Submicron Particle Agglomeration by an Electrostatic Agglomerator

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Abstract

The new-type electrostatic precipitator(ESP) was proposed to elevate the collection efficiency for submicron-sized particles in exhausted gas from a fine-grained coal-burning boiler. This ESP is combined with an electrostatic agglomeration apparatus(EAA). This paper firstly describes the basic concept and structure of this new-type ESP. Secondly, this paper describes the theoretical and measured agglomeration operation. Finally this paper also describes the theoretical collection efficiency of the new-type model ESP. A measured weight percentage of submicron-sized particles under 1 μm decreased 20 % and a mean diameter of aerosol particles increased to four times of that at an inlet when an EAA was used. The new-type ESP is expected to increase the collection efficiency from 95 % to 98 % due to a calculation of the collection efficiency using the measured agglomeration particle-size distribution in the range of 0.06 - 12 μm.

1 Introduction

In exhausted gas from a fine-grained coal-burning boiler, there are a lot of submicron-sized carbon particles with flyash particles. The measured particle size distribution is from 0.01 μm to 1 μm as shown in Fig.1.[1] The submicron-sized particles give the fatal effects on the environments due to the following reasons:

(a) deposition at an alveolus
(b) adhesion of harmful heavy metals to a particle surface
(c) production of acid rain on a particle surface
(d) production of cloud nulcei

From these reasons, the high efficient ESP is needed for the collection of submicron-sized particles.

Fig.1 Particle-size distribution at the furnace exit.[1]

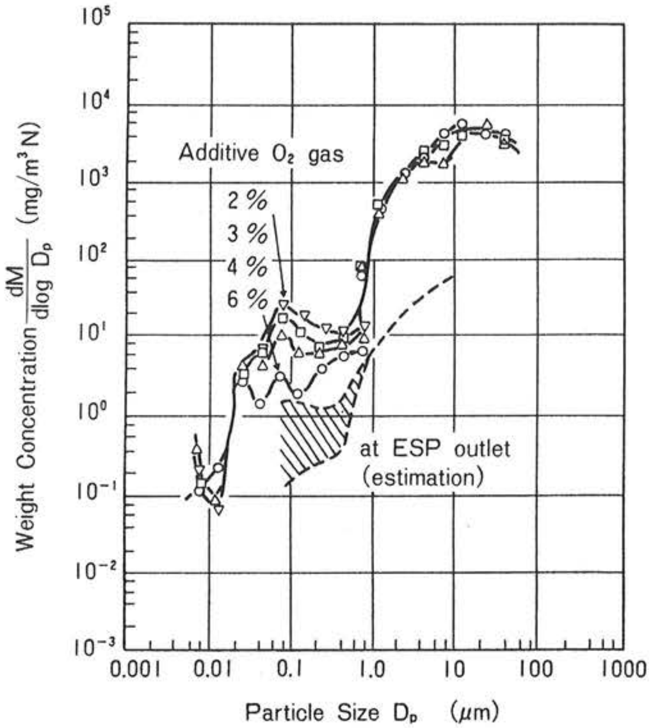
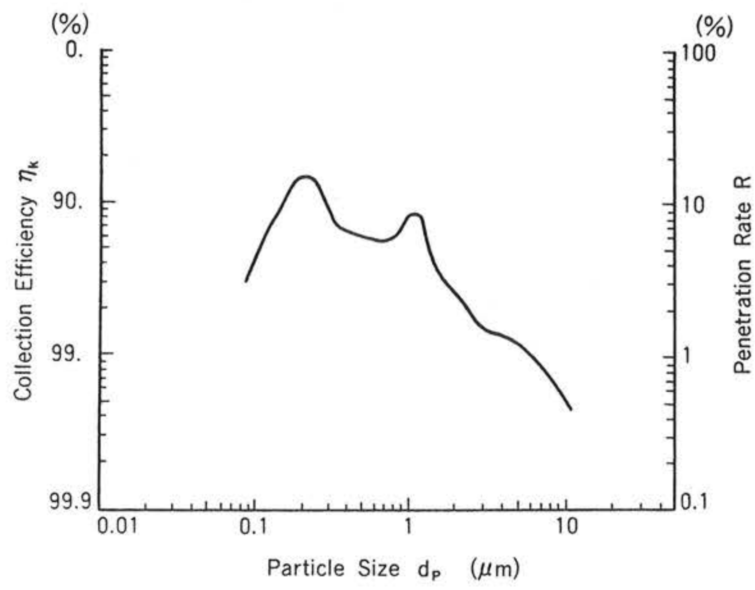


Fig.2 Partial-collection efficiency of an ESP for 520-MW coal burning boiler.[2]



2 The new electrostatic precipitator with an electrostatic agglomeration apparatus

2.1 *The concept of a new electrostatic precipitator*

The collection efficiency of a conventional ESP extremely decreases in a submicron region as shown in Fig.2.[2] This decrease is due to the lack of particle charge. The new ESP should be economically designed so as to be retro-fitted to a conventional one. The basic structure of this ESP is shown in Fig.3. The first and final stages are conventional ESP units. In the intermediate stage, the thick and long high-voltage electrodes are installed in a conventional ESP unit instead of discharge electrodes. These electrodes are charged by AC voltage superimposed on DC voltage to accelerate an electrostatic agglomeration. Each stage operates as follows:

(a) The first stage serves to collect large micron-sized particles and to precharge submicron-sized particles.
(b) The intermediate stage promotes an agglomeration of submicron-sized particles.
(c) The final stage collects the enlarged particles.

