Experimental study of membrane-based electrostatic precipitators with high filtration accuracy

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Abstract. Electrostatic precipitators (ESPs) with the membrane-based collecting electrode play an important role on the welding flue gas cleaning process. The research has been conducted on both bench and pilot scales with novel electrostatic precipitation using PTFE microporous membranes. Two types of membranes collector were used for testing—the charged and uncharged PTFE microporous membranes substrate. Tests were performed to measure the collection efficiency of the membranes. The result indicated that uncharged membrane is effective as charged membrane plates as a collection surface in a bench-scale ESP for the capture of PM2.5, but the charged membrane has a higher efficiency when particle size is lower than 0.3 μm, which is more suitable for collecting fine particulates. The preliminary data of the pilot-scale experimental also indicated that charged membranes exhibited excellent particulate capture efficiencies for welding flue gas, and the collection efficiency was reached 99.1%, which can achieve an ultra-low concentration emission of flue gas less than 1 mg/m³.

1. Introduction

Fine particulates, particles with aerodynamic diameters less than 2.5 μm, also known as PM2.5, are considered a significant problem. It has been estimated that 2.1 million people premature deaths in the worldwide scale every year may be attributed to respiratory distresses associated with the effects of fine particulate matter. The World Health Organization (WHO) estimated in 2005 that fine particulate air pollution (PM2.5), causes about 3% of mortality from cardiopulmonary disease, about 5% of mortality from cancer of the trachea, bronchus, and lung, and about 1% of mortality from acute respiratory infections in children under 5 years, worldwide. Therefore, controlling the discharge of fine particulates, especially PM2.5, is an important measure to improve air quality and protect public health and the environment.

Electrostatic precipitators (ESPs) are widely used to reduce the emissions of smoke, fumes and dust [1] because of the low pressure drop, low energy consumption, high collection efficiency and long service life. However, many current ESPs cannot be adequate to address the challenges of fine particulate collection [2]. Electrostatic precipitators exhibit reduced collection efficiencies for particles in the diameter range of 0.1-2.0 μm due to inherent charging mechanism limitations on particles in this size range [3]. Researchers at Ohio University developed and patented a novel membrane ESP that successfully addresses many of the problems associated with ESPs [4-6]. Membranes made from light, strong, and corrosion-resistant advanced materials were used to replace steel collecting plates. Such replacement facilitates tension-based rapping, which shears the adhered particles layer from the collector surface more effectively than hammer-based rapping.
Extensive research has been conducted at our works in the last three years to develop a new electrostatic precipitation in which heavy metal plates are replaced by light and thin membranes made from advanced, mainly fibre-based and other similar materials. Membrane applications could be beneficial to both dry and wet ESPs, and possess great potential for reducing the cost and increasing particle capture efficiency. Although applicable to numerous industries, these changes may allow the implementation of advanced technologies to reduce fine particulate, as well as acid aerosol emissions from coal-burning power plants, and thus help to meet the proposed WHO PM2.5 standard. It is expected that the knowledge and experience from this study could be used in the near future to develop hybrid and retrofitted ESPs. The research has been conducted on both bench and pilot scales with novel electrostatic precipitation using PTFE microporous membranes. In the following article, some recent results related to particle collection and removal efficiencies, selection of membrane materials and other relevant issues, as well as comparisons with existing ESP technologies are presented.

2. Experimental facility

2.1. Bench-scale Experimental
The bench-scale experimental ESP, schematically shown in Figure 1 and imaged in Figure 2, was used to examine the performance of different electrode structures and different collecting membrane in a controlled environment simulating conditions experienced in typical welding fume-dust. The experimental facility consisted of four different parts: an ash fluidizer, an inlet section, a test section, and an outlet. The ash fluidizer introduced dispersed fly ash into the test section of the precipitator by blowing compressed air underneath a fine screen supporting the fly ash.

For the experiments, two types of electrodes structures were used. One of the electrodes structure is a wire-plate electrode module and the other is a line-cylinder electrode module as shown in Figure 3 and Figure 4. Several charging electrodes were located in the main test section for each module. The charging electrodes were made of 1/4-in. copper tubes with protruding nails to enhance corona current. The grounding terminals for the pre-charging electrodes were located at the precipitator wall across from the pre-charging electrodes.

