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Performance Evaluation of a Novel Pilot-Scale Wet Electrostatic Precipitator in a Bio-Drying-Assisted Solid Recovered Fuel (SRF) Generation Plant: Particulate Matter (PM) Collection Efficiency

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Citation: Kim, M.-S.; Jo, H.; Park, Y.; Han, U.; Thapa, A.; Kim, K.; Choi, D.H.; Park, G.J.; Cho, S.-K. Performance Evaluation of a Novel Pilot-Scale Wet Electrostatic Precipitator in a Bio-Drying-Assisted Solid Recovered Fuel (SRF) Generation Plant: Particulate Matter (PM) Collection Efficiency. *Sustainability* **2022**, *14*, 8702. https://doi.org/10.3390/su14148702

Academic Editors: Guo Wei, Ehsan Elahi and Tasawar Nawaz

Received: 9 June 2022
Accepted: 13 July 2022
Published: 15 July 2022

Abstract: The production of solid recovered fuel (SRF) from sewage sludge has been credited with facilitating Korea's waste management shift toward a resource circular economy. In this study, a novel pilot-scale wet electrostatic precipitator (WESP) was developed and installed in a bio-drying-assisted solid recovered fuel (SRF) generation plant for the first time. To investigate the performance of the novel WESP, various sizes of particulate matter, i.e., total particle matter (PM), particle matter smaller than 10 μm (PM_{10}), and particle matter smaller than 0.1 μm ($PM_{0.1}$), collection efficiencies were evaluated and demonstrated promising performances. Under optimal operating conditions (flow rate of 5 m^3/min and an applied voltage of 30 kV), 99.76% PM and 91% PM_{10} collection efficiencies were achieved, and the PM concentration was 0.16 mg/m^3, which met the exhaust emission standard. However, a dramatic increase in $PM_{0.1}$ was observed and could be explained by the break-up theory, binary homogenous nucleation, and ion-induced nucleation. The experimental findings could serve as useful information to understand the WESP system.

Keywords: wet electrostatic precipitator; particulate matter; collection efficiency; sewage sludge; solid recovered fuel

1. Introduction

Rapid population growth and economic development have undoubtedly impacted energy consumption, waste generation, and environmental pollution, all of which are hampering the sustainable development of the world [1]. In addition, the growing threat of climate change has forced countries to harmonize economic development with environmental concerns. Sustainable development has been suggested as an optimal strategy to achieve coexistence rather than trade-off between economic development and environmental protection by the application of so-called smart and/or eco-friendly technologies [2–6]. Among them, renewable energy production and valuable resource recovery from various wastes have played pivotal roles in reducing fossil fuel demands [7].

To address this sustainability crisis, the Korean government announced the "Renewable Energy 3020 Plan" to increase the proportion of renewable energy generation from 2.2% in 2016 to 20% in 2030 [8]. To achieve these goals, a circular economy and resource security have become the priorities of Korea's environmental policy [9]. The Framework Act on Resource Circulation (FARC) became effective on 1 January 2018 and aims to "control waste generation with efficient use of resources and promote the circular use and proper disposal of waste, thereby minimizing natural resources and energy exploitation, preserving the environment, and achieving a sustainable resource-circulating society. Through the FARC, South Korea aims to shift from a pure waste management approach toward a new paradigm, emphasizing a resource circulating society" [9].

The annual production of sewage sludge in South Korea was approximately 4.22 million tons in 2020 and is expected to increase to 5.4 million tons in 2025 [10]. With the increasing generation of sewage sludge, various environmental processes (incineration, composting, anaerobic digestion, etc.) have been applied to sewage disposal since the "London protocol" agreement, which prohibits the ocean dumping of sewage sludge [11]. Due to the FARC act, the production of solid recovered fuel (SRF) from sewage sludge has been recently widely recognized as a promising alternative process since generated SRF can be used as a co-firing fuel in power plants, reducing carbon emissions and fossil fuel usage [12,13].

