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Enhanced white plume removal using a novel electrostatic precipitator with hydrophilic collection plates

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Abstract

This study investigates the performance of a novel electrostatic precipitator (ESP) integrated with hydrophilic collection plates and a trumpet-shaped duct for effective white plume mitigation. The ESP was evaluated at airflow velocities of 5 and 8 m s^{-1} using various collection plate configurations, including untreated aluminum, sandblasted aluminum, and membrane-coated plates. At 5 m s^{-1}, all configurations demonstrated a stable white plume reduction efficiency exceeding 95% with minimal spark occurrences. However, at 8 m s^{-1}, the untreated aluminum plate exhibited a high average spark frequency of 80 per minute, compromising the measurement reliability. Hydrophilic treatments significantly improved the performance; sandblasted aluminum plates achieved a reduction efficiency exceeding 80%, albeit with some instability. The membrane-coated plate showed superior performance, with a stable reduction efficiency of 90% and an average spark frequency of just 3.1 per minute. The trumpet-shaped duct effectively minimized droplet-induced sparks by facilitating liquid drainage, further enhancing stability. These findings highlight the importance of surface modifications and structural enhancements in optimizing ESP performance under high-velocity conditions.

Keywords: White plume, electrostatic precipitator (ESP), hydrophilic surface, trumpet-shaped duct, particle removal efficiency.

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1. Introduction

White plumes are observed when exhaust gases from steel mills or waste incineration facilities combine with water vapor and fine particles in the atmosphere, primarily in low-temperature environments. These plumes are commonly observed around industrial sites or power plant chimneys, where the water vapor in exhaust gases condenses into fine droplets or ice crystals upon contact with cooler external air, resulting in a white appearance. In addition to water vapor, white plumes can contain pollutants such as fine particles, sulfur oxides (SO_x), and nitrogen oxides (NO_x), which pose environmental and health risks [1, 2]. Particularly in winter, under low-temperature and high-humidity conditions, the formation of white plumes becomes more pronounced [3], often leading to complaints from local communities owing to their visual impact. The fine particles and pollutants contained in the white plumes can adversely affect respiratory health, necessitating the development of effective mitigation technologies. Various methods have been explored to reduce white plumes, and electrostatic precipitators (ESPs) are widely used for the effective removal of fine particles [4]. Wet electrostatic precipitators (WESPs) are particularly promising for environments in which water vapor and fine particles coexist, because they utilize water to wash away the collected particles from the collection plates [5]. ESPs operate by imparting a negative charge to the particles in exhaust gases, which are then attracted to positively charged collection plates. However, although dry ESPs can achieve over 90% fine particle removal under high-velocity conditions, their efficiency significantly decreases in humid environments. To address this limitation, we developed a WESP to replace the mechanical mist eliminators in power plants [6]. The performance of the WESP was evaluated at a gas velocity of 5 m s^{-1}, demonstrating effective removal of fine particles, although the efficiency decreased under high-humidity conditions. This decline was attributed to the formation of water droplets on the collection plates, which caused sparking owing to the non-uniform electric field between the electrodes and plates. Such sparking reduces the collection efficiency. To suppress water droplet formation, it is crucial to reduce the contact angle on the collection plate surface. A lower contact angle indicates a more hydrophilic surface, which reduces droplet formation and enhances collection efficiency. This study proposes a surface treatment as a method to minimize water droplet formation and improve collection efficiency. By comparatively analyzing the removal efficiency of the treated surfaces, we aim to address existing challenges and provide a foundation for the development of more effective white-plume mitigation technologies.

2.1 Particle Collection Mechanism in Electrostatic Precipitator

The Electrostatic precipitators (ESPs) are widely used for removing fine particles and mist from industrial exhaust gases. The particle collection mechanism in ESPs relies on the electrostatic attraction between charged particles and the oppositely charged collection plates. When a high voltage is applied to the discharge electrode, a corona discharge occurs, generating ions that charge the airborne particles. These charged particles then migrate toward the collection plates due to electrostatic forces. The efficiency of this collection process is influenced by several factors, including the strength of the applied electric field, gas flow velocity, and surface properties of the collection plates. One of the key challenges in ESP performance, particularly in humid environments, is the formation of water droplets on the collection plates, which can lead to electrical instability and spark generation. The accumulation of liquid on the collection surface can disrupt the uniform electric field, reducing collection efficiency. To address this issue, surface modifications such as hydrophilic treatments have been applied to improve water drainage and minimize droplet formation. In this study, we investigate how hydrophilic collection plates enhance ESP performance by reducing droplet-induced electrical discharge and improving collection efficiency. By comparing different surface treatments, including untreated aluminum, sandblasted aluminum, and membrane-coated plates, we aim to optimize the ESP design for stable and effective white plume mitigation.

