Electrostatic Precipitation

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ABSTRACT
Electrostatic precipitators have been used widely in industry, and play an important role in environmental protection. Electrostatic precipitator (ESP) can be operated with a high collection efficiency and a low pressure drop. Recently, ESP also has been used for cleaning indoor air. In this review, principles of electrostatic precipitation, such as particle charging, migration velocity of charged particles and collection efficiency, are described. Performance of ESP deteriorates by abnormal phenomena, including back corona for treating high resistivity dust, abnormal re-entrainment for low resistivity dust, and corona quenching for fine dusts. To cope with these phenomena, new technologies have been developed. Pulsed energization is a technique to cope with high resistivity dusts, and this results in lower power consumption. Using pulsed energization, non-thermal plasma can be generated and chemical reactions can be promoted for treating gaseous pollutants such as NO and volatile organic compounds. Wet ESP can also remove dusts and gaseous pollutants simultaneously. These new advancements will widen the field of application of electrostatic precipitation. Some novel applications of ESP, such as removal of dioxin from incinerators, are also included in this review.

1 INTRODUCTION

Electrostatic precipitation is a technique to remove suspended particles in a gas using an electrostatic force [1-3]. Electrostatic precipitator (ESP) has been used widely in various industries such as utility boilers, cement kilns, etc., and also has been applied in cleaning of indoor air in houses, offices, hospitals, and factories for food processing. ESP can be operated with a high collection efficiency and a low pressure drop. The collection efficiency is usually >99%. Submicrometer particles (diameter <1 μm) also can be collected effectively. The pressure drop is normally <1000 Pa. This is an important advantage of ESP, resulting in low operation cost.

2 PRINCIPLE

As shown in Figure 1, an ESP setup contains sharp discharge electrodes and smooth collecting electrodes. When HVDC is applied to the discharge electrode, a corona discharge takes place. Ions and electrons are produced at the corona point, and ionic current flows through the space. The ion polarity is either positive or negative. These ions attach to suspended solid particles. These charged particles are moved towards the collecting electrode by a Coulomb force, and are collected on that electrode. When the thickness of the layer of the collected solid particles reaches a predetermined level, the collecting electrode is rapped mechanically using a hammer, and the layer falls down into a hopper located below. These particles are then carried away to outside the ESP.

2.1 CORONA DISCHARGE

The voltage-current characteristics of a corona discharge [4-5] usually is expressed as

\[ I = AV(V - V_c) \]

where \( A \) is a constant, \( V_c \) the corona starting voltage, \( I \) the electric current and \( V \) the applied voltage. The flashover voltage of negative corona at an electrode separation \( d > 5 \times 10^{-2} \) m, is \( \sim 15d \) kV, with \( d \) in cm, and that of the positive corona is about half that of the negative corona [4]. Usually the negative polarity is used because of the higher
flashover voltages of negative corona, giving a larger margin of operating voltages. For indoor air cleaning, the positive polarity is used because of lower ozone generation.

2.2 PARTICLE CHARGING

Suspended particles are charged by attachment of ions produced by the corona discharge. Ions are transported by the electric field and/or by thermal diffusion. Particle charging due to the ions transported by electric field is called 'field charging'. For larger particles ($\gtrsim 2 \mu m$), field charging is dominant. For smaller particles ($\lesssim 0.2 \mu m$), thermal diffusion becomes dominant, and 'diffusion charging' becomes important[6-9].

In field charging, ions are transported to suspended particles along the field lines as shown in Figure 2. The field lines are repelled as the particle charge becomes high, and finally no electric field line reaches the particle. This condition causes charge saturation. The charge of a spherical particle is given by

$$q(t) = q_s \frac{t}{1 + t/\tau}$$  

where $q_s$ is the saturation charge (C), $t$ the charging time (s), $\tau$ the time constant of the field charging (s), $\varepsilon$ the permittivity of vacuum $8.85 \times 10^{-12} F/m$, $\sigma$ the specific permittivity, $d_p$ the particle diameter (m), $E$ the field strength (V/m) and $J$ the current density (A/m$^2$).

The saturation charge $q_s$ is proportional to the field strength. The time constant $\tau$ is inversely proportional to the ionic current density $J$. Therefore, in order to impart a higher charge, $E$ and $J$ should be high.

