle stream and the air stream drawn through the openings. On the other hand, if the air velocity is too high, the particles move with a higher velocity so that there is not enough time for the charge particles to be separated in the electrical field.

8. Effect of Splitter Position on the Electroseparation Efficiency

At a certain position of the splitter, the proportion of the particle stream partitioning can be adjusted by moving the splitter laterally. As the splitter moves more towards the positive electrode, particles with higher negative charges (particles containing less carbon) will be collected, but concurrently the recovery will decrease. Tests were conducted to investigate the effect of the position of splitter on the separation efficiency at seven different positions of 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. These positions were controlled by rotating the splitter from the center to the negative electrode as shown in Fig. 2. It was found that the positions of 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0

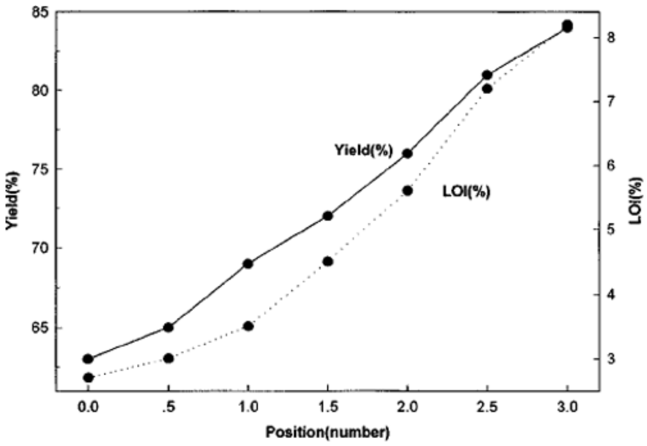


Fig. 12. Effect of position of splitter on the electroseparation efficiency.

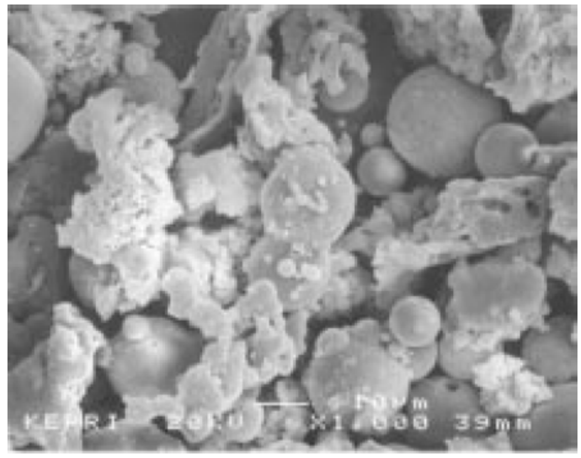
resulted in a distance from the center to the negative electrode of 0, 0.25, 0.55, 0.9, 1.3, 1.75, and 2.25 cm, respectively.

Fig. 12 shows the LOI and recovery of clean ashes for various lateral positions of the splitter at diffuser slit gap of 4 mm, ejector air rate of 1.75 m^3/min, feed rate of 50 kg/hr, electric field of 5 kv/cm, and distance between the diffuser slit and splitter of 15 cm. As expected, as the splitter is closer to the center between the electrodes, the LOI of the clean ash stream decreases. It indicates that the LOI of clean ashes can be controlled by moving the splitter at various lateral positions. Also, the splitter positing can be used as a means of controlling the dependence on the LOI of the feed fly ash; the splitter position can be adjusted to recover the clean ashes with less than LOI 3%.