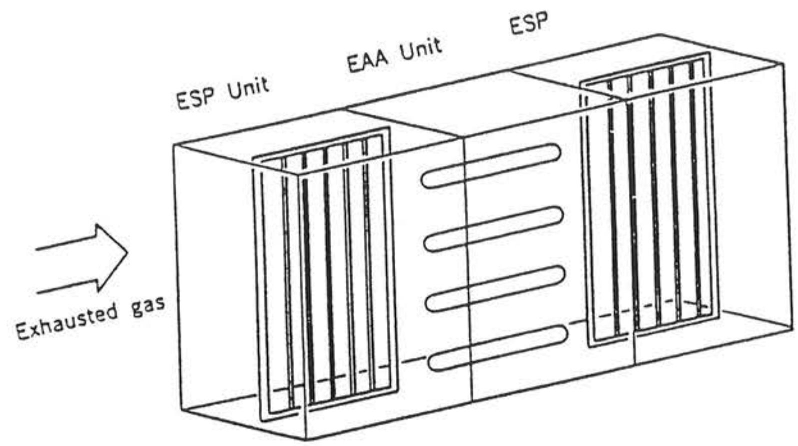


Fig.3 The basic structure of a new-type ESP.

2.2 *The key parameters of an electrostatic agglomeration apparatus*

The typical model for submicron-sized particle agglomeration is a Brownian a one. Based on the model in Fig.4, Fuches derived a Brownian agglomeration operation constant [3]. Fig.5 shows an agglomeration operation constant K_B for mono-dispersion and multi-dispersion particles calculated by equation(1).

$$K_B(r_i, r_j) = (2kT/3\mu)\cdot\{(C_c/r_i)+(C_c/r_j)\}\cdot(r_i+r_j)\cdot[2\bar{r}/(2\bar{r}+\bar{\delta})+4\bar{D}/(\sqrt{2}\cdot\bar{C}\cdot\bar{r})]^{-1} \quad (1)$$

Quantities are as these.

k : Boltzmann constant $\quad$ μ : viscosity coefficient $\quad$ C_c : Cunningham coefficient
T : gas temperature $\quad$ $\bar{r}$: effective radius $\quad 0.5\cdot(r_i+r_j)$
$\bar{D}$: effective diffusion coefficient $0.5\cdot(D_i+D_j) \quad D_i = kT/(6\pi\mu r_i)$
$\bar{\delta}$: radius of region where particles encounter with thermal velocities $\quad [(\delta_i^2+\delta_j^2)/2]^{1/2}$
$\delta_i = (\sqrt{2}/(6r_i l_{pi}))\cdot[(2r_i+l_{pi})^3-(4r_i^2+l_{pi}^2)^{3/2}]-2\sqrt{2r_i}$
$l_{pi} = (8/\pi)(D_i/\bar{C}_i) \quad \bar{C} = [(\bar{C}_i^2+\bar{C}_j^2)/2]^{1/2} \quad \bar{C}_i = (8kT/\pi m_i)^{1/2}$
m_i : weight of $i-th$ particle

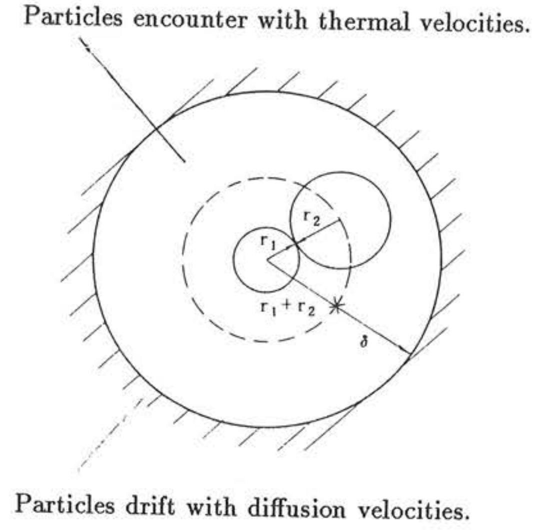


Fig.4 The agglomeration model of fine particles.

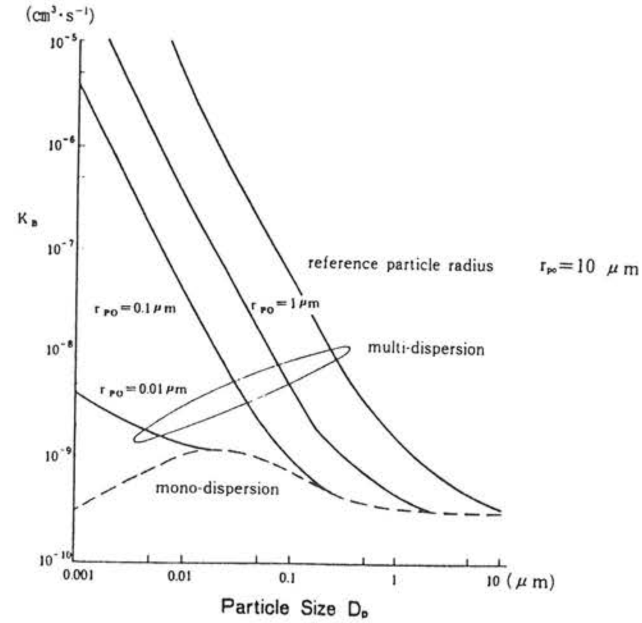


Fig.5 A Brownian agglomeration operation constant K_B to a particle diameter D_p (in air at 20°C and 1 atm)

For mono-dispersion, a peak agglomeration rate K_B is achieved for a particle diameter between 0.01 and 0.1 μm. For multi-dispersion, the K_B value increases with the difference in particle sizes, and is considerably higher than that for mono-dispersion. The following indicates the calculation results of the time required for Brownian agglomeration to halve the number of particles, and of particle diameters during the time. For mono-dispersion of 0.1 μm-particles with a density of 1 g/cm^3 and a concentration of 10^9 particles/cm^3, the number of particles will halve in 1.3 seconds, with a resultant size of 0.14 μm. For multi-dispersion of particles, at the same concentration, with sizes between 0.01 μm and 0.1 μm, the number of particles will halve in about 0.06 seconds, with size increasing to 0.44 μm in one second.