Fig. 2. Electrostatic field around a solid particle [1] (a) no charge, (b) with charge.

The particle charge by diffusion charging $q_d(t)$ is expressed as [1]

$$q_d(t) = q^* \ln(1 + t/\tau^*)$$  

where $q^*$ is a charge constant (C), $\tau^*$ the time constant of the diffusion charging (s), $k_B$ the Boltzmann constant $1.38 \times 10^{-23}$ J/K, $T$ the temperature (K), $e$ the electronic charge $1.6 \times 10^{-19}$ C, $c_1$ the thermal velocity of ion (m/s), $n_i$ the number density of ions in space (m$^{-3}$), $m_1$ the ion mass (kg) and $\mu_1$ is the ion mobility (V m/s$^2$).

In diffusion charging, the particle charge increases logarithmically, therefore the particle charge at $t = 500 \tau^*$, or $q_{500} = 6.2q^*$, can be regarded as the saturation charge. $q^*$ and $q_{500}$ are independent of $E$ and $J$, but proportional to the temperature $T$. The time constant of the diffusion charging, $\tau^*$ is in proportion to $J^{-1}$.

2.3 THEORETICAL MIGRATION VELOCITY OF CHARGED PARTICLES

The Coulomb force of a suspended charged particle in an electric field is

$$F = qE$$

where $F$ is the Coulomb force (N), $q$ the particle charge (C) and $E$ is the electric field (V/m). The viscous force on a moving particle is given by

$$F_v = \frac{3\pi \mu \omega_c d_p}{C_m}$$

The particles are moved towards the collecting electrode with a velocity $\omega_c$ [10]

$$\omega_c = \frac{qEC_m}{3\pi \mu d_p}$$

$$C_m = 1 + 2.54 \left( \frac{\lambda}{d_p} \right) + 0.8 \left( \frac{\lambda}{d_p} \right) \exp \left( -0.55 \frac{d_p}{\lambda} \right)$$

$$\lambda = 6.6 \times 10^{-8} \left( \frac{T}{293} \right) \left( \frac{101.3 \times 10^5}{P} \right)$$

where $\omega_c$ is the migration velocity (m/s), $\mu$ the viscosity (Pa s), $d_p$ the diameter of particle (m), $C_m$ the Cunningham correction factor, $\lambda$ the mean free path of gas molecules (m), $T$ the temperature (K), and $P$ the pressure (Pa). $\lambda = 0.07 \mu m$ for air at atmospheric pressure and room temperature (300 K). For particles $\lesssim 1 \mu m$, the correction factor $C_m$ is necessary to account for viscosity.
When field charging is applicable, the migration velocity is written as [1]

$$\omega_c = \frac{qE}{3\pi \varepsilon_0 \mu_p} = \frac{\varepsilon_0 s}{\mu (s + 2)} d_p E^2$$  \hspace{1cm} (13)

The migration velocity is proportional to the particle diameter $d_p$ and to the square of the field strength $E^2$. The migration velocity in the diffusion charging is [1]

$$\omega_c = 6.2 \left( \frac{2\pi \varepsilon_0 d_p kT}{3\pi \mu_p \varepsilon} \right) E C_m$$

$$= \frac{4\varepsilon_0 k}{\mu \varepsilon} TEC_m$$  \hspace{1cm} (14)

### 2.4 COLLECTION EFFICIENCY

The collection efficiency, $\eta$, of ESP is given by Deutsch [10]

$$\eta = 1 - \exp \left( -\omega_c f \right)$$

$$= 1 - \exp \left( -\omega_c A / Q \right)$$  \hspace{1cm} (15)

where $\omega_c$ is the migration velocity (m/s), $f = A/Q$ the specific collection area (s/m$^2$), $A$ the area of the collecting electrode (m$^2$) and $Q$ the gas flow rate (m$^3$/s).