Two types of membranes were used for testing - the charged and uncharged PTFE microporous membranes collecting plate. Test for particles collection efficiency was conducted. A controlled feeding system was used to introduce a known particle concentration into the test section. Particulates removed in the precipitator test section and the initial loading mass were used to determine the actual collection efficiency, which was then compared the collection efficiency of those two different membranes observed in the experiments.

![Figure 1. Diagram of the electrostatic precipitator test section](image-url)
2.2. Pilot-scale Experimental

A pilot test section was built at a welding workshop of Guangzhou zhengjian packaging materials technology co. LTD (Guangdong Province, China) to demonstrate the membrane-based precipitator technology developed at our work. A 0.60×0.6×1.5m precipitator box with two 1.2×0.59m charged PTFE membranes, was constructed as schematically shown in Figure 5 and imaged in Figure 6.

2.3. Analysis and measurement
Particle size distribution at the inlet and outlet to the precipitator test section was determined from isokinetic sampling of the particulate suspension and analyzing the sample using the following equipment: TSI DustTrak (8532), Laser airborne particle counter (Y09-6), Malvern Mastersizer 3000, Atomic absorption spectrometer (HITACHI Z-5000), and Scanning electron microscope (SEM, Zeiss LEO1530VP).

The collection efficiency of PM2.5 is calculated as the following equation:

$$\eta = \frac{M_0 - M_1}{M_0}$$

Where $M_0$ is the ash mass concentration at the 0 kV (mg/m$^3$) and $M_1$ is the escaping ash mass concentration at the 25 kV (mg/m$^3$)

### 3. Results

#### 3.1. Bench scale collection experiments

A series of collection efficiency and particle analysis tests were performed in the previously described precipitator unit using both uncharged and charged membrane collection plate. Membranes behaviour was examined under various conditions at gas flow velocities ranging between 1-3 m/min, voltage of 25kV and current flow of about 0.4-1.8mA. The collection efficiency results using uncharged and charged membranes are shown in Table 1. These data indicate that charged membrane is a better collector than uncharged membrane, especially when particle size is lower than 0.3 μm, and the collection efficiency of the uncharged membrane is 39.46%, and the charged membrane is 82.24%. And for both uncharged and charged membrane, the collection efficiency for PM2.5 is 92.43% and 93.78%, respectively. This is proved that membrane collection plates can promote condensation and more efficient capture of fine particulates. Charged membrane can achieve corona power levels that are several times higher than uncharged membrane, which greatly enhances charging and collection of submicron-sized particulates.

| Test parameter                        | Particle size | Collection efficiency |
|---------------------------------------|---------------|-----------------------|
|                                       | 0.3μm         | 0.5μm                 | 1.0μm | PM2.5 |
| Uncharged membrane collection plate   | 39.46%        | 50.64%                | 86.41%| 92.43%|
| Charged membrane collection plate     | 82.24%        | 86.41%                | 95.70%| 93.78%|
| Collection efficiency increased by charged membrane | 42.78%  | 35.77% | 9.29% | 1.35% |

The data in Table 2 shows the relationship between the collection efficiency, wind resistance, and filtration velocity and operation time. For a long time running experimental, the collection efficiency of the charged membrane based ESP is relatively stable, but the wind resistance increase and filtration velocity decrease with the operation time. The results of the experiment show that when the membrane is running continuously for 6-7 hours, the wind resistance and filtration velocity reach their ultimate value. At this time, the collection efficiency is also reduced. This is suggested that the membrane need to clean or replace.

#### 3.2. Pilot-tests results

Basic testing was performed to examine the collection efficiency of the charged membrane substrate in the pilot-scale electrostatic precipitator. Here, a China Industry Standard (HJ 836-2017 Stationary source emission—Determination of mass concentration of particulate matter at low concentration—Manual gravimetric method) was used to determine the particle collection efficiency. Long-time concentration detection of welding fume and Mn oxides were conducted at the inlet and outlet of the ESP facility, the data are shown in Table 3. The results showed that approximately 99.1% of the
particles were removed from the welding fume gas stream. And for Mn and its compounds (Calculate by MnO₂), the removal efficiency is about 98.6%. The results show a highly unexpected and encouraging collection efficiency, which can be reasonably explained by particle agglomeration. The data show that the charged membrane based ESP is high efficient way to treat and purify heavy metals in flue gas, which can achieve an ultra-low concentration emission of flue gas less than 1 mg/m³. Based on our experimental, the charged membrane based ESPs are especially suitable for collection of fine particulates.

