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Electrostatic Precipitability of the Coal Fly-Ash by the Pilot Scale Test

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The equation of the particle collection efficiency proposed by Deutsch has been modified through the various experiments to correct the errors caused by the assumptions made for the equation. In order to get an modified Deutsch equation that can be applied to real conditions, a pilot scale electrostatic precipitator is used. The effects of operational variables on the particle collection efficiency are evaluated. Particle resistivity, gas temperature, moisture contents in gas, gas velocity and particle concentration are used as the operational variables. Two different types of coal fly-ash obtained from the fluidized bed combustor and the pulverized coal combustor are used as test particulate to evaluate the effect of the physiochemical and electrical characteristics of the particle on the particle collection efficiency. The experimental results are fitted with the modified Deutsch equation made by Matts-Öhnfeldt and the extended Deutsch equation made by E. C. Potter to evaluate the effect of the particle characteristics and the operational conditions on the particle collection efficiency of the electrostatic precipitator.

Key Words: Electrostatic Precipitator, Coal Fly-Ash, Pilot Scale Test, Modified Deutsch Equation, Extended Deutsch Equation

1. Introduction

Two coal combustion methods are widely used in the power plants or process steam boilers. One is the pulverized coal combustion(PC) and the other is the fluidized bed combustion(FBC). Usage of coal in pulverized form provides very critical advantages in power generation, such as the flexibility of the firing system and the ability to burn low-grade fuel. Pulverized coal combustion has, thus, now become important for electrical power generation. The fluidized bed combustion is rather a solid fuel combustion technology, currently being developed for commercial use around the world. Combustion mechanism is different between fluidized-bed combustion boiler and pulverized-coal combustion boiler. Particularly, shape of fly-ashes obtained is different because of flame temperture and mean diameter of flyash because of crushed conditions of supplied coal. Because fluidized-bed combustion boiler is supplied with CaO, dust resistivity of flyash is different. Therefore, since combution mechanisms of two combution systems are different from each other, characteristics of fly-ashes appeared differently even under the same operating temperature.

Among various pollutants from the coal combustion system, fly-ash particles formed from the mineral matter in the coal are one of the most important emissions of environmental concern.

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Since the fly-ashes are emitted with the flue gas, it is necessary to remove the ash before discharging the flue gas to atmosphere, and electrostatic precipitation is almost universally used for this purpose.

The use of electrostatic precipitators to collect the coal fly-ash generated from pulverized coal combustor is well established and reported by White (1977). Whilst far more recent, the use of precipitators to collect fly-ash from fluidized bed combustors, is also well reported. Several aspects of fluidized bed fly-ash collection including feasibility studies (Bush, 1978), operation (Schale, 1969) and performance (Mittleman et al., 1980), mostly with respects to high temperature, high pressure applications have been published. However, only one comparison study has been conducted on the collection of fly-ash from a fluidized bed combustor and a pulverized coal combustor by Paulson et al. (1984).

The fundamental theory of electrostatic precipitation is developed enough to permit derivation of theoretical equations for the collection efficiency under certain idealized conditions. The simplest case to consider is that of uniform conditions for particle size, gas flow, and electric field distribution, etc. . Extensions of this theory can be made to introduce non-uniformity in these factors. However, the disturbances and particle losses caused by reentrainment, gas sneakage, and rapping cannot be calculated from the theory, which must be accounted by modifications of the parameters based on empirical data. In practice, the losses due to rapping and the like should be minimized as much as possible in order to achieve best performance and so that the design can be based essentially on the theoretical equations (White, 1977).

The theoretical problem of particle capture under these conditions can be treated by a well-known classical equation (White, 1963),

$$\eta = 1 - \exp\left(-\frac{A}{Q}\omega\right) \qquad (1)$$

where

η=the particle collection efficiency in %
Q=the gas flow rate in m^3/s
A=the collecting electrode surface area in m^2
ω=the migration velocity of the particle in m/s.

This equation was first derived by Deutsch (1922) using a differential equation method, but the Deutsch equation has been modified through the various experiments to correct the errors caused by the assumptions made for the equation. Many models have been proposed over the years to account for a wide variety of effects observed in electrostatic precipitators. These models range from the simplest analytical expressions to complex numerical simulations, yet all have implicit or explicit assumptions glossing over unmodeled effects. The unaccounted effects in the models often appear to be as adjustable parameters whose values are determined empirically, but this approach leaves the model user open to criticism when extrapolating beyond the realm of experience (Lawless, 1984).

