The Applications and Interactions of Three Different Material Collection Plates in Wet Electrostatic Precipitator

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Abstract

Particle back-corona slows the efficiency of the dry-electrostatic precipitator (dry-ESP), especially during the removal of high resistivity particles. In this study, a new type of wet-electrostatic precipitator (wet-ESP) was designed and built using stainless steel (SS), conductive glass (CG), and original glass (OG) for its collection plates. The objectives of this research included the efficiency characteristics of both the dry-ESP and the wet-ESP, how the materials used in the dust collectors affect the ESP performance including SS, CG, and OG, and the effects on the electric resistivity of the particle of its performance, and the ozone generation rates of the wet-ESP. The experiment results indicated that the wet-ESP could improve the dust-cake phenomenon caused by high electrical resistivity particles that often occurred on dry-ESP in order to prolong its efficiency. Furthermore, the results indicated that during the most penetrating particle size (MPPS) penetration of SSESP and CGESP were both below 6% while OGESP was over 40% under the dry condition. When OGESP was placed and operated under the wet condition, its particle penetration dropped to below 20% under the MPPS. The results confirmed that compared to the dry-ESP, wet-ESP performed at a higher and better efficiency. In addition, as ozone concentration acts on the corona current under the same voltage, the result found that the ozone concentration of OGESP was lower than both CGESP and SSESP under the wet setting.

Keywords: Wet electrostatic precipitator, Particle penetration, Conductive glass, Electrical resistivity.
1 INTRODUCTION

In the modern world, power plants continue to burn more fossil fuels to provide sufficient electricity in order to satisfy the demands of ordinary people’s life and the growth of technology. However, heavy metals and other harmful pollutants were produced during the combustion process which can be deadly to humans (Varonos et al. 2002; Park et al., 2018). These exhaust gases are contained mostly of nanoparticle ($d_p < 100$ nm). Many industrial hygienic and epidemiological studies have stated that nanoparticles can cause inflammation to human lungs and cardiovascular diseases, and it can cause severe damage to the environment (Oberdorster et al., 2005; Kreyling et al. 2006; Grigoriu et al., 2012).

Currently, electrostatic precipitator (ESP) is widely used in pollution control devices. In those devices first, it employs corona discharge to charge particles, and it separates the ionized particles from the airflows using electrostatic force, the ionized particles are then trapped on the inner surface of the dust collectors (Zhao et al., 1996; Lin et al., 2012; Gao et al., 2019; Zen et al., 2019; Yang et al., 2020). Traditional dry ESPs are known to have poor collection efficiency after over-time build up deposition particles on the discharger wires and collection plates, that may cause the re-entrainment and back-corona (Paulson and Rea, 1997; Xu et al., 2021). Hung and Chen (2003) designed a small dry electrostatic precipitator to observe the interactions between particle loading and the filter. With cement particles for instance, their experiment found that the dust deposition on the collection plate increased over time which restrained corona from discharging, caused the
electrical current to slow, then resulted in a poorer particle collection efficiency. According to the
research by Mizuno, A. (2000), the dust resistivity larger than $5 \times 10^8 \, \Omega \cdot m$ would cause the back
corona. Besides, airflow causes particles to resuspend from the collection plate in dry-ESP. If those
particles are sticky or corrosive, they could damage the precipitator system and further affect the
performance of the device. Some wet-ESP experiments had been done in the past by injecting an
appropriate amount of water onto the surface of the dust collector to keep the particles from rising
in order to prolong the device’s life and performance (Altman et al. 2001; Saiyasitpanich et al.
2007; Bologa et al. 2009). Kim et al. (2011) used a two-stage wet-ESP by using a carbon brush pre-charger
with a negative high voltage power supply and collection electrodes with water film to improve the fine
particle collection efficiency of wet-ESP with low ozone emission. Besides, some literature focused on the
treatment of ultrafine particle or gas phase pollutions by the spraying droplet type ESP (Sadeghpour et al.,
2021; Liu et al., 2022).