Actually, the collection efficiency is affected by many factors, such as the geometry of the electrodes, the characteristics of dust particles, etc., and there are many reports to amend the theoretical collection efficiency [11–17]. One example is

$$\eta = 1 - \exp \left( -\omega_c A / v_o b \right)$$  \hspace{1cm} (16)

where $L$ is the length of the collecting electrode along the gas stream (m), $v_o$ the gas velocity (m/s), $b$ the separation between the discharge and the collecting electrode (m), and $K$ a correction factor determined from actual measurements.

$$t_o = \frac{L}{v_o}$$  \hspace{1cm} (17)

This detention time $t_o$ and the gas velocity $v_o$ are important factors for determining the ESP performance. Usually, $t_o$ and $v_o$ are designed to be $\sim 10$ s and 0.5 to 2 m/s, respectively.

![Figure 3. Fractional collection efficiency [41].](image)

Typical fractional collection ESP efficiencies are shown in Figure 3 [1]. For submicrometer particles with 0.1 to 1 µm diameter, the efficiency is smaller. Because the migration velocity is proportional to $C_m$, the collection efficiency of smaller particles $\lesssim 0.1$ µm becomes high. This is an important advantage of ESP which has been used for collection of fine particles such as acid mists. Larger particles are collected effectively, because the migration velocity is proportional to the diameter of the particle.

Concerning the effect of the voltage and the current on the collection efficiency, the following relationship is often found in many industrial ESP, with the value $n \approx 2$

$$\eta = V^n I$$  \hspace{1cm} (18)

Usually a higher collection performance can be obtained when ESP is operated with the maximum available voltage.

### 3 CONSTRUCTION OF ESP

#### 3.1 TYPES OF ESP

There are various types of industrial ESP according to their applications, and they are classified as Cylindrical type and plate type (shape of collecting electrodes); Vertical gas-flow and horizontal gas-flow (direction of gas-flow); One stage and two stage (electrodes geometry); and Dry and wet type (with and without using water).

![Figure 4. Typical construction of plate type electrostatic precipitator [41].](image)

Figure 4 shows a plate type ESP consisting of parallel plate electrodes for dust collection. The discharge electrodes are located between the plates. The gas flow is horizontal. This is a dry, one stage ESP. This type is used commonly in many industrial applications. As shown in Figure 5, one-stage ESP uses a corona discharge to charge and collect particles at the same time, while two-stage ESP uses corona discharge for particle charging and parallel plate electrodes for particle collection.

One-stage ESP is better to suppress re-entrainment of collected particles, while in two-stage ESP, the area of the collecting electrode can be increased by reducing the electrode spacing and the size of the ESP can be reduced. Two-stage electrodes can be applied for collecting mists and adhesive particles.

The wet type ESP uses water spray, or running water on the collecting electrode. A higher performance can be obtained because the re-entrainment of collected particles can be eliminated [18]. The back corona also can be suppressed. Gaseous pollutants can be absorbed at the same time. These wet type ESP can be used to achieve very low emission of particles from flue stacks.
As shown in Figure 4, ESP consist of discharge electrodes and collecting electrodes. Discharge electrodes are fixed in a frame. Sometimes discharge electrodes are pulled down using weights. Mechanical strength is required in order not to vibrate. Erosion of the electrodes should be avoided by selecting proper materials. There are many configurations of discharge electrodes as shown in Figure 6(a). The discharge electrodes are supported using insulator bushings. These bushings usually are placed in an air-purged, dust-free chamber to keep their surface clean.

Plate-type collecting electrodes are used commonly for larger ESP. As shown in Figure 6(b), the cross section of the collecting electrode is designed to give sufficient mechanical strength and to minimize the re-entrainment of particles. The separation between two successive collecting electrodes is usually 20 to 25 cm. For small scale ESP, cylindrical collecting electrodes are sometimes used.

Usually an ESP is divided into several sections. The electrical characteristics are different in the upstream and downstream of the gas flow. In upstream, the dust particle density is large, and the corona current is often suppressed by the space charge formed by charged small particles. In downstream, the particle density becomes low, and more corona current can be supplied. In order to operate an ESP with optimum conditions, it is therefore necessary to divide an ESP into several sections, and to control the applied voltage separately in each section.

Mechanical rapping is done continuously to the discharge electrodes, and with a constant interval on the collecting electrodes. The particles deposited on the discharge and collecting electrodes are moved into hoppers by the mechanical shocks.