2.2 Experimental setup overview

The electrostatic precipitator (ESP) used in this study employed a single-stage electrostatic precipitation method. Fig.1 is a photo of an actual ESP, and the overall size of the experimental set-up is 80 cm × 32 cm × 205 cm (width × length × height). It consists of a charging electrode (diameter: 40 mm, length: 380 mm) and collecting plates with a rectangular channel structure (70 mm × 430 mm × 4 units). The term “4 units” referred to the four collecting surfaces inside the rectangular duct, each having dimensions of 70 mm × 430 mm. Specifically, collecting plates were installed on all four inner walls of the ESP, forming a rectangular channel with a collecting surface on each side. A white plume was supplied from bottom to top of the ESP. The collecting plates were an aluminum plate, an aluminum plate treated with sandblasting to enhance hydrophilicity, and a hydrophilic membrane-collecting electrode. The airflow velocity through the ESP ranged from 5 to 8 m s^{-1} with a flow rate of 90 to 140 m^3 h^{-1}. A trumpet-shaped duct was installed to prevent droplet or water film growth at the bottom of the collection section by allowing the liquid to flow downward along the duct due to gravity. This study also compared the results with and without the duct. The white plume used in the study was generated using an ultrasonic humidifier (power consumption: 350 W) installed in a 57.6 L water tank. The concentration of the white plume was measured every 6 s using an Optical Particle Counter (OPC, GRIMM, 11-D), and the reduction efficiency of the white plume was evaluated based on the Total Suspended Particles (TSP) concentration. The ESP was operated at an applied voltage of −11 kV, with the corresponding current measured as −0.93 mA. To visually observe the reduction of the white plume, a transparent acrylic duct was installed above the ESP and insulator chamber. The ultrasonic humidifier used in this study was manufactured by Weirui'er in China, with the model number JWD481007-001S. The high voltage power supply (H.V. PS) was supplied by PS solutek, a company based in the Republic of Korea, and its model number is PSDC-EPC 25kW. Additionally, the hydrophilic membrane utilized in the experiment was produced by SAEMYONGHITE Co. Ltd., also located in the Republic of Korea. These components were selected for their performance and compatibility with the experimental setup. Fig. 2 presents the different types of dust collection plates used in this study: (a) untreated aluminum plate, (b) sandblasted aluminum plate, and (c) membrane plate. The untreated aluminum plate serves as a baseline for comparison, representing a standard collection surface without modifications. The sandblasted aluminum plate has increased surface roughness due to microstructural modifications introduced through sandblasting, which enhances hydrophilicity by reducing the contact angle. The sandblasted aluminum plate exhibits increased surface roughness as a result of microstructural modifications introduced by the sandblasting process. During sandblasting, high-velocity abrasive particles impact the surface, creating microscale asperities and irregularities. These surface features increase the effective surface area and alter the surface energy distribution. when a hydrophilic material such as aluminum undergoes an increase in surface roughness, the wettability of the surface is enhanced. This is observed as a decrease in the water contact angle, indicating improved spreading of water droplets on the surface. Therefore, the sandblasting treatment promotes hydrophilicity by enabling more intimate contact between the liquid and the roughened surface texture. Lastly, the membrane-coated plate features a hydrophilic surface treatment designed to further improve liquid drainage and minimize droplet accumulation. These variations allow for a comparative analysis of how surface modifications influence white plume removal efficiency and ESP performance.