The aim of this research is to understand how the properties of dust and process variables influence to the system performance. A pilot scale electrostatic precipitator is used to get an improved Deutsch equation that can be applied in real conditions. The effect of operational variables on the particle collection efficiency are evaluated. Particle electrical resistivity, gas temperature, moisture contents in gas, gas velocity and particle concentration are used as the operational variables. Two different types of coal fly-ashes obtained from the fluidized bed combustor and the pulverized coal combustor are used as the test particulate to evaluate the effect of the physiochemical and electrical characteristics of the particle on the particle collection efficiency.

The experimental results are, then, fitted with both the modified Deutsch equation made by Matts-Öhnfeldt (1963), and the extended Deutsch equation made by E. C. Potter (1978) to evaluate the effect of the particle characteristics and the operational conditions on the particle collection efficiency of the electrostatic precipitator.

2. Theoretical Background

2.1 Modified Deutsch equation

The Deutsch equation of the particulate collection efficiency in the electrostatic precipitators is the basis for sizing them in the design stage, and for testing their performance. If all the particles suspended in the gas at the entrance of the electrostatic precipitator have the same size, the collection efficiency can be theoretically expressed by the Deutsch equation, which indicates that with the increase in specific collection area (SCA), collection efficiency, η, increases as (Shibuya, et al., 1984)

$$\eta=1-\exp(-SCA\cdot\omega) \tag{2}$$

where

SCA=the specific collection area in s/m
ω=the migration velocity of the particle.

However, it is empirically known that the $SCA-\omega$ curves are not fitted with Eq. (2) and the dust collection efficiency is saturated at large . A further work on the topic was done by the Swedish scholars, Allander and Matts (1957), who considered the apparent loss of efficiency due to the monodispersity of particulate used in the Deutsch equation. By the words "apparent loss", Allander and Matts (1957) mean that the collection efficiency for a distribution of particle sizes is less than that for a distribution in which all particles are of a same size equal to the mean of the original distribution. Starting from the results of Allander and Matts (1957), Matts and Öhnfeldt (1963) subsequently obtained via plausibility considerations, an equation in which the exponent appearing in the Deutsch formula is replaced by a fractional power of the exponent.

$$\eta=1-\exp(-SCA\cdot\omega_k)^k \tag{3}$$

where

k=a modification parameter obtained experimentally
ω_k=modified migration velocity in m/s.

The Matts-Öhnfeldt equation is a modification of the Deutsch equation, intended to accommodate for variations in particle distributions for electrostatic precipitator of nearly equivalent size. If the exponent, k, is equal to 1.0, the Matts-Öhnfeldt equation is identical to the Deutsch equation. Shibuya et al. (1984) tried to obtain the "k" value by calculating the characteristics of fly-ash, especially, the particle size distribution. They assumed that the fractional power term of the exponent in Eq. (3) is mainly attributable to the fact that the particles suspended in the gas at the entrance of the electrostatic precipitator have a certain size distribution. A smaller particle has a lower migration velocity due to its smaller charge, therefore, collection of smaller particle becomes more difficult. For this reason, the fraction of smaller particles increases at the rear section of the electrostatic precipitator to such an extent that the collection efficiency is not improved with the increase of SCA.

2.2 Extended Deutsch equation

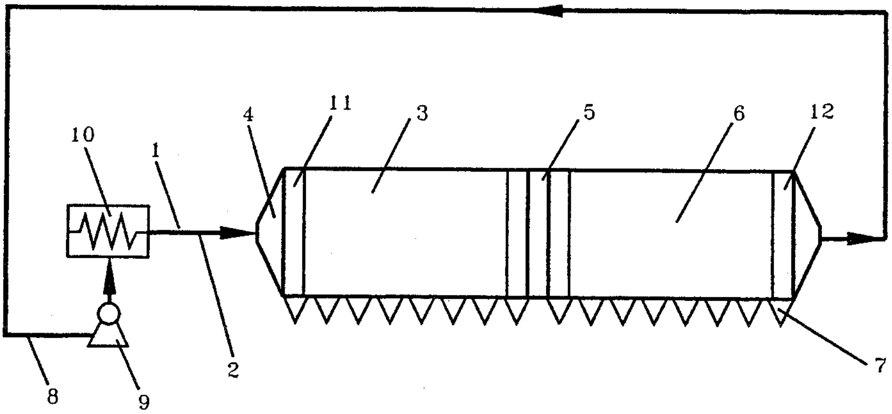
The customary expression of precipitability as an effective migration velocity calculated from the Deutsch equation is replaced by a performance line obtained from a semi-logarithmic plot of collection efficiency against a combined function of specific collection area and operating voltage. The important effects of voltage, particle size, and carrier gas additives clearly emerge from the extended Deutsch equation and the proper value of pilot plant testing has been realized (Potter, 1978).