To achieve better performance, by-passing air should be minimized. In the hopper, a plate is inserted for prevention of air bypass. Inside a hopper, convection of the hot gas usually is not enough and the temperature often decreases, resulting in sticking of dust particles by condensation of moisture. The hoppers should be insulated thermally to avoid sticking. Dust particles are transported using a screw conveyer to the outside of the ESP.

The electrical characteristics of an industrial ESP changes according to the operation condition, such as the density of dust particles, the layer thickness of dust deposit on electrodes, the apparent dust resistivity, the gas temperature and the pressure. Sparking takes place frequently, and sometimes an arc channel is established. A HV power source for ESP should be designed to cope with this variable load property. The applied voltage is controlled to achieve maximum collection efficiency. For instance, sparking is controlled at a constant rate by adjusting the voltage level. A protection against short circuit also should be provided to the ESP power source.

### 4 SELECTION OF ESP

#### 4.1 FEATURES OF ESP

ESP have the following features.

1. Fine particles can be collected effectively over a wide range of temperatures and pressures.
2. The power consumption is low because the pressure drop is small 1 to 2 kPa, and the current density is low (~ 0.5 mA/m²).
3. Maintenance is easy as the number of moving parts is small.
4. The collection efficiency is affected by the dust resistivity \( \rho_d \). When \( \rho_d < 10^{12} \, \Omega \, \text{m} \), abnormal dust re-entrainment takes place. When \( \rho_d > 5 \times 10^9 \, \Omega \, \text{m} \), back corona takes place. For these extremely low or high resistivity dusts, the collection performance decreases.
5. Rapping causes dust re-entrainment.
6. The collection efficiency of submicrometer particles is low.
7. Corona quenching takes place when dust particle density is high, because the space charge causes electric field reduction at the discharge electrode. Especially fine particles cause this phenomenon.
8. Rapping is sometimes not effective, especially for adhesive dust particles.
9. ESP cannot be used for explosive or flammable dust particles or mists.
10. Average gas flow velocity is 0.5 to 2 m/s, and gas treatment time is \( \sim 10 \, \text{s} \), so that the ESP size becomes large.
11. Initial cost is high, because ESP use HV equipment.

4.2 TYPE OF ESP

An appropriate ESP should be selected according to the gas and dust condition, and to fulfill the requirement of emission regulation. Using the Deutsch equation, the gas flow rate and the required efficiency the specific collecting area can be calculated.

4.2.1 DRY TYPE ESP

One-stage, plate type dry ESP are widely used in industry. When this type of ESP is used, the operating conditions should be adjusted so that the apparent dust resistivity is \( 10^2 \) to \( 10^6 \, \Omega \, \text{m} \). In two-stage ESP, the area of the collecting electrode can be increased and the size of the ESP can be reduced. Two-stage ESP can be applied when the dust concentration is relatively low, such as in indoor air cleaning. For adhesive dusts and mists, two stage ESP can also be applied. In order to collect submicrometer conductive particles effectively, two stage ESP can be used as the first stage to coagulate fine particles. The coagulated larger particles can be collected more effectively by the following ESP.

4.2.2 WET TYPE ESP

Wet type ESP can be used for dust with extremely low or high resistivity, or to fulfill a requirement of very low emission (i.e. \(< 1 \, \text{mg/m}^3 \) ). Wet type ESP also can remove soluble pollutants such as \( \text{SO}_2 \), \( \text{NO}_2 \), \( \text{HCl} \), and \( \text{NH}_3 \). Water is sprayed using spray nozzles in the horizontal or the vertical direction, and the dust collected on the water film of the collecting electrode is washed into the hopper. Instead of spraying, water can be supplied as a water film on the surface of the collecting electrode. In the wet-type ESP, re-entrainment of dust can be avoided and the collection efficiency for fine particles, including submicrometer particles, can be increased. A wet-type ESP can be used after a dry-type ESP to reduce particle emission.

5 ABNORMAL PHENOMENA AND ABATEMENT

5.1 EFFECT OF APPARENT DUST RESISTIVITY ON ESP PERFORMANCE

The collection performance of an ESP is affected by the apparent dust resistivity \( \rho_d \). The measurement of \( \rho_d \) is therefore important to estimate the performance of an ESP. The gas temperature, water content, and the gas composition such as \( \text{SO}_3 \), affect \( \rho_d \). Usually, the peak value of \( \rho_d \) appears at \( \sim 150 \) to \( 200 \, \text{C} \).