To exploit SRF as a renewable fuel, first it needs to meet the net calorific standard (>3000 kcal/kg) in South Korea. Thus, the water content of sewage sludge should be reduced to below 10~15% [14–16]. The most common way to reduce the water content in sewage sludge is by using the direct heating method. However, the high operational costs of heating sources have been considered one of the biggest bottlenecks to this method. To overcome this, the bio-drying process, a promising method for reducing the water content in sewage sludge with minimum aerobic degradation, has been developed and successfully demonstrated [17]. The main mechanism of bio-drying is convective evaporation, which utilizes metabolic heat generated from the degradation of organic matter. Then, the removed water is transported by airflow to exhaust gas and finally collected as water condensate [18]. The effective moisture reduction by the bio-drying process was demonstrated in SRF generation and other systems by controlling air replacement and the flow rate [19].

Various sizes of suspended particles are known to be generated during SRF production, particularly in the drying process. To prevent environmental pollution, exhaust gas from the drying process must undergo a proper treatment process [20]. In the case of exhaust gas from the direct heating drying process, a bag filter has been widely used because of its simplicity and effectiveness. However, exhaust gas from the bio-drying process is fully saturated, so a conventional bag filter cannot achieve higher particle collection efficiency due to clogging issues. Thus, a wet electrostatic precipitator (WESP) was developed to treat the humid exhaust gas and sticky particles.

The WESP, utilizing water flow and an electrode, is known as a cost-effective technology for collecting various-sized particles from the humid exhaust gas and has been mostly applied to power plants and factories equipped with pyrolysis processes [21]. Unlike dry ESPs, back-corona discharge and particle re-entrainment can be avoided because the electrodes in WESPs are cleaned continuously by a water spray [22]. Previous studies showed that WESPs could effectively collect the particles in exhaust gas under various conditions, with 90–97% and up to 99% collection efficiencies in single-stage and two-stage processes, respectively [21,23,24].

A novel pilot-scale WESP successfully developed by Jinenertech (South Korea) was installed in a pilot-scale bio-drying-assisted SRF generation plant for the first time. To demonstrate the performance of the novel WESP, this study investigated the particle collection efficiency of the novel WESP. Two commonly used indices, total particle matter (PM) and particle matter smaller than 10 μm (PM_{10}) were applied to evaluate the performance of the novel WESP. To determine the optimal operating conditions, PM and PM_{10} collection efficiencies were measured at various conditions at voltages of 15–30 kV and flow rates of 1, 3, and 5 m^3/min. In addition, particle size analysis was conducted to investigate changes in particle number distribution based on particle sizes in the exhaust gas after WESP treatment.

2. Materials and Methods

2.1. Wet Electrostatic Precipitator

The novel pilot-scale WESP was developed for saturated gas pre-treatment to meet the exhaust emission standard and patented in South Korea with registration number 10–2347105. As shown in Figure 1, the WESP was designed for exhaust gas to first undergo a dual cyclone to remove the coarse and high-density particles, and then the exhaust gas was moved to electrostatic chambers. The WESP consisted of nine discharge and precipitation electrodes and each set of electrodes was placed in each of the nine chambers. When negative voltage was applied to the discharge electrodes, electric corona discharge ionized the particles in the exhaust gas, and they were moved toward the precipitation electrode due to electrostatic forces, as shown in Figure 1C, and finally washed down by a water sprayer at the top of each chamber. An additional water sprayer was installed at the bottom of the chamber, facing upward and downward, to increase particle collection efficiency. The water at the bottom of the chamber was recycled to the water sprayers and discharged regularly to maintain high particle collection efficiency. The applied voltage of the WESP ranged from 0 to 30 kV and current was measured at each voltage at a flow rate of 1, 3, and 5 m^3/min to determine the voltage–current relationship.