The extended Deutsch equation is derived by substituting accepted expressions for the migration velocity (based on electrostatic theory and Stoke's law) into the original Deutsch equation. At constant temperature, the equation becomes as follows.

$$\log(1-\eta)=\log(1-\eta_s)+K\cdot d\cdot\cdot SCA\cdot E_c\cdot E_p \tag{4}$$

where

d=the mass mean diameter of particle in μm
E_c=the charging electric field strength in kV/cm
E_p=the precipitating electric field strength in kV/cm
K=a conversion constant



1. Ash Feeding System
2. Gas Conditioning System
3. Ist Field
4. Gas Distribution Section
5. Transition Section
6. 2nd Field
7. Hopper
8. Opacity-meter
9. Fan
10. Electric Heater
11, 12. Transformer Rectifier

Fig. 1 Schematic diagram of pilot scale etectrostatic precipitator

SCA=the specific collection area in s/m
η_s=the particle collection efficiency at corona onset in %.

Once the corona is established, E_c and E_p can be assumed to be equal to the mean electric field (E) applied across the gas space. A plot of log $(1-\eta)$ against $SCA \cdot E^2$ (known as the Performance Line) is expected to be linear beyond η_s in semi-logarithmic (Paulson et al., 1984).

3. Experimental System and Procedure

Figure 1 shows a schematic diagram of pilot-scale electrostatic precipitator and the composition of the device. The electrostatic precipitator used in this study is the so called "single-stage type" in which charging and precipitating of the dust particles take place in the same section of the precipitator. The pilot-scale precipitator is the wire-plate geometry with a plate-to-plate spacing of 400mm, a height of 1.33m and a length of 6. 12m per each field, discharge electrodes are placed 240mm apart.

In order to measure the collection efficiency of the electrostatic precipitator correctly, the properties of the gas and feeding rate of fly-ash must be maintained as being stable. This was accomplished by stabilizing the condition of the gas temperature with an auto-controlled electrical heater and by setting feeding rate of fly-ash constant with vibrating screw feeder. The particles for the present study were generated by dry powder dispersion of a bulk quantity of the solid particles. A vibrating screw feeder, consisting of a dust reservoir and a screw connected to a variable speed motor was used to feed fly-ashes at the venturi meter throat.

An induced draft fan delivers air into the electrostatic precipitator. The air stream induced into the electrostatic precipitator is heated via passing an electric heater placed at the inlet of electrostatic precipitator. Gas mean velocity in the electrostatic precipitator is varied by controlling of the fan speed. The velocity distribution was measured with both a standard pitot tube-micromanometer assembly and a hot wire anemometer. The standard deviation of the velocity distribution, normalized to the average velocity, varied from a low value of 5.5% at an average velocity of 0.3m/s to a high value of 19%

at 2.0m/s. Since these values are considered very good and acceptable, the non-ideal effect of a poor velocity distribution could be ignored in this study (White, 1963 ; Burton, 1975). As a conditioning agent water was sprayed to electrostatic precipitator in a finely atomized form. For analysis and subsequent modeling of the results from precipitation experiments, the dusts were fully characterized in terms of their particle size distribution and electrical properties, and so on.

The electrical resistivity was measured by the ordinary laboratory resistivity measurement cell in a thermo-hydrostatic oven made under the JIS CODE (B 9915). The particle size distribution was analyzed in a laboratory by the optical and diffusion methods (LS 130, Coulter Ltd., Co.). Particle shapes and chemical composition of the fly-ash were also analyzed.