The evenness of the water film on the collection plates was an essential process in a wet-ESP.
Take the stainless-steel plates as an example, the surface of the stainless-steel plates is hydrophobic;
therefore, it is difficult for the water to travel through them evenly. Uneven water flows often
resulted in poor cleaning and unnecessary water wasting. How to increase the hydrophobicity on
the surface of the collection plates was the key to improve the evenness of the water film and it
was believed it could save water as well. Generally, when the contact angle between the water
droplets and the surface is less than 80° it is hydrophilic; when it is greater than 80° it is hydrophobic. Lin et al. (2009) pointed out that when the surface of the collection plate was coated with TiO₂ nano-particles after sandblasting, the hydrophilicity of the surface increased. Their experiment tested three types of copper plates. Respectively, untreated copper plate, smooth copper plate, and the copper plate coated with TiO₂ after sandblasting treatment. It was found that the contact angles of the three types of copper plates with water droplets were at 117.17° ± 2.83°, 104.03° ± 1.73°, and 6.0° ± 4.2°, respectively. The copper plate coated with TiO₂ after sandblasting treatment greatly increased its surface hydrophilicity. Some researchers investigated the removal efficiency of wet-ESP by using different materials of collection electrodes such as terylene, polypropylene, and carbon fiber-reinforced polymer (Chang et al., 2011; Kim et al., 2012), however, there is no research investigated the influence of the conductive glass-based collection electrodes on the particle removal efficiency of ESP.

In this study, a wire-plated wet-ESP was set up using a stainless-steel wire and two stainless-steel plates. A direct current (DC) negative high voltage power supply (HVPS) was used to provide the energy that corona discharge needed to charge the particles, in order for the collection plates to gather the charged particles. After a period of time, an appropriate amount of water was injected and flown through the surface of the collection plates to remove the dust deposition, and the characteristics of the particle penetration were carefully observed. Due to the common corroded
issues that stainless-steel plates often encountered in both traditional dry-ESP and wet-ESP, different material collection plates were used in this study, such as conductive glass. Different material collection plates were installed in wet-ESP systems and their particle removal efficiencies were compared.

2 METHODS

This research set up a wet-ESP system test model with a DC negative HVPS device, a separated particle generator, and a measurement device. The experimental system was set up to further test the particle resistivity, particle loading, particle penetration, and ozone concentration under various operation factories as the layout is shown in Figure 1; and the operation parameters conditions are shown in Table 1. The descriptions of the models and materials are shown below.

2.1 Particle Generation

Long-term operation while collecting particles, in this study Poly (methyl methacrylate) (PMMA) powder was used to replace the common high-resistivity particles which often causes dry-ESPs to slow their particle collection efficiency. The electrical resistivity of PMMA was above $2 \times 10^{15} \, \Omega \cdot \text{cm}$ (Na & Rhee, 2006). PMMA was suspended in liquid and used a constant output atomizer (Model 3075, TSI Inc., St. Paul, MN, USA) to produce test particles in this study. The newly produced particles traveled through the drying chamber to remove their excessive moisture. The particle was passed the Am$^{241}$ neutralizer to help the particles reach Maxwell–Boltzmann distribution, and then checked the neutralization of PMMA particle before the test by using the
aerosol electrometer (3068A, TSI, USA).

2.2 Wet Electrostatic Precipitator System

The wet-ESP test model set-up in this study was divided into two sections, the corona discharge section and the particle collecting section. Among them, the evenness of the water film was crucial in cleaning the collection plate; thus, further descriptions were discussed below.

2.2.1 Corona Discharge System

The wet-ESP test model was set up using stainless-steel wire as its discharge electrode and was connected with the DC negative HVPS. Its corona discharge system was consisted of three stainless-steel wires and two collection plates. The two collection plates were created detachable to allow easier replacement process with different material plates, including stainless steel (SS), conductive glass (CG by using the fluorine-doped tin oxide glass, FTO glass), and original glass (OG), when needed in the later experiment. The detailed corona system is shown in Figure 2.

2.2.2 Collection Plate Cleaning System

A collection plate cleaning system was constructed using mainly of acrylic, with a water inlet on its top and a water outlet at its bottom. On top of the cleaning system, a self-made water storage tank was connected to it. The water storage tank was designed to control the proper amount of water going through the system as such. Inside of the main section of the system, two shorter acrylic plates were added at the neck of the chamber with a spacing of 2 mm in between them and the collection plates. They worked as baffles to keep the injected water from splashing, in order for the
water to flow into the wet-ESP evenly and clean the collection plates thoroughly. As the water flowed to the end of the chamber, two additional acrylic boards were added to prevent water from back splashing before it reached the waste water tank, and affect the accuracy of the collected particle measurements.

### 2.2.3 Water Film Uniformity of Collection Plate

Based on the findings of Lin et al. (2009), an untreated stainless-steel collection plate and a stainless-steel plate coated with TiO$_2$ were put under the test for comparisons in this study. The results showed that the angle between the water droplets and the untreated stainless-steel collection plate was larger than the TiO$_2$ coated stainless steel plate, as shown in Figure 3. The hydrophilicity of the surface was significantly increased on the later.