![Figure 7. Effect of apparent dust resistivity on collection efficiency](https://example.com/figure7.png)

As shown in Figure 7, \( \rho_d \) should be within \( 10^2 \) and \( 5 \times 10^6 \, \Omega \, \text{m} \) for good performance of a dry ESP [19]. An abnormal re-entrainment of dust takes place with \( \rho_d < 10^2 \, \Omega \, \text{m} \), and back corona leads to an improper performance of ESP with \( \rho_d > 5 \times 10^6 \, \Omega \, \text{m} \).

5.2 RE-ENTRAINMENT

Re-entrainment is the re-entry of collected dust into the inter-electrode spacing [20]. Dust particles are coagulated on a collecting electrode, and this re-entrained dust usually is easy to collect if they are charged appropriately. Some fine particles, however, also can re-entrain without coagulation. These fine particles are difficult to collect. In normal operation of an ESP, dust re-entrainment takes place with rapping, or carried over by increased gas velocity near the collecting electrode.

![Figure 8. Abnormal dust re-entrainment](https://example.com/figure8.png)

When the apparent dust resistivity becomes \( < 10^8 \, \Omega \, \text{m} \), and the adhesion of dust particles is poor, severe re-entrainment, or 'abnormal re-entrainment' takes place. The collection efficiency of the ESP becomes very poor. Figure 8 shows abnormal re-entrainment. Conductive particles lose their charge when they are collected, and are charged to opposite polarity due to induced charging. These particles are lifted into the space by the electric field, and then again are charged by the corona discharge. These particles jump on the collecting electrode, and the exhausted to the outside of the ESP.

(1) The re-entrainment can be eliminated by the following three methods. Injection of adhesive agents sometimes is used to minimize re-entrainment, especially to cope with abnormal re-entrainment of...
conductive dust particles. Ammonia, ammonium sulfate, or oil mists are used for this purpose.

(2) Wet ESP is very effective to eliminate re-entrainment. Recent regulations require very low dust emission of \(<10\) mg/m³. Particles with diameter \(<2.5\) μm also have been of concern, and these fine particles should be collected effectively. To meet these requirements, the use of wet type ESP is very effective. Wet ESP can be used as the final section of a series of ESP.

(3) Alternatively, rapping, or scraping or brushing of collecting electrodes, is effective to prevent re-entrainment [21].

5.3 BACK CORONA

When the apparent dust resistivity \(\rho_d \gtrsim 5 \times 10^8\) Ω m, back corona takes place [22-24]. Inside the dust layer on the collecting electrode, an electric field \(E_d\) is established due to the corona current

\[
E_d = \rho_d \times id \ll E_{db}
\]

where \(id\) is the corona current density \((A/m^2)\), and \(E_{db}\) the breakdown strength of the dust layer \((V/m)\). With increasing \(\rho_d\), \(E_d\) becomes high and an electric breakdown takes place when \(E_d\) reaches \(E_{db}\). From the breakdown point, ions of opposite polarity to the corona discharge are emitted, resulting in neutralization of the particle charge, and increase of corona current (Figure 9). When negative corona is used, the breakdown causes positive streamers propagating towards the discharge electrode and/or surface of the dust layer. This streamer propagation results in a reduction of the flashover voltage. In the range of \(\rho_d\) between \(5 \times 10^8\) and \(10^9\) Ω m, back corona causes excessive sparking. The number of the breakdown points is limited, and streamers propagate towards the discharge electrode. These streamers bridge the electrode spacing and turn to flashover, or excessive sparking. The operation of the ESP becomes unstable. With further increases in \(\rho_d\) between \(10^9\) and \(10^{10}\) Ω m, the number of breakdown points in the dust layer increases and finally the entire surface of the dust layer glows. This is called 'general glow mode'. A large number of ions of opposite polarity is emitted to the space. This causes an increase in the corona current. The propagation of streamer into space is diminished. This back corona neutralizes the particle charging, and the function of the ESP is severely deteriorated.