Experiments were performed under the conditions of gas mean velocity range from 0.3 to 2.0m/s, gas mean temperature from 50 ℃ to 150℃, dust concentration in gas from 0g/Nm^3 to 50g/Nm^3 and absolute humidity in gas was about 15vol.%. The specific collecting area can be varied from approximately 20s/m to over 100s/m by varying gas mean velocity. Collection efficiency was measured by the opacity-meter installed at the outlet of the electrostatic precipitator.

This measuring method of the opacity-meter (Maker : SICK, RM41~03) is based on the damping phenomena of reflection, absorption and dispersion of lights by dust.

4. Results and Discussion

The physicochemical analysis of ash particles provides a lot of information about their formation processes. The characteristics of ash particles relative to the combustion processes and to the collection efficiency are discussed. The chemical composition, shape, and size, electrical resistivity of fly-ash particles from the two combustion systems were compared.

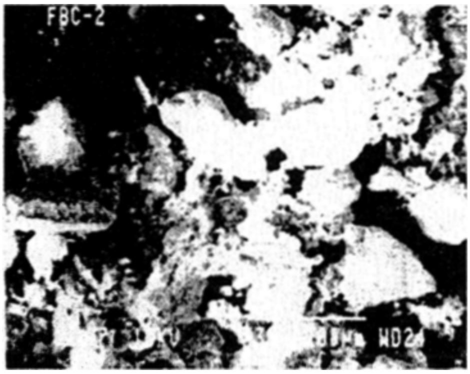


Fig. 2 Shape of fly-ash from fluidized bed coal combustion

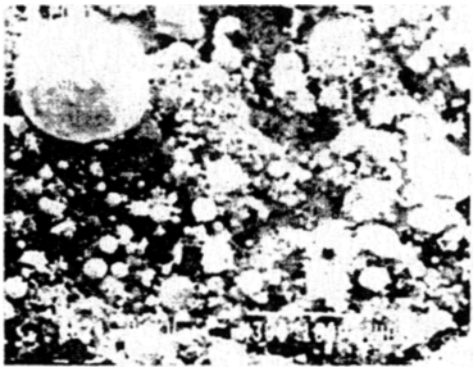
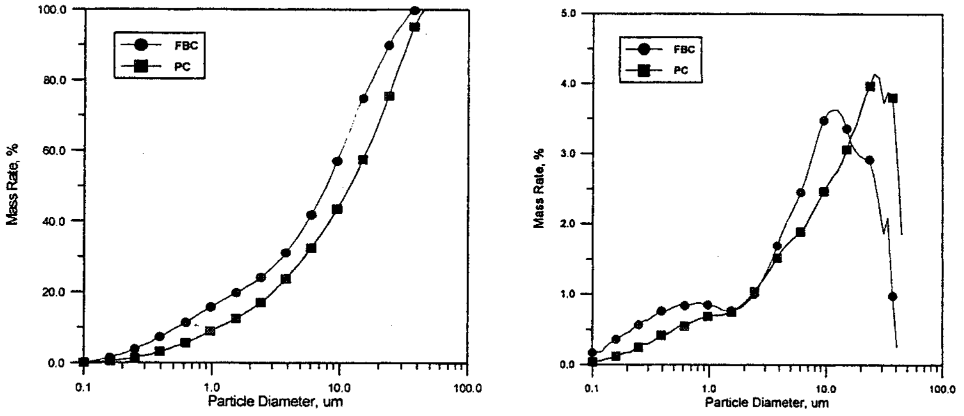


Fig. 3 Shape of fly-ash from pulverized coal combustion

4.1 Shapes of particles

The shapes of two fly-ashes were examined with a scanning electron microphotograph in Fig. 2 and Fig. 3. It can be seen that the fly-ash generated in the fluidized bed consisted of a mixture of large, irregularly-shaped, angular, ash particles. The pulverized coal fly-ash was quite different in that the particles were mostly either spherical or well-rounded and appeared to be larger than those generated in the fluidized bed, consistent with other study (Paulson et al., 1984).