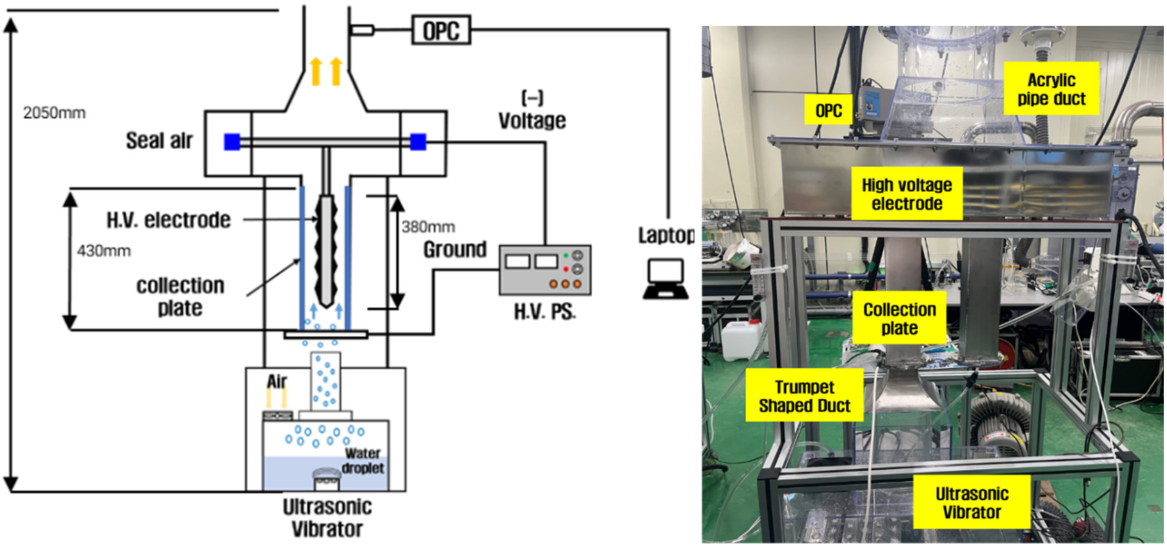

Fig. 1. Configuration of the lab-scale electrostatic precipitator module and the actual equipment setup.

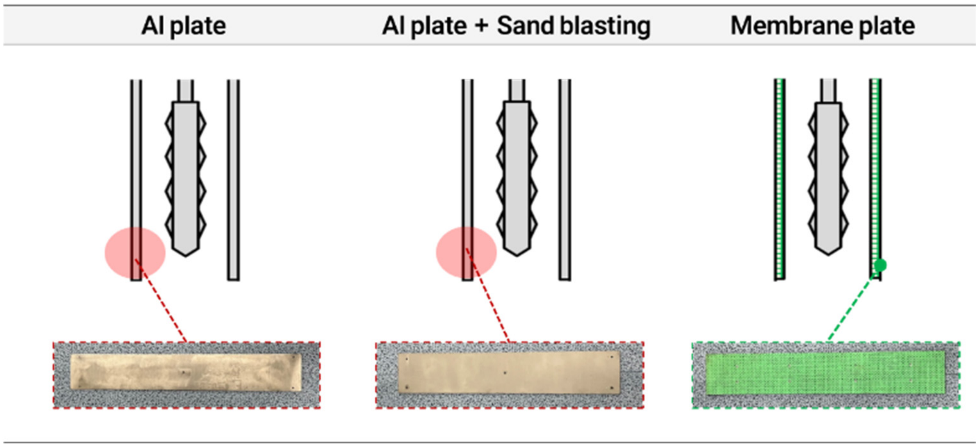

Fig. 2. Types of dust collection plates. (aluminum plate, aluminum plate with sandblasting, and membrane)

3. Results and discussion

3.1 The effect of voltage-current (VI)

The VI curve of the system was obtained in the range of 0 to −16 kV, as shown in Figure 3. As the applied voltage increased, the current remained nearly zero until approximately −8 kV, after which a sharp increase in current was observed, indicating the onset of corona discharge. For this study, the operating condition was set at −11 kV with a corresponding current of approximately 0.93 mA, which lies in the stable corona region.

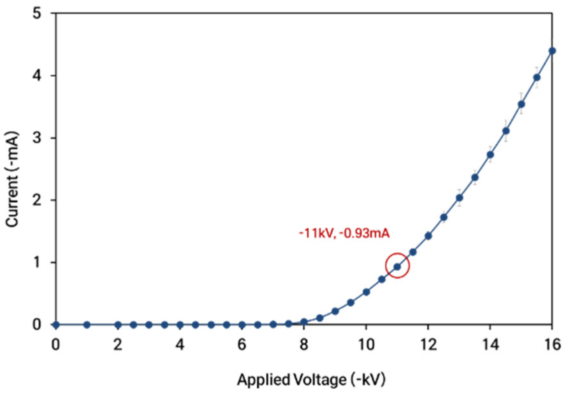

Fig. 3. Voltage-current (VI) characteristics of the electrostatic precipitator system