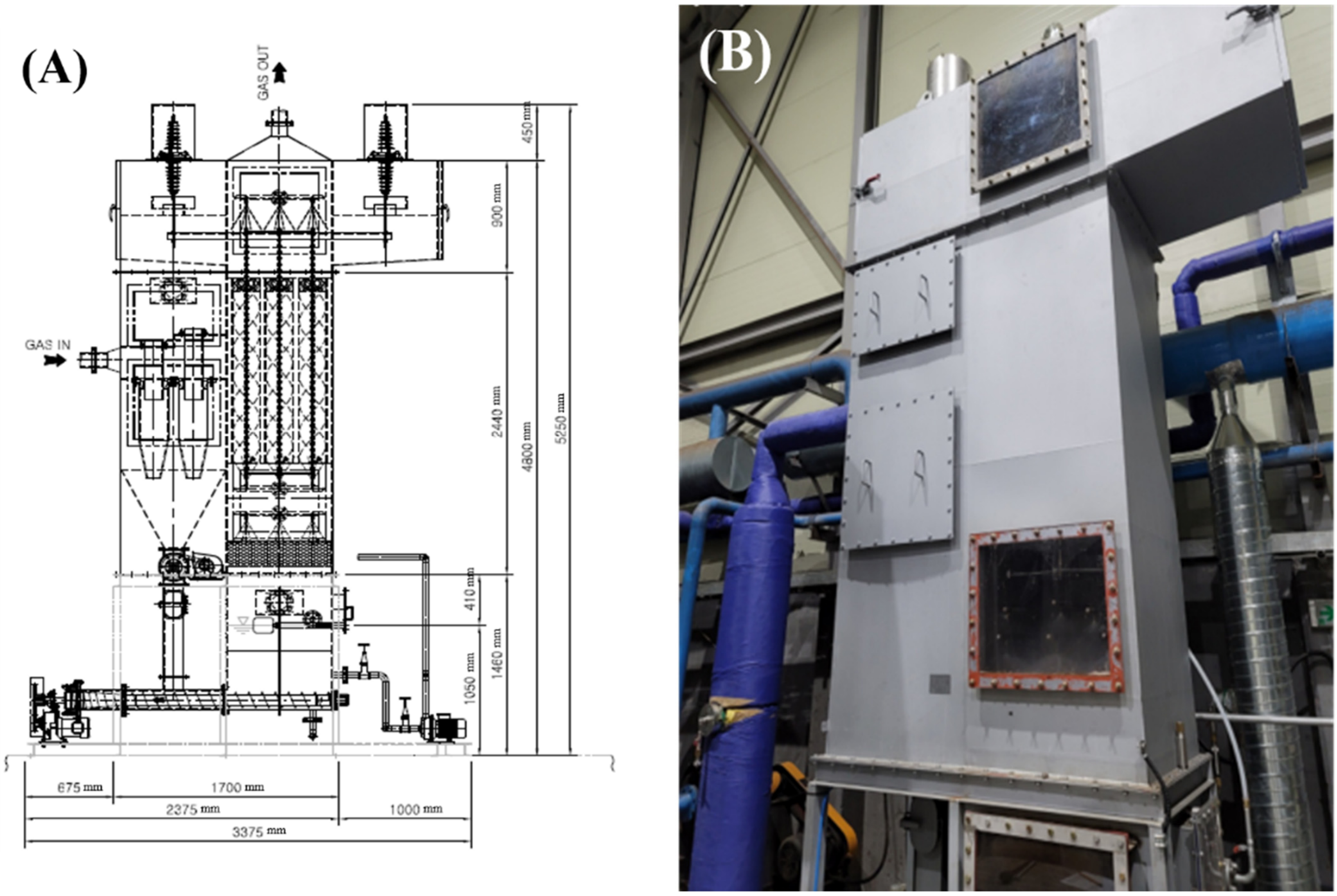

Figure 1. *Cont.*

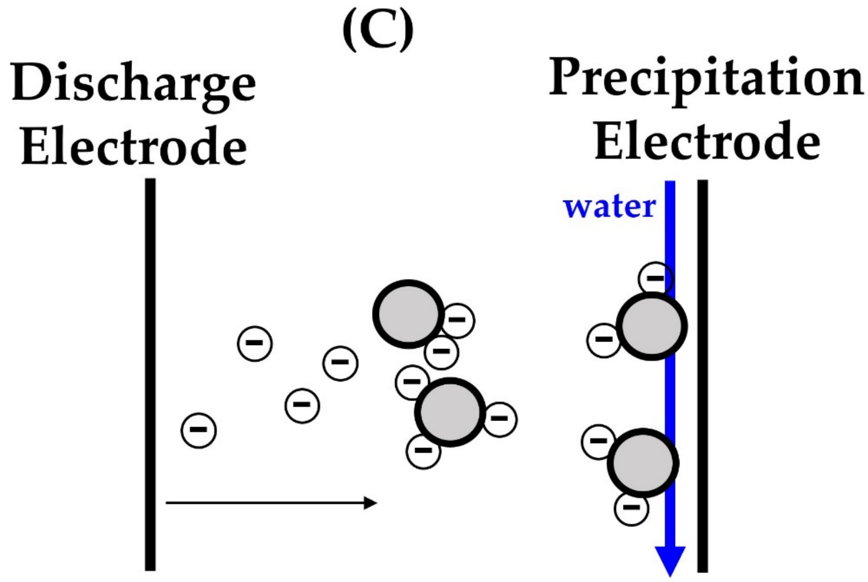

Figure 1. Details of the novel pilot-scale WESP: (**A**) blueprint (**B**) picture of the front view, and (**C**) working principle of the discharge and precipitation electrode.

2.2. A Pilot-Scale Bio-Drying-Assisted SRF Generation Plant with the WESP

The novel WESP was installed at a pilot-scale bio-drying-assisted SRF generation plant using sewage sludge with a capacity of 5 tons/day with 10–14 days of retention time, located in C county, South Korea. As illustrated in Figure 2, the plant consisted of bio-drying, heat-drying, palletization, and wet scrubbers. For the experiments, sewage sludge was collected from a wastewater treatment plant located in B city, South Korea. The chemical characteristics of the sewage are given in Table 1. The sludge was mixed with a bulking agent and an amendment to facilitate subsequent processing. Then, the sludge passed consecutively through a two-stage drying process. The water content was decreased to 35% and 13–15% after bio-drying and heat-drying, respectively. The dried sludge was then transferred to the palletization process, where the sludge's final moisture content was reduced to 10% (Figure 2). The exhaust gas containing various-sized particles from the bio-drying and heat-drying processes was first transferred to the WESP and then to wet scrubbers to meet the exhaust emission standard.