Particles of appreciable size (above about 5μm in diameter) are usually relatively easy to reentrain, but their shapes are far from being spherical. Due to this geometry and their increased surface area, these particles may acquire charges more than those of equivalent-volume spheres, which probably increases the collection efficiency. As the primary particles have submicron size, severe agglomeration may occur and these agglomerates can have much larger



(a) Cumulative (b) Differential

(FBC: Fludized Bed Combustion, PC: Pulverized Bed Combustion)

Fig. 4 Size distribution of fly-ashes from two coal combustion

surface area than that of equivalent-volume spheres, and larger collection efficiencies than predicted from theories developed for spherical particles. Smith et al. (1961), White (1963), and Hignett (1967) stated that the effect of non-sphericity on the charge acquired by a particle is to produce an increase in the charge due to the larger specific surface area.

4.2 Size distributions of particles

The fly-ash from fluidized bed combustion is much finer than that from pulverized coal combustion. The mass mean diameter for the pulverized coal combustion fly-ash sample was about 16μm, whilst the fluidized bed fly-ash had the mass mean diameter of about 11μm. The particle size distribution of fly-ash is well described by log-normal distributions in Fig. 4. The effect of particle size on electrostatic precipitation is well documented (Gooch et al., 1974 ; White, 1977). According to the theory, particle size should be of great importance. Since fine particles are more difficult to be collected than coarse particles, the fluidized bed fly-ash should be more difficult to be collected than the fly-ash from the pulverized coal combustion.

Control of particulate emissions to the atmosphere is important in terms of human health. Electrostatic precipitator collects particles by means of an electrostatic forces so that fine particles are collected at high collection efficiency. As seen in Fig. 4, two coal fly-ashes have much finer particles (PM10) which have smaller diameter than 10μm. According to the early studies, particles larger than about 10μm in diameter were either trapped in the upper respiratory system or were not inhaled at all, and particles smaller than 1μm in diameter were not effectively retained in the lungs. For these reasons, particles in the size range of 1 to 10μm were initially thought to be of greatest importance in terms of human health. In each experiment, it can be shown that particles collected at the outlet of electrostatic precipitator have much smaller portion of that size range.

4.3 Chemical compositions and electrical resistivity

Collection efficiency is strongly affected by the electrical properties such as electrical resistivity and dielectric constants of particles, which will be determined by the chemical compositions of particle surface (Okazaki, 1984).

It is generally accepted that electrical resistivity of particle is the most significant factor in determining precipitation behavior, and much work has been carried out by many investigators to determine the relationship between collection efficiency and electrical resistivity of particle. If the electrical resistivity of particle exceeds a criti-

Table 1 Chemical analysis of fly-ash from two coal combustion

Elements \ Concentration, Wt. %	FBC	PC
SiO_2	63.08	45.21
Al_2O_3	4.90	19.46
Fe_2O_3	10.14	13.63
CaO	2.64	3.83
MgO	1.41	0.76
K_2O	0.63	0.84
Na_2O	0.79	0.67
TiO_2	3.03	10.44
P_2O_5	0.33	0.36
Moisture	0.05	0.06
Unburned carbon	13.00	4.74

FBC : Fluidized Bed Combustion, PC : Pulverized Coal Combustion

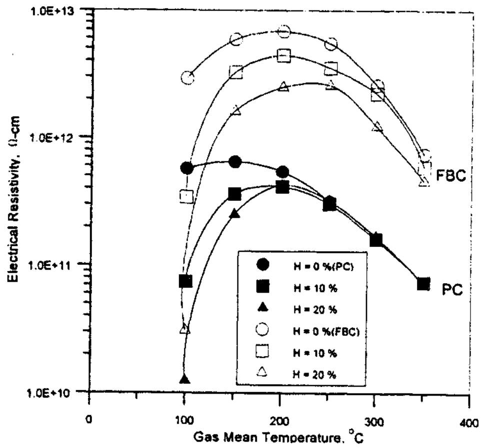


Fig. 5 Comparison of electrical resistivity of fly-ashes from two coal combustion(H=gas humidity)

cal value of about $10^{11}\Omega \cdot$ cm, corona currents will be limited by electric breakdown of the collected dust layers. Electrical resistivity depends primarily on the chemical composition of the ash, the ambient flue gas temperature, and the water vapor and SO_3 in the flue gas (White, 1977).

Development of practical methods for solving high electrical resistivity problems has been a major goal of electrostatic precipitation technology after the pioneering applications of the process. The beginning endeavors were necessarily empirical, but led to useful results including the discovery of conditioning by moisture and by SO_3 to increase the conductivity of the particles.