3.2 The effect of velocity

Fig. 4 shows the performance evaluation of the electrostatic precipitator (ESP) system at an airflow speed of 5 m s^{-1} , demonstrating a white plume removal efficiency of over 95% across all tested cases, including the untreated aluminum plates, sandblasted aluminum plates, and hydrophilic membrane-coated plates. In each case, the efficiency remained stable for 20 min, with the occurrence of sparks recorded at less than two instances per minute or none at all. These results highlight the stability of ESP systems at low airflow speeds. The system not only maintained consistent performance under these conditions but also effectively suppressed disruptions caused by water droplets, ensuring reliable white plume removal. This stability can be attributed to the surface modifications that facilitate smoother liquid drainage and minimize the accumulation of water droplets, thereby enhancing the overall performance and efficiency of the system.

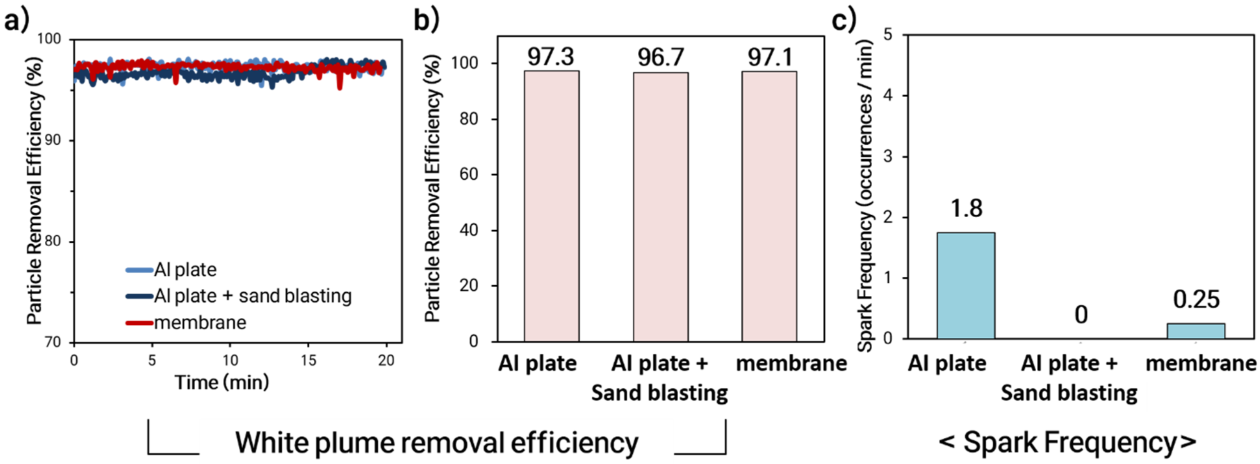

Fig. 4. (a) White plume removal efficiency of different collection plates operated for 20 minutes at 5 m s^{-1}. (b) Average white plume removal efficiency at different collection plates at 5 m s^{-1}. (c) Average occurrences of sparks per minute at 5 m s^{-1}.

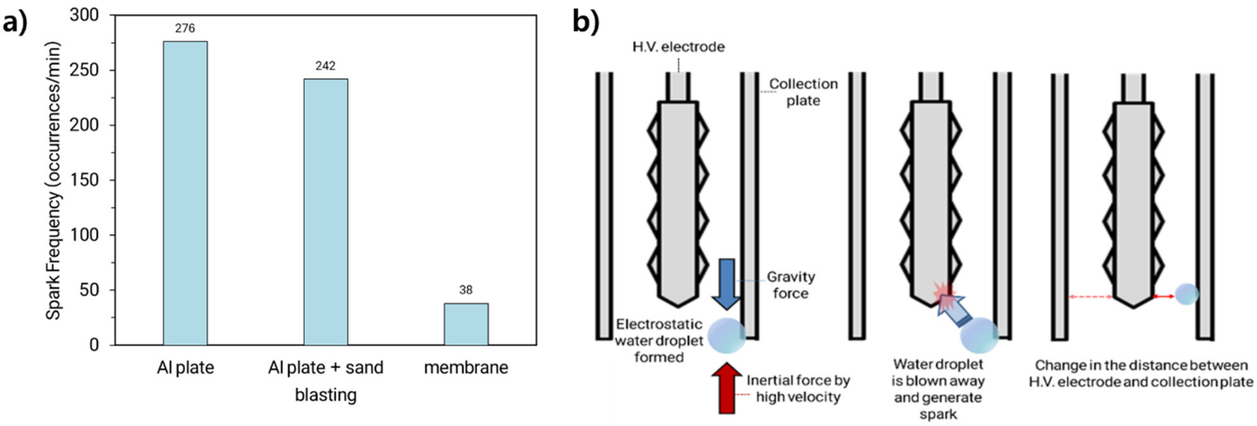

Fig. 5. (a) Average occurrences of sparks per minute at 8 m s^{-1}. (b) Described the cause of the spark.