Based on the above, the agglomeration system must meet the following two conditions.
(i) Expansion of particle motion range · · · In a Brownian agglomeration model, the distance of the agglomeration operation is only the order of mean free paths determined by particle thermal velocities. Including large motions will therefore enhance agglomeration. Application of an AC voltage to charged flyash particles is therefore effective, because such a field causes charged particles to oscillate widely.[4] Charged particles oscillate along electric field lines under AC voltage. An oscillating amplitude difference among particle sizes increases the likelihood of agglomeration. During oscillation, an effective mass of a particle increases due to a viscosity resistance. The calculated particle oscillating amplitudes are shown in Fig.6. The calculation is based on the following condition: The flyash particles are precharged at 3 KV/cm and $2\cdot10^{-4}$A/m^2 in 20°C air for one second. The relative dielectric constant of the particles is 3, and their density is 10^3 Kg/m^3. Fig.6 shows these advantages.

(a) A particle oscillating amplitude increases with a particle size from submicron to micron. This amplitude increase is opposite to the drift length tendency in Brownian motion.

(b) Application of AC voltage promotes agglomeration in addition to that caused by Brownian motion.

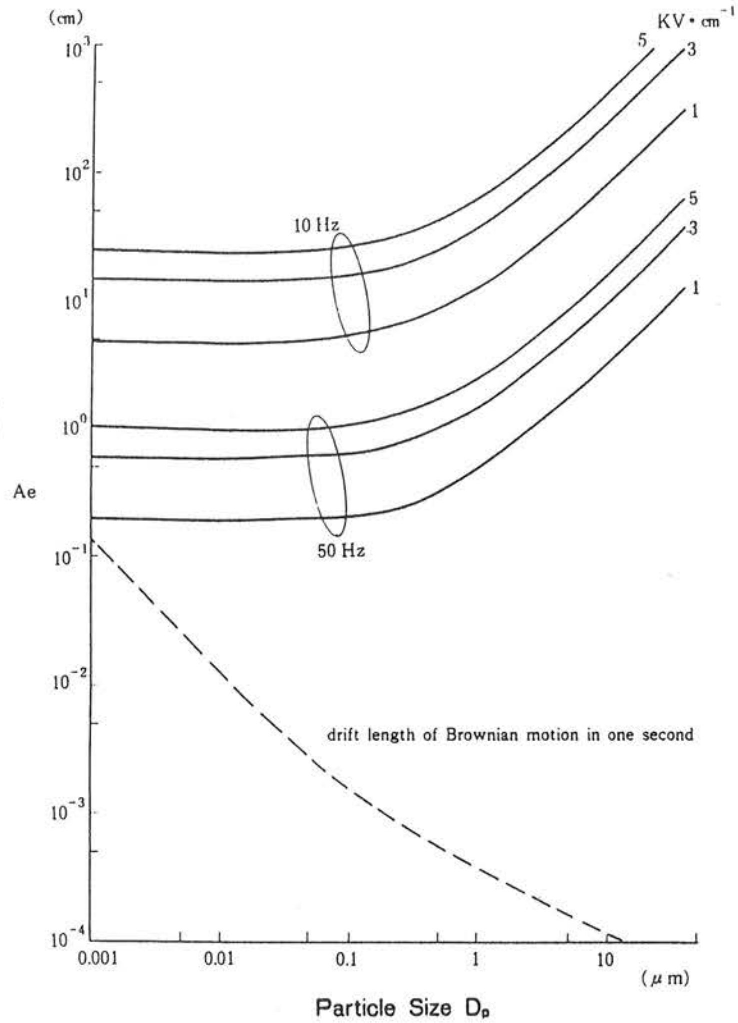


Fig.6 The amplitudes of charged flyash particles under AC electric field.

(ii) Promotion of agglomeration between different particle sizes · · · Electric dipole occures in a conductive particle under an electric field. Many polarized particles form "pearlchain" as analytically shown by Zëbel.[5] So it is expected that carbon particles form "pearlchain"-like enlarged particle especially in the high electric field.

To meet the need for promoting electrostatic agglomeration, a system incorporating multipole electrodes is proposed as shown in Fig.3. A quadrapole electric field, which is a basic electric field in the intermediate stage, offers the following features.

(a) Charged particles tend to gather in the central region of very low, suddle-point electric field, when AC voltage is applied.
(b) Polarized conductive particles tend to collect in the strong electric field regions near the two cylindrical electrodes.
(c) Synergium of both agglomerations.

3 Experiment

3.1 *Experimental apparatus*

Fig.7 shows an experimental agglomeration apparatus installed in a rectangular duct 50-cm wide, 50-cm high and 1-m long. In order to allow observation, the top and bottom of the duct are of Pyrex glass, while the sides are of transparent conductor-coated glass and earthed plates. An agglomeration unit has two thick, cylindrical, high-voltage electrodes 6-cm in diameter, and two earthed plane electrodes with 50-cm distance, which produce a modified quadrapole electric field. Fig.8 shows the calculated equi-voltage lines. The maximum electric field on a cylindrical electrode surface is 1.3 kV/cm at 10 kV charging. The AC voltage superimposed on DC voltage is charged between the cylindrical and plane electrodes.