Various methods can be used to cope with high resistivity dusts.

Mechanical scraping or brushing also is effective to suppress the back corona. One example is shown in Figure 10 [25]. The collecting electrodes are moved, and the dust layer is removed by brushing. Compared with conventional rapping, this method is very effective in keeping the electrode surface clean.

The apparent dust resistivity \(\rho_d\) can be controlled by varying the temperature and the humidity. High-temperature ESP, operating above 300°C was used [26]. Recently low-temperature ESP, or colder ESP, has been developed. The operating temperature is selected below 130°C, where \(\rho_d\) becomes lower. Figure 11 is an example of the effect of temperature on the collection efficiency [27]. When the temperature was lowered, the performance of the ESP increased sharply due to the elimination of back corona [28]. At the same time, the re-entrainment became large, and proper care should be taken to suppress re-entrainment to achieve high performance.

Injection of SO₃ or NH₃ is sometimes used to reduce \(\rho_d\), and to improve the collection efficiency. In coal fired plants, sometimes high-sulfur coal is blended with low-sulfur coal, to adjust the dust resistivity.

Use of wet ESP also is very effective to cope with high resistivity dust. As described above, wet-type ESP can remove acids and other gaseous pollutants at the same time.

Intermittent energization is effective for abatement of back corona [19]. The applied voltage is turned off before the surface charge accumulates to trigger a breakdown of the dust layer. During the voltage-off period, the surface potential decreases. This method is effective not only to improve the collection efficiency of high resistivity dusts, but also to reduce energy consumption.

Pulse energization also is effective to reduce back corona [29-33].
Instead of dc, pulsed voltage is applied. The peak voltage of the pulse can be higher than the dc flashover voltage, and more uniform corona points can be obtained even with some irregularity of electrode spacing. The ions emitted from the discharge electrode spread due to space charge, and a more uniform corona current distribution can be obtained. For large scale ESP having large capacitance, durations of ms or ps can be used. Using semiconductor switching devices, efficient pulse power supplies can be realized. To apply a pulse voltage, the ESP capacitance should be charged, and then discharged rapidly. As shown in Figure 12, an LC oscillator circuit is used, and the energy stored in the ESP capacitance can be recovered effectively. As shown in Table 1, the collection efficiency was improved with a ps pulse energy that consumed less power. For small scale applications such as diesel exhaust control, as pulse energization has been investigated. Using very short pulses, intense electric fields can be established in the space, and nonthermal plasma can be formed. Using chemical reactions promoted by non-thermal plasma, simultaneous removal of dust particles and NOx and other gaseous pollutants can be obtained.

5.4 CORONA QUENCHING BY SPACE CHARGE

When the dust particles are very small and the density is high, space charge formed by charged particles reduces the field strength at the tip of the discharge electrode, resulting in quenching of the corona discharge. Sometimes the space charge enhances the field strength at the collecting electrode and causes flashover.

The use of pre-filter, pre-charger, or cascade connection in an ESP is necessary to increase the collection efficiency [34–35]. The 2-stage ESP is effective to coagulate fine particles, especially that of low resistivity particles. Coagulation reduces the corona quenching.

6 NOVEL APPLICATIONS OF ESP

6.1 SCRUBBER WITH POLARIZED WATER DROPLETS

Figure 13 shows a scrubber for sulfuric acid mist [36]. The operating temperature is reduced to 110°C to condense acid. Water is sprayed in front of the parallel plate electrodes. Water droplets enter into the parallel plate electrodes, and are polarized. Acid mists are also polarized, and the chance of collision between water droplets and acid mists increases. Table 2 shows the effect of the electric field to remove dust and HCl. With the voltage application, higher removal performance can be achieved.
6.2 WET TYPE ESP FOR SMALL SCALE INCINERATOR

Figure 14 shows a system of flue gas cleaning for a small scale incinerator of 200 kg/h using a wet type ESP [37]. The flue gas from the incinerator is introduced into an afterburner, in which the temperature of the flue gas is kept at 850°C for 2 s. This afterburner consists of ceramic foam and a propane burner. This afterburner is effective in decomposing dioxin. For example, 66 ng toxic equivalency quantity (TEQ) of dioxin at the output of the incinerator can be reduced to 0.22 ng TEQ (Table 3). The flue gas is introduced to a radiator, and the gas temperature is cooled down rapidly to 170°C. After cooling, the flue gas is introduced to a scrubber, in which water is sprayed. Then the flue gas is introduced into a wet type ESP. Figure 15 shows the wet type ESP. The diameter of the cylindrical electrode is 300 mm, and running water is supplied on the inner wall of the electrode. Negative dc voltage is applied to the discharge electrode. Water is circulated, and the collected dust particles are separated from the water by a filter. The used filter is burned at 1200°C using a separate small furnace.