Control of particle electrical resistivity by moisture and chemical conditioning of the carrier gases plays an important role in electrostatic precipitation practice. Conditioning by steam injection, water sprays, or wetting of the raw materials used in the industrial process are a standard method, especially where the natural moisture content of the gases is low. Conditioning by humidification is always more effective at temperatures below about 150℃, as would be expected because of the greater adsorption of the water vapor on the particles at these temperatures (White, 1977).

Electrical resistivity of the fly-ash formed from two coal combustion systems are shown in Fig. 5. Two fly-ashes used in this study have high electrical resistivity in our experimental range, which break out back corona phenomena and decrease collection efficiency. Fly-ash particles generated from fluidized bed combustion have a larger electrical resistivity than that of fly-ash particles from pulverized coal combustion and electrical resistivity decrease with increasing gas humidity due to the improvement in ion mobility of gas and particle conductivity. Particle conductivity is increased by adsorption of moisture and chemical substances from the gas. The adsorption affects surface conductivity of particle and is greater at lower temperature.

Chemical compositions of the fly-ash formed from two coal combustion systems are shown in Table 1. If it is accepted that precipitator performance is related to electrical resistivity of the ashes and that resistivity is a function of ash composition, the performance should be directly related to ash chemistry. Electrical resistivity increased with increasing amounts of SiO_2, Al_2O_3, and CaO and MgO and decreased with increasing Na_2O and SO_2. It is known that electrical resistivity of fly-ash is influenced mainly by the quantity of alkaline metals contained in the ash particle, which is thought to contribute to both volume and surface conductivity, and by the SO_3 and CaO content together with gas humidity, which both contribute to surface conductivity

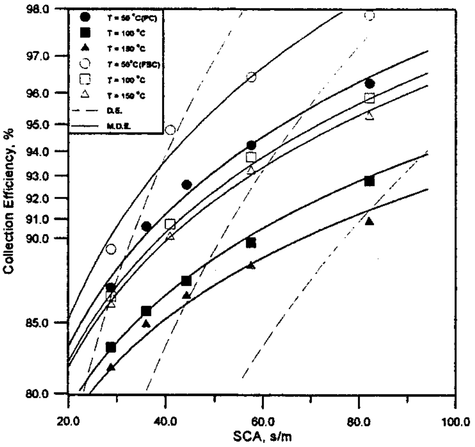


Fig. 6 Effects of variation in gas mean velocity and temperature on collection efficiency(D.E.: Deutsch Equation, M.D.E.: Modified Deutsch Equation)

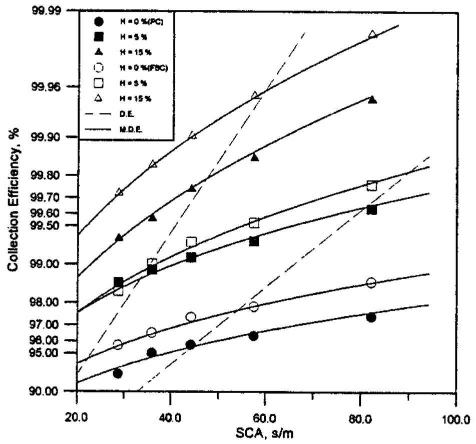


Fig. 7 Effects of gas humidity on collection efficiency(H=gas humidity)

(Bickelhaulpt, 1979). Bichkelhaupt (1979) found that alkali metals on the ash surface acted as charge carriers and the combined lithium and sodium correlated well with resistivity and that these effects improved if the secondary role of iron in releasing potassium to take part in the reaction, was taken into account. Resistivity also generally decreased with increasing Fe2O3. The rapid decrease in resistivity with a relatively small increase in unburned carbon agrees with data published by Sekhar (1977) for ashes derived from Canadian coals.

4.4 The effects of gas mean velocity and temperature on collection efficiency

Figure 6 shows the effects of gas mean velocity and temperature on collection efficiency. Such changes would result in an important change in the treatment time of fly-ash and gas flow rate in the precipitator and the specific collection area. Increase in gas mean velocity reduces specific collection area and increases reentrainment of fly-ash and particle is not enough to charge due to decreased treatment time in electrostatic precipitator. Therefore increase in gas mean velocity makes collection efficiency decrease. Figure. 6 also suggests that modified Deutsch equation (M.D.E.) is well correspondent with the experimental results, while Deutsch equation (D. E.) with ideal assumptions is not.