The tested charged particles are supplied in front of the agglomeration unit to simulate the charged particles in the practical ESP. A mixed-particle-production apparatus produces a particle-size distribution similar to the one observed in a combustion furnace.[1] The submicron-sized carbonic particles are supplied with joss-stick burning. The micron-sized flyash particles are supplied from air dispersion of standard test dust No.15. A precharging apparatus produces charged particles similar to those estimated in a conventional ESP.

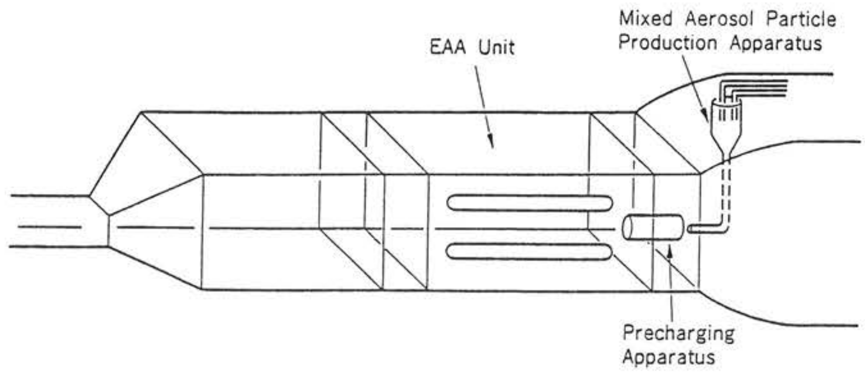


Fig.7 The experimental electrostatic agglomeration apparatus.

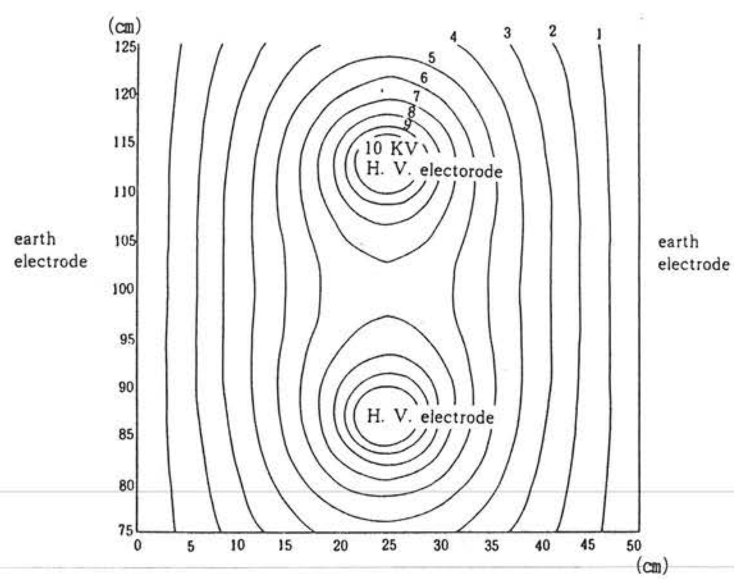


Fig.8 The equi-voltage line distribution in an electrostatic agglomeration apparatus with a quadrupole electric field.

An agglomeration unit is installed in a "racetrack"-shaped air circulation circuit, such as shown in Fig.9. The flow rectifier and agglomeration unit were made of stainless steel to prevent rusting. The collecting unit and pipes were plated with zinc-oxide. These are electric heaters inside pipe.

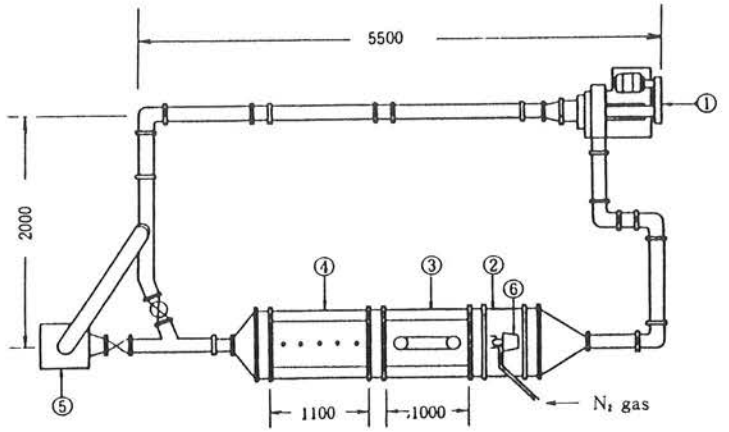


Fig.9 The arrangement of experimental apparatus and units.

3.2 *Experimental results*

Three kinds of charged aerosol particles were used to measure the operation of an EAA as shown in Fig.10. Type A is rich in carbon particles, and type B is rich in flyash particles. Type C contains both particles in eaqual amounts.