Due to the limitation in the measurements of dioxin, the following results were obtained without using the afterburner, and supplying the flue gas with high dioxin concentration. A waste of 15 kg containing fragments of lumber, plastic and vinyl were burned for 15 min and a gas sample was taken during that time. The measurements were repeated four times and the data were averaged. Table 4 shows the concentration of dust, polychlorinated dibenzo-p-dioxins (PCDD) and poly-chlorinated dibenzofurans (PCDF), dust and HCl at the inlet and outlet of the exhaust gas treatment system. The collection efficiency of dust particles was >99%, and the HCl also was removed effectively. The concentration of dioxin and furan was converted to TEQ by the international toxic equivalency factor (TEF). The concentration of dioxin was reduced significantly from 160 to 13 ng/m³, and thus the removal efficiency was ~92%. The fractional removal efficiency for each dioxin including 2,3,7,8-tetrachlorinated dibenzo-p-dioxin (TCDD) was also >90%. The dioxin concentration at the output depended on the dioxin concentration at the input. In order to reduce the output dioxin, the input dioxin concentration should be reduced by the use of an afterburner.

For further reduction of dioxin emission, plasma chemical reactions, promoted by a pulsed voltage application are effective [25].

6.3 INDOOR AIR CLEANING

ESP can be used for indoor air cleaning. A 2-stage ESP has been used for this application because of the advantage of the increased collecting electrode area.

Figure 16(a) shows a combination of ESP and a fabric filter. Particles are precharged and thus polarized by the electric field, enter the dust outlet.
collection part consisting of the fabric filter. High performance can be achieved with a low pressure drop.

Another example is a combination of a pulsed discharge plasma with a catalyst. As shown in Figure 16(a), a plate to wire electrode is used, and a pulsed voltage superimposed on a dc voltage is applied (Figure 16(b)) [38]. The electrode is followed by a ground mesh coated with TiO₂ catalyst, known as a photo-catalyst. The particles are collected at the grounded electrode. The catalyst surface can be activated by ozone, and the gaseous pollutants adsorbed on the catalyst can be oxidized. Active charcoal or other catalysts also can be used for simultaneous removal of dust particles and gaseous pollutants. The exhaust of ozone should be minimized when an ESP is used for indoor air cleaning.

### 6.4 COLLECTION OF FINE PARTICLES

Particles having <2.5 μm diameter are of concern to human health. These small particles are generated by clustering or condensation from the gas phase, and attach heavy metals or absorb volatile organic compounds (VOC) on their surface. The number of these airborne particles is large, and the emission of such particles should be lowered. As described above, there are several methods to increase the partial collection efficiency of such particles [39–40]. These are summarized as

1. Use of two-stage ESP to increase the area of the collecting electrode, as the collection efficiency of fine particles follows the Deutsch equation.
2. Use of pre-agglomeration device as described above.
3. Reduce the dust re-entrainment by wet-type ESP.
4. Reduce the operating temperature to cause condensation of water. This increases the diameter of the particles, and reduces the dust re-entrainment by increasing adhesion.

### 7 CONCLUSIONS

The ESP plays an important role to maintain a clean environment and to achieve more healthy air quality. Wet ESP, or dry ESP coupled with a catalyst, can remove small particles and gaseous pollutants. Due to the increasing concern to human health, such novel, high-performance ESP will be used more commonly in the future.

### REFERENCES


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**Table 6. Dioxin removal by using wet type ESP [37].**

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**Figure 16.** (a) Setup of plasma reactor combined with TiO₂ photocatalyst [38]. (b) Waveform of pulse voltage.

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