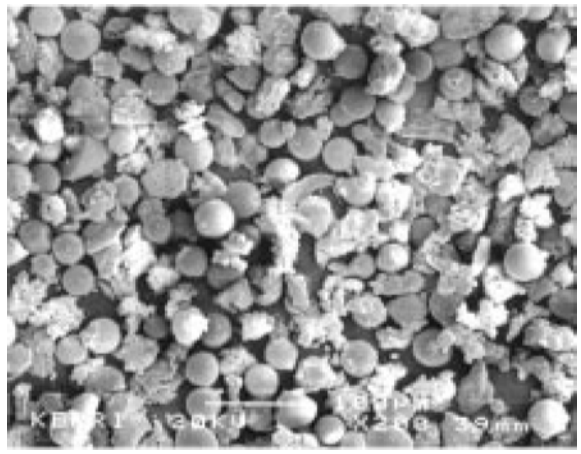
9. Characteristics of the Cleaned Fly Ash

Table 2 shows the chemical composition and physical properties of feed, clean, and waste ashes. It can be seen that after separation, the contents of SiO_2 and Al_2O_3 of the clean fly ashes are increased, while the Fe_2O_3, CaO, and MgO contents are decreased. It indicates that fly ash particles containing Fe_2O_3, CaO and MgO are selectively separated from the clean fly ash. This can be explained by the fact that the work functions of Fe_2O_3, CaO, MgO components are similar to that of the unburned carbon [Gupta et al., 1993]. The increase in the content of SiO_2 and Al_2O_3 is beneficial for using fly ash as an additive of concrete because it promotes the pozzolanic activities.

Fig. 13 shows the SEM images of the fly ash particles before and after separation. It can be seen that raw fly ash particles are composed of bulky, porous unburned carbon particles and spherical pure ash particles. However, after separation, the fly ash particles become more homogeneous, mainly consisting of finer, spherical particles. Size analysis shows that the mass median diameter is decreased from 31 μm to 20.4 μm after separation. Also, Blaine surface area was found to be increased after separation. These results would give another advantage to using fly ash as an additive of concrete since the strength of concrete increases with increasing fineness with fly ash [Pratt, 1989].



(a)



(b)

Fig. 13. SEM images of fly ash (a) before and (b) after the triboelectrostatic separation.

CONCLUSION

The charge density of fly ash particles has been evaluated for three different types of materials at various solids loading conditions using a Faraday cage. It was found that the charge density was the highest when ejector throat was made of stainless steel (SUS304). The charge density generally increased with increasing the feed air rate. But, when the air rate was increased over 1.75 m^3/min the recovery decreased and the LOI of the clean ash began to increase, probably due to shortening of the residence time and increasing turbulence inside the plates. On the other hand, when the ejector air

Table 2. Characteristics of fly ash before and after the electrostatic separation

Item	SiO_2	Al_2O_3	TiO_2	P_2O_5	Fe_2O_3	CaO	MgO	Na_2O	K_2O	LOI	Blaine (cm^2/g)	d_{50} (μm)
Feed	52.8	27.0	1.3	0.6	4.9	1.8	0.6	0.84	0.56	9.6	3,550	31.0
Clean ash	58.7	29.6	1.3	0.5	3.9	1.2	0.5	0.84	0.52	2.9	3,680	20.4
Waste ash	41.8	22.2	1.3	0.78	6.75	2.91	0.78	0.83	0.63	22.0	3,520	31.8

rates are too low, the LOI of the clean ash becomes higher due to the decrease in the charge density.

Also, it was found that the charge density decreased as the feed rate increased due to the crowding effect. Optimum solids loading condition to obtain a product with less than 3.0% LOI was about 0.074 kg/cm^2·hr.

Carbon removal efficiency was significantly affected by the relative humidity of the surrounding air. When the relative humidity was higher than 50%, there was a tendency for fly ash particles to agglomerate. Generally, it was found that the relative humidity of surrounding air should be maintained at less than 30% to recover the clean ash with less than 3% LOI.

The design factors affecting the separation efficiency were the width of the diffuser slit and the location of the splitter. It was found that the system produced the best results with a diffuser slit gap of 4 mm and a distance between diffuser slit and splitter of 15 cm. With these optimum conditions, the maximum separation capacity could be achieved at an electric field of 5 kV/cm.

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