### 2.3 Particle Measurement

A scanning mobility particle sizer (SMPS, Model 3934, TSI Inc., St. Paul, MN, USA) was used to measure the size distribution and number concentration of the particle exhaust of ESP in this study. The measurement size range of the SMPS was between 0.028 μm to 0.661 μm. Each measurement was carried out at least three times under the same setting conditions, and an average was concluded based on the figures.

### 3 RESULTS AND DISCUSSIONS

A small wet-ESP was set up in this study to probe its efficiency characteristics. The results found in its efficiency characteristics included the relationship between the voltage and current (V-I Curve)
in the ESPs, the impacts of high-resistivity particles on the wet-ESPs, the effects of diverse collection plate materials on the efficiency of the wet-ESPs, the characteristics of long-term operating wet-Conductive Glass ESP (wet-CGESP), the characteristics of long-term operating wet-Original Glass ESP (wet-OGESP), and the ozone generation in the wet-ESPs. All six results were further discussed below.

3.1 V-I Curve of ESP

Figure 4 shows the V-I curve of dry-ESP and wet-ESP. It can be seen in Figure 4 that when the voltage was higher, the current amount increased. The starting voltage for dry-ESP was at -8.9 kV whereas it was at -7.5 kV for wet-ESP, which indicated that the wet-ESP could generate corona discharge at a lower voltage and was more energy saving. It is known that the conductivity of water is about $10^{-2}$ S/m whereas the conductivity of air is about $10^{-10}$ S·m$^{-1}$ as shown in Table 2 (Nouri et al., 2012; Kumar & Nagaraja, 2020). Therefore, water was able to create more powerful conductivity on the wet-ESP and indirectly accelerate the movement of ions. The experiment found that under the same voltage conditions, the wet-ESP could generate a higher current than the dry-ESP, and the results share a similar trend with the literature (Chakrabarti et al., 1995). Besides, the current of wet-OGESP under long-term operation had good stability as shown in Table 3.

3.2 The impacts of high-resistivity particles on the wet-ESPs
PMMA was applied to both wet-ESPs and dry-ESP to compare their total numbers of particle concentration changes, as shown in Figure 5. Besides, Figure 6 shows how ascending voltage interfered with the current of SS, OG, and CG under the wet-ESP setting. It is shown in the figure 5 that when the operating voltage was at -10 kV and the dry-ESP (water off) operating time reached 7,200 seconds, the total number of particles concentration count was about $8.3 \times 10^3$ #·cm$^{-3}$ (approximately 97.8% in efficiency, the average value was between 6,760 s and 9,630 s). High-resistivity particles continuously accumulated on the dust collection plates during the long-term filtration, forming dust cakes which performed as insulators and caused back corona phenomena to occur. Such phenomena then indirectly affected the particles collection efficiency, the result has a similar trend with the literature (Huang et al., 2003). When the operation time reached 9,640 seconds, water was turned on to simulate a wet-ESP. It was found that the total number of particles dropped to about 117.9 #·cm$^{-3}$ in average (from 9,640 s to the end). This result showed that water could effectively clear the attached particles on the collection plates and restored the efficiency of the device.

### 3.3 The effects of diverse collection plate materials on the efficiency of the wet-ESPs

From the previous chapter, it was found that the wet-ESPs could validly improve the dust cake phenomena that often occurred on dry-ESPs; however, wet-ESPs had encountered the following problems in application in this study. As the wet-ESP system was exposed to high humidity over a
long period of time due to the use of flowing water, the stainless-steel particle collection plates began to rust, as shown in Figure 7. Normally, stainless steel relies on chromium oxide film formed on the surface to prevent the oxidation of oxygen atoms and obtain corrosion resistance. It was suspected that when the collection plates came in contact with layers of particles that contained water over a long period of time, electrochemical corrosion might occur.

In choosing the material for the collection plates in this study, stainless steel stood out due to its low cost, corrosion resistance, and wear resistance among all metal materials available. Additional materials such as ceramics, conductive ceramics, or corrosion-resistant coatings were not considered for this experiment as they did not exceed higher requirements. Nevertheless, glass contains the characteristics of acid and alkali resistance, high-temperature resistance, abrasion resistance, and stable chemical properties, and it is easy to obtain. Therefore, in this experiment, two types of glass were used. Original glass (OG) and conductive glass (CG), which was original glass coated with transparent conductive oxide on one side, such as fluorine-doped tin oxide (FTO), were used to replace stainless steel for testing the particle collection efficiency of the wet-ESP.