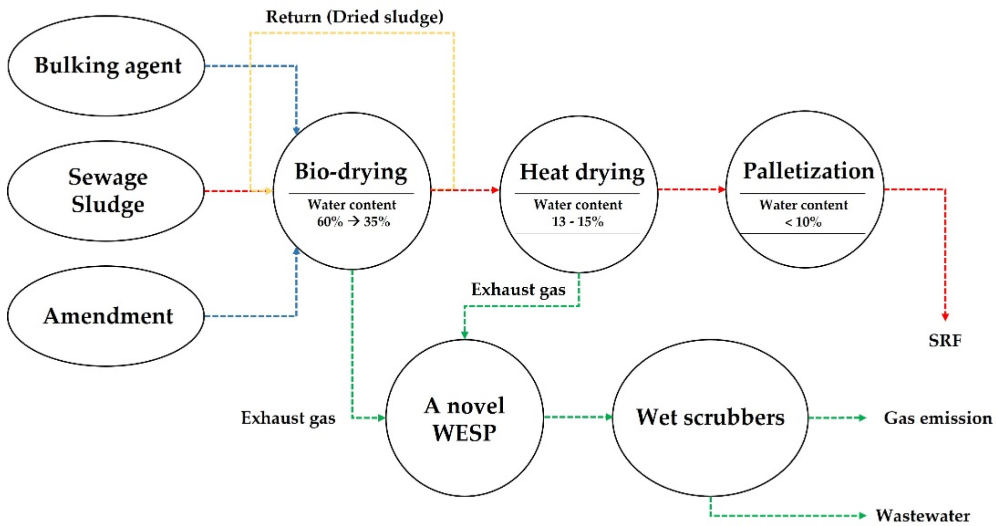

Figure 2. Process flow of a bio-drying-assisted SRF generation plant.

Table 1. Characteristics of sewage waste.

Parameters	Value
Water content (%)	81.8
Combustible volatile matter (%)	14.4
Ash content (%)	3.8

2.3. PM Collection Efficiency Test

A silica thimble filter (R88, Advantec, Tokyo, Japan) with an inner diameter of 22 mm, an outer diameter of 25 mm, and a height of 90 mm was used to collect the total PM. The thimble filter could withstand temperatures of up to 1000 °C and had a collection efficiency of more than 99.9% (0.3 µm DOP%). The test was carried out according to the standard method set by the Ministry of Environment of South Korea [25]. Before the experiment, the thimble filter was dried for 2 h at 105 °C in a heat dryer, and then its weight was measured. After that, a thimble filter was connected to the HJD260V 740 mmHg vacuum pump (Hanjin Air, South Korea) by a filter holder. Samples were taken from both the inlet and outlet of the WESP (Figure 3). Four hundred liters of exhaust gas were collected by the vacuum pump, and then the filter was dried for 2 h at 105 °C to determine the weight. The total PM collection efficiency test was carried out at voltages of 15–30 kV and flow rates of 1, 3, and 5 m^3/min. The total PM collection efficiency was calculated using Equation (1):

$$
\begin{aligned}
\text{PM collection efficiency } (\%) &= [\{\tfrac{W_1 - W_2}{V}\} - \{(\tfrac{W_3 - W_4}{V}\}]/\{(\tfrac{W_1 - W_2}{V}\} * 100 \\
W1 &= \text{weight of the inlet ceramic cup after collection (g)} \\
W2 &= \text{weight of the inlet ceramic cup before collection (g)} \\
W3 &= \text{weight of the outlet ceramic cup after collection (g)} \\
W4 &= \text{weight of the outlet ceramic cup before collection (g)} \\
V &= \text{total collected gas (L)}
\end{aligned}
\tag{1}
$$