Table 2. The relationship between the collection efficiency, wind resistance, and filtration velocity with operation time

| Time (h) | 0.3μm | 0.5μm | 1.0μm | PM2.5 | Wind resistance (Pa) | Filtration velocity (m/min) |
|---------|-------|-------|-------|-------|----------------------|---------------------------|
| 0       | 80.38%| 80.30%| 98.66%| 96.68%| 200                  | 3.35                      |
| 1       | 80.87%| 89.13%| 99.36%| 96.60%| 220                  | 3.17                      |
| 2       | 81.24%| 90.08%| 99.64%| 94.26%| 240                  | 3.25                      |
| 3       | 75.29%| 85.68%| 99.32%| 96.50%| 240                  | 3.00                      |
| 4       | 77.64%| 87.01%| 99.60%| 94.62%| 350                  | 2.23                      |
| 5       | 77.14%| 80.88%| 99.17%| 94.69%| 400                  | 2.03                      |
| 6       | 59.79%| 62.75%| 90.70%| 94.82%| 660                  | 1.12                      |
| 7       | 53.94%| 51.53%| 89.26%| 94.12%| 700                  | 0.55                      |
| Average efficiency | 73.29% | 78.42% | 96.96% | 95.29% | /                   | /                         |

Table 3. Collection efficiency of the pilot-scale ESP with charged membrane collector

| Sample Locations | number of samples | Rapping test results (mg/m³) | welding fume (The total dust) | Mn and its compounds (Calculate by MnO₂) |
|------------------|-------------------|-------------------------------|------------------------------|------------------------------------------|
| Tubing entry points | F1, A3-1 | 63.75 | 1.43 |
| Tubing outlet points | F1-2, A3-2 | 0.58 | 0.02 |
| collection efficiency | 99.1% | 98.6% |

Particle samples were collected by air sample membrane at both inlet and outlet point of the flue pipe, the collecting time was 30 seconds. The collected samples and their surface morphology and characteristic were observed by scanning electron microscopy (SEM), as shown in Figure 7. Figure 7(a) shows the samples collected at the entrance of the flue pipe, from the SEM picture, we can see that welding fume particles are uniform distributed on the surface of the sample membrane. The fine particles deposited on the membrane surface are mostly spherical, and the single particle size was mostly below 2.5μm (PM2.5). After deposition, the particles are agglomerated together, and have a certain adsorption effect on other particles due to their larger specific surface area. Figure 7(b) shows the samples collected at the outlet of the flue pipe, and the sample surface is almost clean, which indicated that the membrane-based ESP have a high collection efficiency for fine particulates. This result is consistent with the previous description.
Figure 7. Sample membrane and its surface under the scanning electron microscopy (SEM). (a) Samples collected at the entrance for 30 seconds; (b) Samples collected at the outlet for 30 seconds

4. Conclusion
The research conducted has indicated some key possibility for the use of light and smooth PTFE porous membrane as replacements collector for ESPs facility. PTFE porous membrane materials possess superior properties, such as low price, mechanical strength and resistance to temperature, combustion and corrosion. Membrane based ESP facility also showed excellent collection efficiency and separation properties that are extremely important in ESP applications, and in turn could resolve many of the PM2.5 regulation requirements for China ambient air quality standards (GB3095-2012). A comparison of bench-scale experimental was taken for both uncharged and charged membrane collection plates. The result indicated that uncharged membrane is effective as charged membrane plates as a collection surface in a bench-scale ESP for the capture of PM2.5, but the charged membrane has a higher efficiency when particle size is lower than 0.3 μm, which is more suitable for collecting fine particulates. The preliminary data of the pilot-scale experimental also indicated that charged membranes exhibited excellent particulate capture efficiencies for welding flue gas, and the collection efficiency was reached approximately 99.1%. As a collection plate, membrane cleaning and membrane regeneration were not quantified during this work and should be the subject of future work. In addition, alternative rapping techniques, specifically ones that do not induce side forces (shaking), must be explored in future work to further minimize re-entrainment.

5. References
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