Figure 8 (a) shows the particle penetration rate under the most penetrating particle size (MPPS) of stainless-steel (SS), original glass (OG), and conductive glass (CG) collection plates in the dry-ESP. The figures show that both SS and CG outperformed OG on particle collection efficiency. Their particle penetration rates were both under 6% while it was over 40% for OG, which
confirmed the fact that OG has weaker conductivity characteristics. As for the interactions between conductivity and electric current, when the electric field strength in the system is fixed, conductivity and current work correspondingly. When conductivity weakens, conductivity slows. As a result, there is not enough current to charge the particles in the system. The performance of the OG confirmed this theory.

Figure 7 (b) shows the particle penetration rate of SS, OG, and CG collection plates under the operation of the wet-ESP. The figures show that the OG’s particle penetration rate dropped from over 40% to below 20% in the wet-ESP setting. Due to the water flows in the wet-ESP, conductivity increased on the surface of the glass and indirectly accelerate the movement of free particles, thereby significantly enhance the ability of corona discharge and collection efficiency.

Based on the results found above, it was clear that both SS and CG collection plates demonstrated satisfying performance under the wet-ESP setting; yet the better ability to resist corrosion and rust from the CG collection plates surpassed the SS collection plates. In the following chapters, this study would focus the study on the CG collection plate, and observe the changes and characteristics of its performance on particle collection efficiency in a wet-ESP setting under long-term operations.

3.4 The characteristics of CGESP and OGESP on the long-term operation

As it is shown in Figure 9, using CG collection plates, when the operation voltage was at -10 kV and the operation time was between 7,200 seconds to 10,800 seconds for the dry-CGESP, the total
particle number concentration of the exhaust rose from $5.8 \times 10^3 \text{ #·cm}^{-3}$ (approximately 98.5% in efficiency) to $1.7 \times 10^4 \text{ #·cm}^{-3}$ (approximately 95.6% in efficiency), also known as dust cake phenomenon. Then wet-CGESP was switched on and water began to flow and clean the surface of the collection plates when the operation reached 10,800 seconds, the result was that the total number of particles was reduced to about $7.6 \times 10^3 \text{ #·cm}^{-3}$ (approximately 98.0% in efficiency).

As Figure 10 shows, using OG collection plates, when the operation voltage was at -10 kV and the operation time was between 1,800 seconds to 3,600 seconds for the dry-OGESP, the total particle number concentration of the exhaust rose from $1 \times 10^5 \text{ #·cm}^{-3}$ (approximately 74.4% in efficiency) to $1.5 \times 10^5 \text{ #·cm}^{-3}$ (approximately 61.5% in efficiency). When the wet setting was turned on and the operation time reached 3,600 seconds, the particle number concentration was reduced to about $8.2 \times 10^3 \text{ #·cm}^{-3}$ (approximately 97.9% in efficiency). In addition, as shown in Table 3, under the dry setting in the experiment above the corona current was 0 mA; whereas under the wet setting, the corona current was $\geq 0.027$ mA. When the operation time reached 10,800 seconds, the total particle number concentration had very little change.

To enclose the findings from above, regardless the materials used for the collection plates, all three types of collection plates including stainless-steel, conductive glass, and original glass experienced dust cake phenomena under long-term operations. The wet-ESP setting proved to enhance the problem by applying water films (flowing water) through the surface of the collection
plates and removing the over-loaded particles on the plates; thus, the collection efficiency was maintained within a customary standard.

Glass contains the characteristics of anti-corrosion, alkali prove, acid prove, high temperature resistant, abrasion resistant and good chemical stability, all of which allowed it to outperform the traditional stainless-steel collection plates. In addition, the cost of glass is lower than stainless steel, and the characteristics of glass mentioned above would allow fewer replacement of the collection plates under long-term operations compared to stainless-steel plates, which are highly cost-effective for small and medium size of wet-ESPs. Even so, the brittleness of glass was an inevitable task for building stronger collection plates. Further planning and reinforcement for the structure will be needed.