Fig. 5 (a) shows the spark-occurrence frequency at 8 m s^{-1}. At an airflow velocity of 8 m s^{-1}, the electrostatic precipitator (ESP) exhibited a significantly high frequency of spark generation, with an average of 276 sparks per minute recorded for the untreated aluminum plate and 242 sparks per minute for the sandblasted aluminum plate. These high spark frequencies render it impossible to accurately measure the white-plume reduction efficiency. However, in the case of the membrane, 38 sparks are generated per minute. This is because the hydrophilic membrane can have a more electrically uniform surface potential distribution, which suppresses local charge accumulation and reduces the phenomenon of corona discharge developing into a spark. In addition, the membrane is likely to have a fibrous or porous structure, unlike a typical metal plate. This structure reduces the electric field concentration phenomenon and makes it difficult to reach the critical electric field required for spark generation. Fig 5. (b) explains the spark generation principle. One of the causes of sparks is that when the inertial force due to high velocity exceeds the gravitational force, water droplets are blown away and generate sparks. Another cause is the change in the distance between the high-voltage electrode and the collection plate due to the presence of water droplets. The primary cause of this phenomenon is the behavior of water droplets or films formed on the collection plate surfaces during operation. As the ESP operates, water droplets accumulate on the collection plate surface, particularly at the bottom edges, due to gravitational forces.

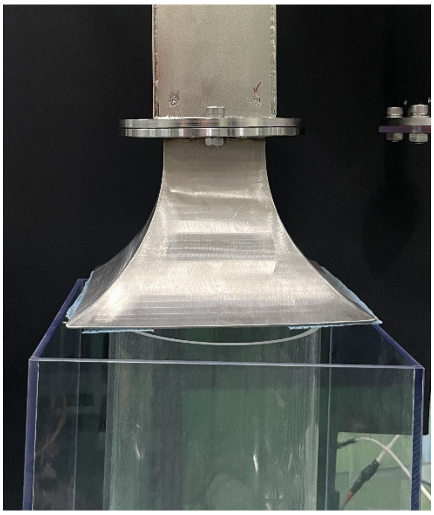

Fig. 6. Trumpet shaped duct installed at the bottom of the collection plate.

At high airflow velocities, the upward inertial forces generated by the rapid gas flow overpower the gravitational pull, causing the accumulated droplets to disperse into the gas stream. This dispersion leads to frequent disruptions in the uniform electric field between the charging electrode and the collection plate, resulting in spark generation. The interaction between the non-uniform electric field and dispersed droplets further amplifies the instability of the system, compromising the performance of the ESP at high velocities. These findings suggest that, under high-velocity conditions, the formation and behavior of water droplets and films on the collection plates are critical factors affecting the stability and efficiency of the ESP. To overcome this problem, a trumpet-shaped duct was installed at the bottom of the collection plate, allowing the accumulated droplets to flow downward along the duct, thereby mitigating spark generation (Fig. 6).

3.3 Effects of trumpet shaped duct

After integrating the trumpet-shaped duct into the electrostatic precipitator (ESP) system, its performance was evaluated at an airflow speed of 8 m s^{-1}, as shown in Figure 7. The untreated aluminum (Al) plate exhibited an average spark frequency of 80 sparks per minute, making it impractical to reliably measure the white plume reduction efficiency. However, the hydrophilic surface treatment improved the performance. Sandblasting aluminum plates reduced the average spark frequency to 28.4 sparks per minute and achieved a white plume reduction efficiency of over 80%, although some instability was caused by intermittent sparking and non-uniform electric fields. The membrane-coated plate showed the most significant improvement, with a low average spark frequency of 3.1 sparks per minute and a stable white plume reduction efficiency of 90%. This stability was attributed to the enhanced hydrophilicity of the membrane, which facilitated uniform liquid drainage and minimized disruption. These results emphasize the importance of surface treatments and structural modifications, such as trumpet-shaped ducts, in reducing sparks and improving the ESP efficiency under high-speed conditions.