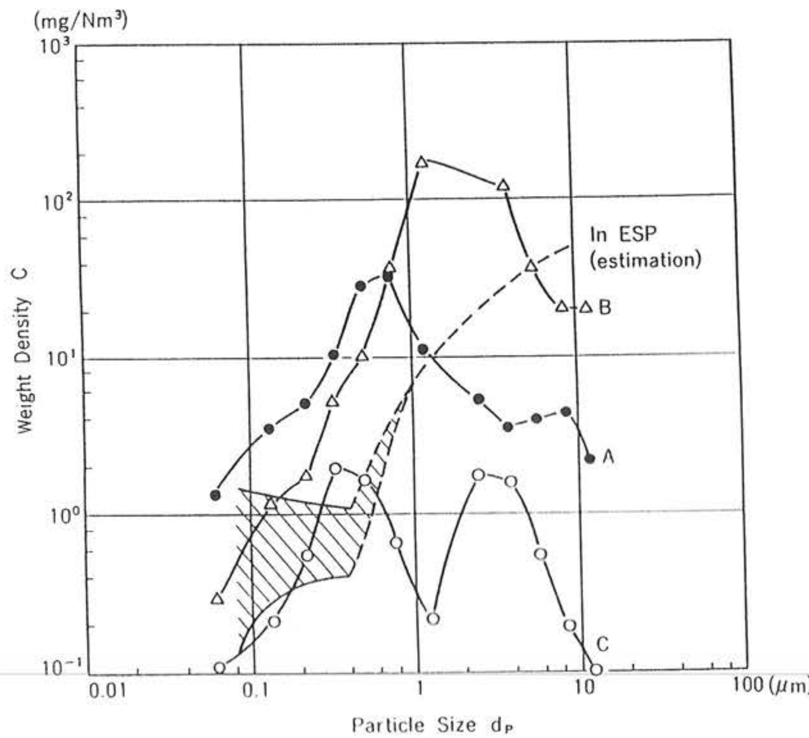
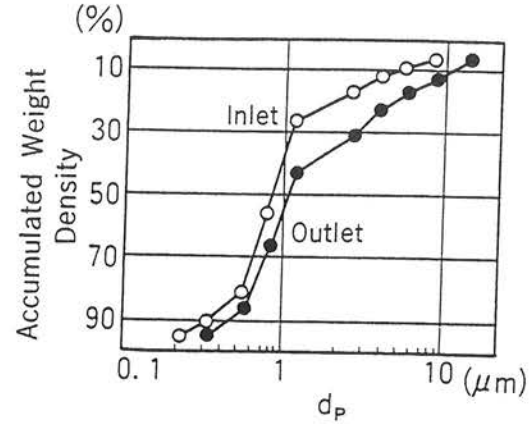


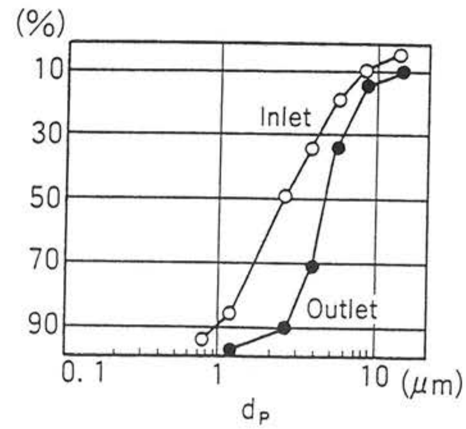
Fig.10 The tested charged-particle-size distribution.

Low-pressure impactors were used to measure the particle-size distributions when an EAA was used. Fig.11 shows these results. With the EAA, a weight percentage of the submicron particles under 1 μm decreased 20 %, and a mean diameter of aerosol particles increased four times to that at an inlet. Figs.12 and 13 show the non-agglomerated and agglomerated particles photographed by a scanning electron-microscope. At an inlet,spherical flyash particles stand isolately and some carbonic particles stickon a flyash particle surface. At an outlet, a spherical surface of flyash particle is ambiguousand. An enlarged train of flyash particles stuck by a numerous cluster of carbonic particles were produced.

Applied voltage to an EAA:
DC 30kV and AC 11kV
Air condition:
T = 25 °C, H = 6.4 g/m³
(a) Type A



Applied voltage to an EAA:
DC -30kV and AC 11kV
Air condition:
T = 60 °C, H = 9.9 g/m³
(b) Type B



Applied voltage to an EAA:
DC -30kV and AC 15kV
Air condition:
T = 60 °C, H = 7.0 g/m³
(c) Type C

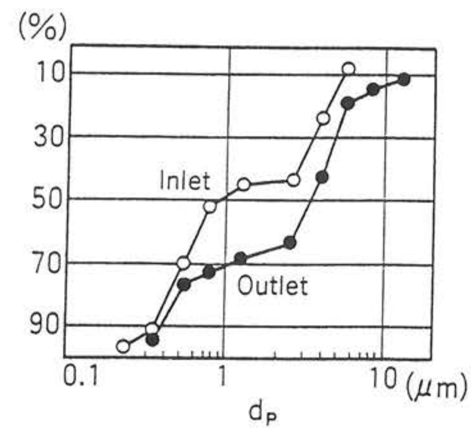


Fig.11 Changes in particle-size distribution in an EAA.

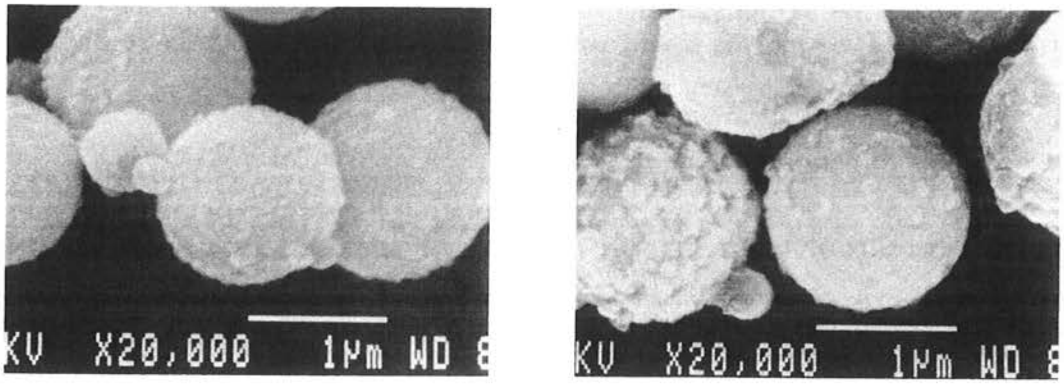


Fig.12 Nonagglomerated particles photographed by a scanning electron microscope.