If gas temperature is below 150℃, the lower gas temperature yields the higher collection efficiency. It is because relative gas humidity increases with decreasing gas temperature and reduces electrical resistivity due to increasing conductivity of charge at the particle surface. But above 260℃, fly-ash particle becomes semi-conductive, which increase the volume conductivity of particle. Moreover, the higher gas temperature yields corona current increase due to the increased ion mobility, while operating voltage is substantially reduced owing to the lower densities of hot gases and the higher electrical resistivity of dust layer. If the dust layer resistivity is low, the voltage drop across it will be low and the voltage-current curve will be shifted as though the electrode spacing were decreased. High dust resistivity can result in large voltage drops and high electric fields within the dust layer. Very fine dust of high resistivity material can act as solid insulator to increase breakdown strength. Gas viscosity increases with temperature, thus reducing collection efficiency.

4.5 The effects of gas humidity on collection efficiency

The variation of measured gas humidity is from 0vol.%~15vol.%, being expressed as volume of water vapor over volume of gas. Figure 7 shows

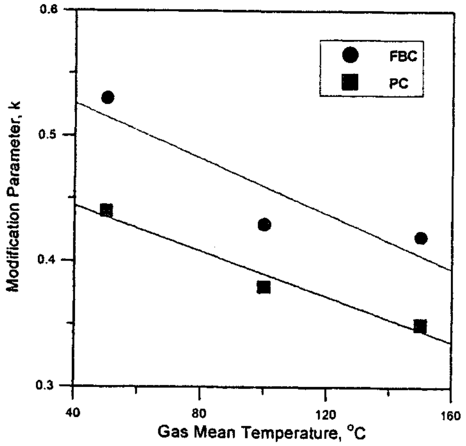


Fig. 8 Trends of modification parameters with variation of gas mean temperature

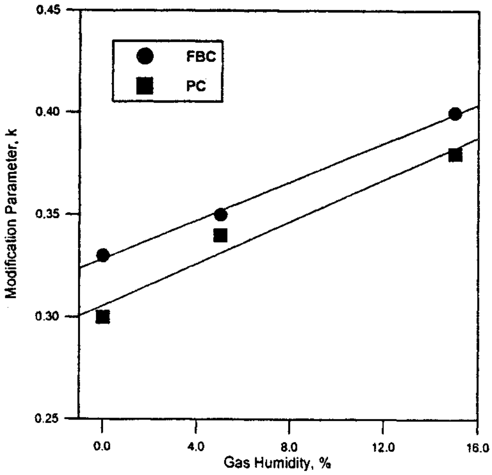


Fig. 9 Trends of modification parameters with variation of gas humidity

that electrical resistivity of fly-ashes decrease with increasing gas humidity, which increases the collection efficiency. Improvement of electrical conductivity between electrodes and reduction of reentrainment in collected dust layer increase collection efficiency with increasing gas humidity.

According to the Deutsch equation which considers only same particle size, ignoring physicochemical properties of particle and reentrainment etc., fly-ashes with larger particle size have higher collection efficiency. But contradictory result is obtained in this study. Although it has smaller size distribution, the fly-ashes from fluidized bed combustion have higher collection efficiency than those from pulverized coal combustion due to its irregular shape and physicochemical properties.