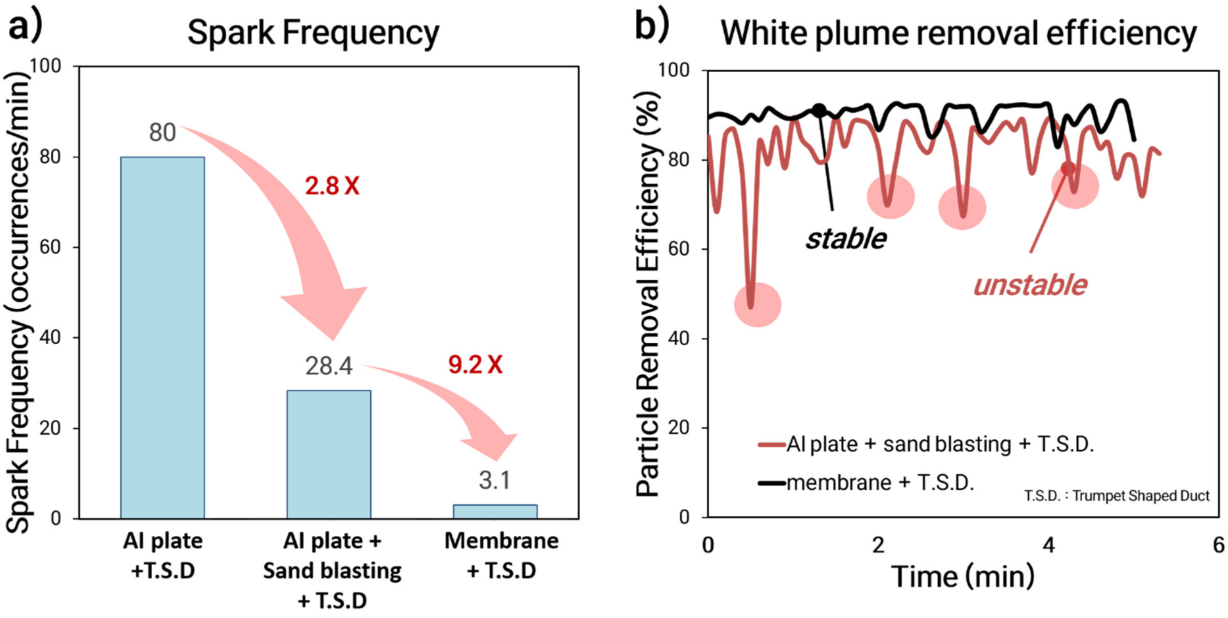

Fig. 7. (a) Average occurrences of sparks per minute at 8 m s^{-1}. (b) Average white plume removal efficiency at different collection plates with Trumpet Shaped Duct at 8 m s^{-1}.

4. Conclusion

This study demonstrates the effectiveness of integrating hydrophilic collection plates and trumpet-shaped ducts into an electrostatic precipitator (ESP) system to mitigate white plume emissions. At a low airflow velocity of 5 m s^{-1}, all tested collection plate configurations, including untreated aluminum, sandblasted aluminum, and membrane-coated plates, achieved stable reduction efficiencies exceeding 95% with minimal spark occurrences. However, at a high velocity of 8 m s^{-1}, significant challenges arose, particularly for the untreated plates, which exhibited high spark frequencies and compromised measurement reliability. The application of hydrophilic surface treatments markedly improved performance under high-velocity conditions. The sandblasted aluminum plates reduced spark occurrence and achieved a white plume reduction efficiency of over 80%, albeit with some instability. Membrane-coated plates provided the most notable improvement, maintaining a stable reduction efficiency of 90% with a minimal spark frequency of 3.1 per minute. The trumpet-shaped duct further enhanced the system stability by facilitating efficient liquid drainage and preventing droplet dispersion and associated sparks. These results emphasize the critical role of surface modifications and structural enhancements, such as hydrophilic treatments and trumpet-shaped ducts, in improving the ESP performance in challenging high-velocity and high-humidity environments. These findings provide valuable insights for designing advanced ESP systems capable of achieving reliable and efficient white-plume mitigation and contributing to improved environmental and operational outcomes in industrial applications.

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