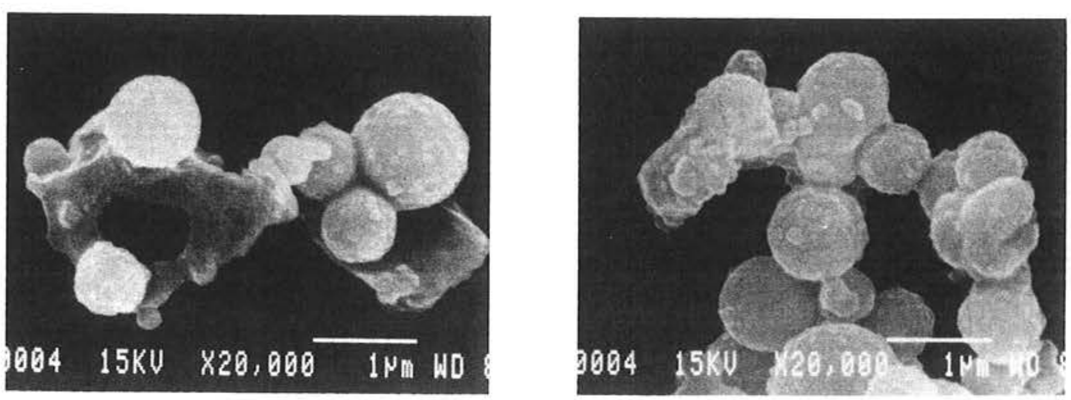


Fig.13 Agglomerated particles photographed by a scanning electron microscope.

4 The theoretical analysis of particles motions in an EAA

The charged particles motions in an EAA were theoretically analyzed based on the following equations. On the assumption that a velocity component of the z-direction is the same with that of a wind velocity 1 m/sec.

$$x\text{-direction} \qquad m\frac{d^2x}{dt^2} = -\frac{6\pi\mu a}{C_c}(\frac{dx}{dt} - u_x) + qE_x(x,y) \qquad (2)$$

$$y\text{-direction} \qquad m\frac{d^2y}{dt^2} = -\frac{6\pi\mu a}{C_c}(\frac{dy}{dt} - u_y) + qE_y(x,y) - mg \qquad (3)$$

Quantities are as these:
m: particle weight μ: viscocity coefficient q: particle charge
C_c: Cunningum coefficient a: particle diameter E_x, E_y: electric field of x and y directions
u_x, u_y : wind velocities of x and y directions

The calculations are based on 1 atm in air. The electric field distribution in an EAA is shown in Fig.14 by the charge simulation method. In this figure, the length of each arrow indicates a field strength.

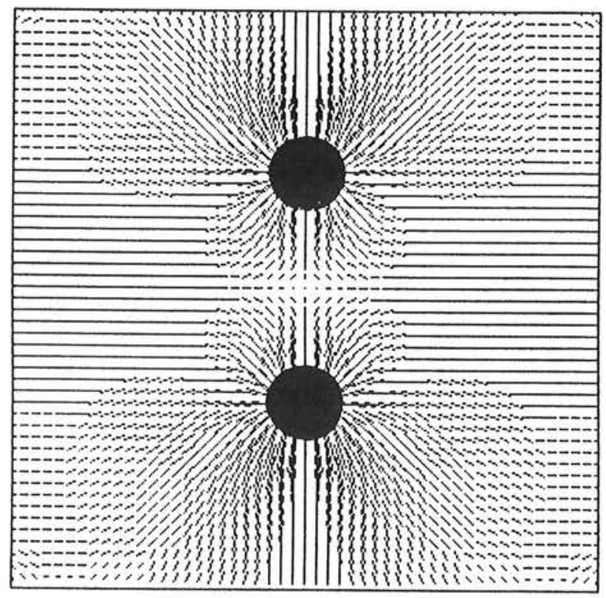
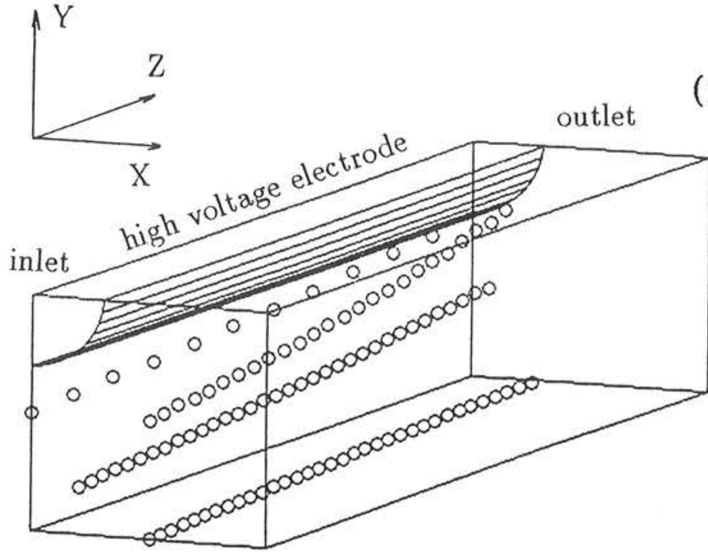


Fig.14 Electric field distribution in an EAA.