3.5 Ozone generation in the wet-ESPs

Figure 11 shows the relationship between how ascending voltage affected the ozone concentration of stainless-steel (SS), original glass (OG), and conductive glass (CG) collection plates in the wet-ESPs in the study. Whereas Figure 6 shows how ascending voltage interfered with the current of SS, OG, and CG under the wet-ESP setting. To give an instance, it is seen in Figure 11 that when the operation voltage was at -10 kV, the ozone concentration is 1521 ppb (SS), 1275 ppb (CG), and 222 ppb (OG). For comparison, while operating at the same voltage (-10 kV) in Figure 11, the current value was 0.028 mA (SS), 0.020 mA (CG), and 0.009 mA (OG) respectively.
In other words, based on the curves in Figure 11 and Figure 6, it concluded that when voltage increased both ozone and current rose; in addition, the stronger current produced more free electrons and therefore caused higher ozone. The original glass (OG) collection plate emitted the lowest ozone concentration due to its low conductivity among the three collection plates of SS, CG, and OG.

4 CONCLUSIONS AND SUGGESTIONS

Based on the above test results, this study has shown how the materials used in the dust collectors affect the ESP performance including SS, CG, and OG, and the effects on the high-electric resistivity of the particle of its performance, and the ozone generation rates of the wet-ESP. Several conclusions are drawn as follows:

A. Wet-ESPs could produce corona discharge at a lower voltage compared to traditional dry-ESPs. For the reason that both wet and dry ESP operated by accelerating the movement of ions under a certain electric field, flowing water in the wet-ESP cleared off the extra particles on the collection plates and further maintained the collection plates’ conductivity. Such result indicated that compared to dry-ESP, wet-ESP had the ability to perform more steadily under continuous operations.

B. Wet-ESPs could overcome the dust cake phenomenon that often occurred in dry-ESPs and furthermore improve the particle collection efficiency. With the moving water, wet-ESPs
were able to clean the layers of dust attached to the collection plates and solved the frequent problems such as back corona and lower collection efficiency that dry-ESPs had.

C. By replacing the stainless-steel collection plates in the wet-ESPs with glass collection plates, corrosion and rust of the plates under long-term operation were resolved. The replacement was both time and cost-saving due to the fewer renewal.

D. Both conductive glass collection plates and stainless-steel collection plates performed fairly well at particle collection in dry and wet ESPs.

E. Glass collection plates carried out poor performance in dry-ESP. The characteristic of high electric resistance from glass failed to create a stronger current under a fixed electric field. When particles could not be charged effectively, the collection efficiency slowed accordingly. The dilemma was fixed when the glass collection plates were operated in wet-ESP. Flowing water helped to increase the conductivity of the glass collection plates, indirectly accelerated the movement of free electrons, and expanded the current. As a result, glass collection plates showed a higher collection efficiency in wet-ESP.

F. In the study, all three material collection plates, including stainless steel, conductive glass, and original glass, encountered the dust cake phenomenon under long-term operations. Nevertheless, the situation was improved when the wet-ESP was up and running.

G. Under the same fixed electric field, original glass (OG) produced much less ozone than
stainless-steel and conductive glass collection plates in the wet-ESP setting, which demonstrated that wet-OGESP is a more Eco-friendly device than its counterparts in this study.

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aerosol in a wet electrostatic precipitator with single terylene or polypropylene collection electrodes. *Journal of Aerosol Science*, 42(8), 544-554.


Table Captions

Table 1 Operation parameters of wet electrostatic precipitator

Table 2 The conductivity of different materials comparison

Table 3 The changes of corona current under long-term operation of OGESP at -10 kV

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Table 1. Operation parameters of wet electrostatic precipitator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Operation condition</th>
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<td>Particle number concentration</td>
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Table 2. The conductivity of different materials comparison

<table>
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Table 3. The changes of corona current under long-term operation of OGESP at -10 kV

<table>
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Figure Captions

**Figure 1** Experimental system

**Figure 2** Collecting Electrode Cleaning System

**Figure 3** The contact properties of stainless-steel plate and water droplet as (a) without coating; (b) coated with TiO$_2$

**Figure 4** The V-I curve of dry-ESP and wet-ESP

**Figure 5** The changes of particle number concentration under long-term operation in the SSES

**Figure 6** The V-I curve of different collection plates in the wet-ESP

**Figure 7** The stainless-steel collection plates (a) before, and (b) after the rust

**Figure 8** The particle penetration and distribution of different collection plates in (a) dry ESP and (b) wet ESP

**Figure 9** The changes of particle number concentration under long-term operation in the CGESP.

**Figure 10** The changes of particle number concentration under long-term operation in the SSES

**Figure 11** The relationship between the voltage and ozone concentration of different collection plates in the wet-ESP
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ESP type: wet ESP
Discharge electrode: SS wire
Wire diameter: 0.3mm
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Figure 11 The relationship between the voltage and ozone concentration of different collection plates in the wet-ESP