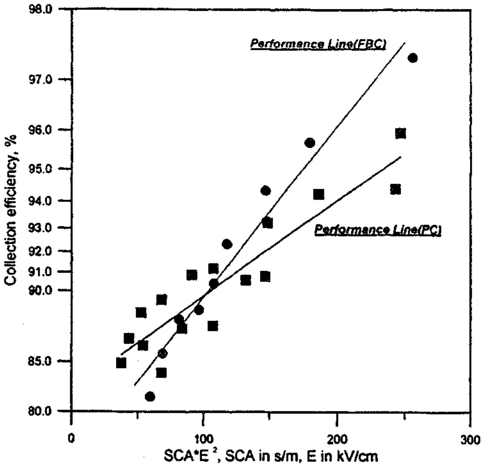


Fig. 10 Performance Line of fly-ashes from two coal combustion

4.6 The trends of power "k" in operational variables

Figure 8 shows that modification parameter, k, in modified Deutsch equation decrease with increasing gas mean temperature. Figure 9 also shows that modification parameters increase with gas humidity. Modification parameters have value range of 0.3~0.44 in pulverized coal combustion, and 0.3~0.53 in fluidized bed combustion. Variation of k means that more specific collection area is required to obtain the same collection efficiency under the condition of higher gas mean temperature and lower gas humidity. Therefore it is thought that modification parameters explain the effects of operational variables on collection efficiency, gas mean velocity and temperature, gas humidity etc., as well as the effects of particle size distribution suggested by Matts et al. (1963).

4.7 Performance line in extended Deutsch equation

The results of the precipitator efficiency measurements are plotted in Fig. 10 using the extended Deutsch equation developed by Potter (1978). To plot against, a straight line called the

Performance Line is drawn with experimental results by the least square method. In accord with Eq. (4), the slope of performance line is directly proportional to the mean size of the precipitated particles, and this makes the significant influence of particle size readily and quantitatively appreciated.

Therefore it is anticipated that performance line slope of fly-ashes from pulverized coal combustion is larger than that of fluidized bed combustion with smaller particle size. But contradictory results were shown in Fig. 10. It might be attributed to the irregular shape of the fluidized bed fly-ashes which could cause the collected dust layer to resist reentrainment. Furthermore, reentrainment, when it occurs, may be of agglomerates rather than individual particles (Paulson et al., 1984).

Reentrainment suggests that the practical precipitator does not succeed in catching a particle first time but normally needs more than one acts of collection before a selected particle is finally captured. However, the intensity of temporary re-entrainment will also be a function of particle shape. As it can be seen from the photomicrographs(Fig. 2.), the pulverized-coal ash particles were mainly spherical or particles were angular. After collection, the pulverized-coal ash particles will be mainly held together by interparticular forces and the outermost layer easily dislodged and re-entrained by either the rapping process, by other particles arriving or by the gas moving past the collected ash layer. The angular fluidized-bed ash particles, however, will interlock due to their shape to form a more cohesive layer and the force required to dislodge them will be consequently greater. Furthermore, due to their ability to interlock, those particles which are re-entrained may be reintroduced easily into the gas stream as agglomerates rather than individual particles and these agglomerates will be more easily recollected. The fluidized-bed flyash was collected at a much higher efficiency than the pulverized-coal flyash in an electrostatic precipitator operating under the same conditions.

5. Conclusions

(1) The appearance of the two ashes was very different. The fluidized bed combustion generated a large number of small, irregular and angular ash particles, whereas the pulverized coal fly-ash consisted of spherical or well rounded particles.

(2) Size analysis revealed that the mass mean diameter of the fluidized bed ash was about 11μm, whereas the ash from pulverized coal combustion had that of about 16μm.

(3) Fly-ashes from two coal combustion systems have high electrical resistivity in our experimental range, which break out back corona phenomena and decrease collection efficiency. Fly-ash particles generated from fluidized bed combustion have a larger electrical resistivity than those from pulverized coal combustion. The electrical resistivity decrease with increasing gas humidity due to improvement in ion mobility of gas and particle conductivity.

(4) Although those have smaller size distribution, the fly-ashes from fluidized bed combustion have higher collection efficiency than those from pulverized coal combustion due to its irregular shape and physicochemical properties.

(5) Modification parameter, k, in modified Deutsch equation decreased with increasing gas mean temperature as well as decreasing gas humidity. These mean that more specific collection area is required for the same collection efficiency in higher gas mean temperature and lower gas humidity. Modification parameter has value range of 0.3~0.44 in fluidized bed combustion, while 0.3~0.53 in pulverized coal combustion.

(6) Modification parameter explains the effects of operational variables on collection efficiency, gas mean velocity and temperature, gas humidity et al, as well as the effects of particle size distribution.

(7) Performance line slope of fly-ashes from fluidized bed combustion is larger than that of pulverized coal combustion although it has smaller particle size. This is contrary to expectations based on the extended Deutsch equation, which may be due to the irregular shape

of fly-ash from the fluidized bed combustion.

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