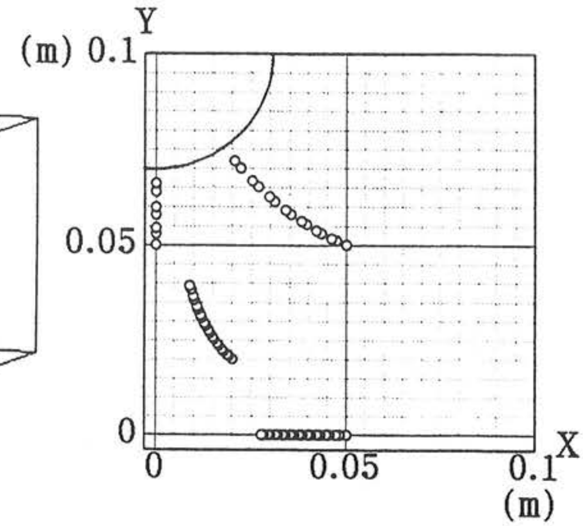
The amount of particle charge is calculated at 3 kV/cm and $2 \cdot 10^{-4}$ A/m^2. The calculation results of two different particle sizes 3 μm and 0.5 μm are shown in Figs.15-18. From these results, the following characteristics of charged particles motions are concluded.

- A charged particle motion is very effected by an electric field strength. · · · When particle initial position is at strong electric field, the drift velocity and oscillation amplitudes are very large. On the other hand, a particle at weak field position has small drift velocity and small oscillation amplitude.
- The large particle have a large drift velocity and oscillation amplitude compared with small one.

These particle motions make an active agglomeration especially between the different size particles.

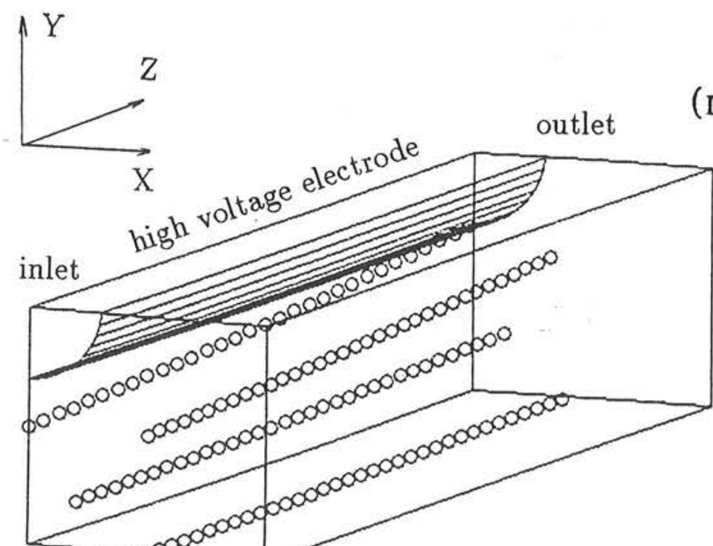


(a) 3-dimensional motions

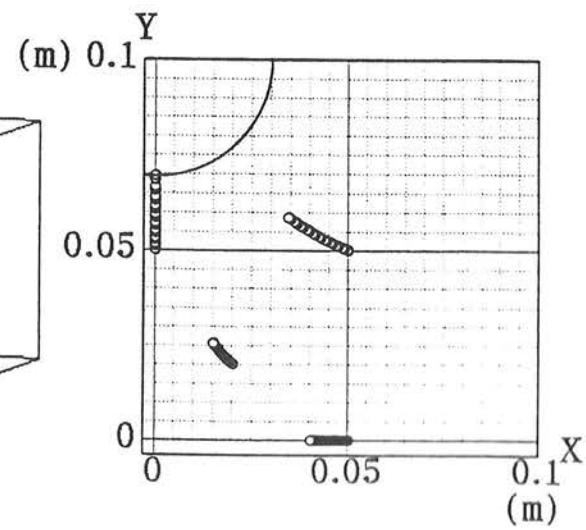


(b) 2-dimensional motions

Fig.15 Particle motions in an EAA — 3 μm in diameter.



(a) 3-dimensional motions



(b) 2-dimensional motions

Fig.16 Particle motions in an EAA — 0.5 μm in diameter.

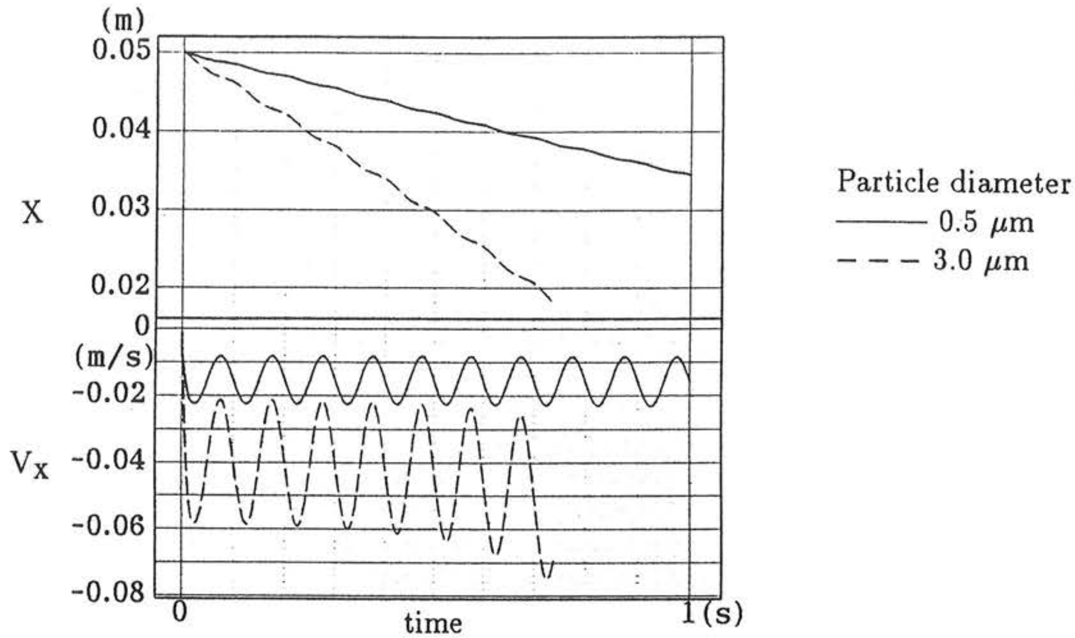


Fig.17 Position and velocity of X component of particles motions — DC +30 kV, AC 15 kV (10 Hz), inlet position (0.05m, 0.05m).

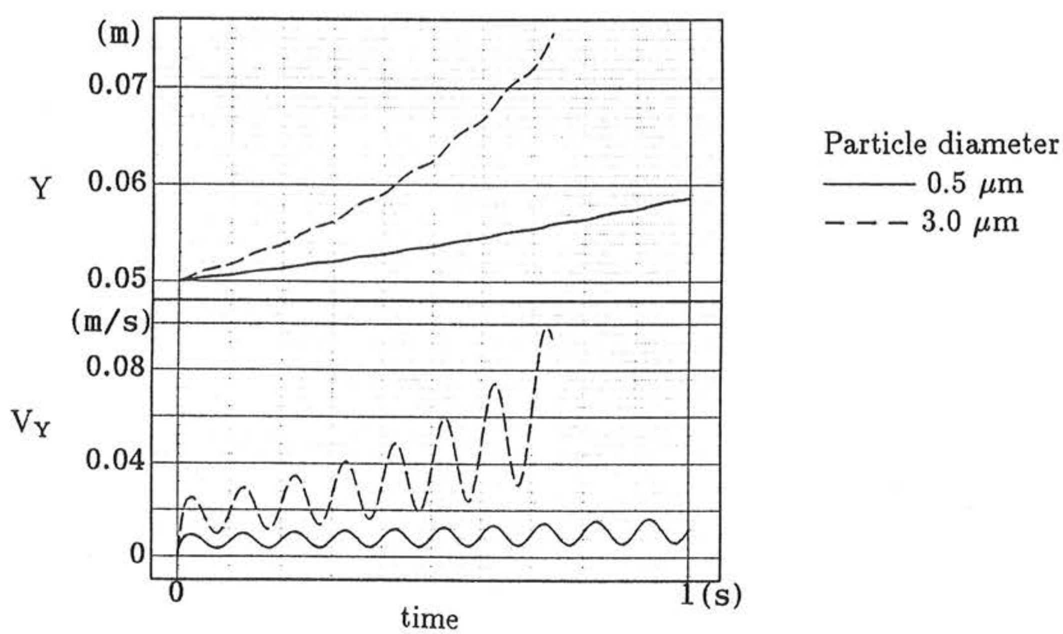


Fig.18 Position and velocity of Y component of particles motions — DC +30 kV, AC 15 kV (10 Hz), inlet position (0.05m, 0.05m).

5 Improvement of the collection efficiency by a new ESP

The collection efficiencies of a new ESP were calculated using the measured particle-size distributions based on the temporal collection efficiency of a conventional ESP as shown in Fig.2.[2] The partial collection efficiency ηk of the $k-th$ particle size is shown at equation (2).

$$\eta k = 1 - C_{out}(k)/C_{in}(k) \tag{4}$$

$C_{in}(k)$ denotes a k-th-size weight density at the inlet of an ESP, while $C_{out}(k)$ is that at the outlet. The total collection efficiency of an ESP is given by equation(3) using (2).

$$\eta = 1 - \sum C_{in}(k) \cdot (1 - \eta k)/\sum C_{in}(k) \tag{5}$$

Using the measured-particle-size distributions over a range from 0.06 μm to 12 μm, the calculated collection efficiencies are shown in Table 1.

Table 1: The calculated collection efficiencies of a new-type ESP and conventional one.

C a s e	Type A	Type B	Type C
Conventional type (without an EAA)	94.5 %	96.0 %	95.1 %
New type (with an EAA)	95.2 %	98.2 %	98.1 %

6 Conclusions

With operation of an electrostatic agglomeration unit, the weight percentage of submicron-sized particles under 1 μm decreased 20 %, and the mean diameter of particles increased four times to that at an inlet. From the calculation of the collection efficiency using the measured agglomerated particle-size distribution, it is expected that the new-type ESP combined with an EAA will elevate the collection efficiency from 95 % to 98 %.

Acknowledgements

The authors would like to express the highest appreciation to the following persons for their fruitful discussions and encouragements; Professor Yasuo Kosaka in the University of Osaka Prefecture, Assistant Professor Akira Mizuno in Toyohasi University of technology, Professor R.H.Davis and Associate in Research W.C.Finney in Florida State University, Professors I.I.Inculet and P.Castle in the University of Western Ontario, Dr.E.C.Potter in CSIRO

Division of Fossil Fuel, Dr.Tosiaki Yamamoto in Research Triangle Institute, Assistant ProfessorJ.F.Hughes in the University of Southampton. The authors would also like to thank for the strong support of Dr.Yasuhiko Nagakura, who is the Dean of engineering faculty of Tokyo Metropolitan University (TMU), for the joint research between Finish VTT, TUT and TMU.

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