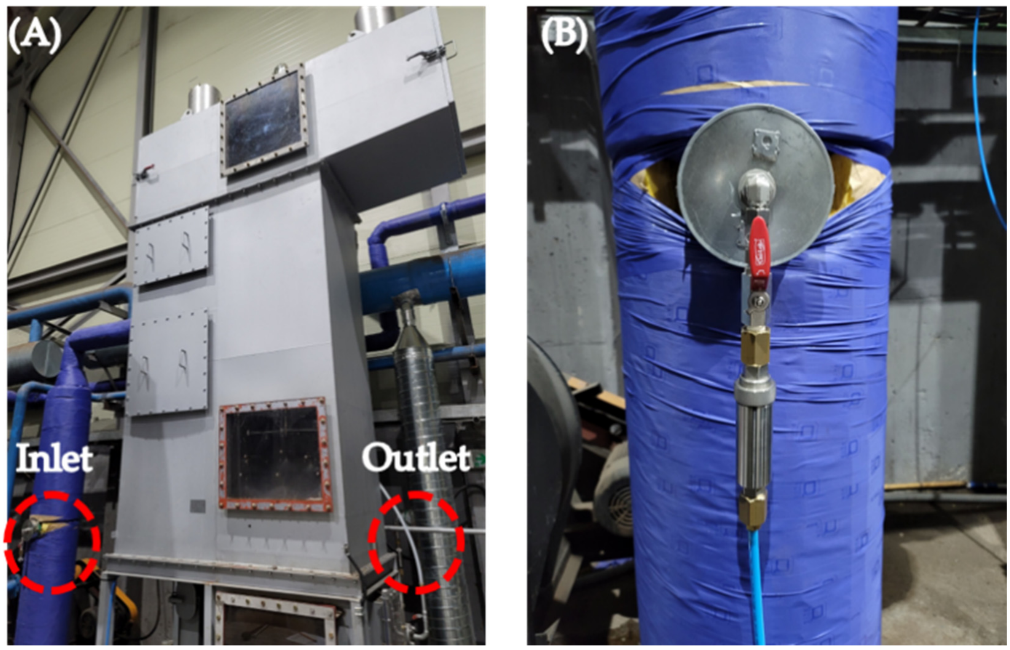

Figure 3. Sampling port of the WESP: (**A**) sampling locations for the inlet and outlet and (**B**) sampling port.

2.4. PM_{10} Collection Efficiency Test

According to the standard method set by the Ministry of Environment of Korea for air pollution tests [26], PM_{10} was collected in a glass jar (240 mL) filled with distilled water for microparticle size analysis (PSA). The 400 L of gas collected from the WESP (Figure 3) was then directly injected into the glass jar from an upward direction. A ceramic cup was dried in a heat dryer for 12 h at 105 °C and its weight was measured. The sample was filtered through filter paper (Whatman, Buckinghamshire, United Kingdom) to selectively separate PM_{10}. The filtered water was collected immediately in a ceramic cup and dried for 12 h before measuring to ensure that all water had evaporated. The PM_{10} collection efficiency test was carried out at voltages of 15–30 kV and flow rates of 1, 3, and 5 m^3/min. The PM_{10} collection efficiency was calculated according to Equation (2):

$$\begin{gathered} PM_{10}\ \text{collection efficiency}\ (\%) = [\{\tfrac{W_1-W_2}{V}\} - \{(\tfrac{W_3-W_4}{V}\}]/\{(\tfrac{W_1-W_2}{V}\} * 100 \\ \text{W1} = \text{weight of the inlet ceramic cup after collection (g)} \\ \text{W2} = \text{weight of the inlet ceramic cup before collection (g)} \\ \text{W3} = \text{weight of the outlet ceramic cup after collection (g)} \\ \text{W4} = \text{weight of the outlet ceramic cup before collection (g)} \\ \text{V} = \text{total collected gas (L)} \end{gathered} \quad (2)$$

In addition, particle size analysis was performed on the non-filtered samples using a Helos Particle Size Analyzer (Beckman, CA, USA) to monitor the changes in particle distribution after the WESP process at 30 kV with a flow rate of 5 m^3/min. The analyzed data were then converted to depict the particle number distribution at three different particle size ranges (<0.1 µm, 0.1–2.5 µm, and >2.5 µm) with a focus on monitoring particle matter smaller than 2.5 µm ($PM_{2.5}$).

3. Result and Discussion

3.1. Voltage–Current Relationship in the Novel Pilot-Scale WESP

The relationship between the current and applied voltage of the discharge electrode is shown in Figure 4 and the highest current (8.4 mA) was observed at an applied voltage of 30 kV and 1 m^3/min flow rate. No current was measured under an applied voltage of 10 kV, suggesting that current could only be generated when an electric field of sufficient strength was emitted. As the applied voltage increased from 15 kV to 25 kV, the current remained around 2 mA at various flow rates, whereas a significant increase in current was observed at 30 kV at all flow rates. Similar findings were reported by Yang et al. [27] and Karwat et al. [28], who observed that a rod discharge electrode generated low current until applied voltages of 25 kV, while the current-producing capacity sharply increased between 25 and 30 kV.

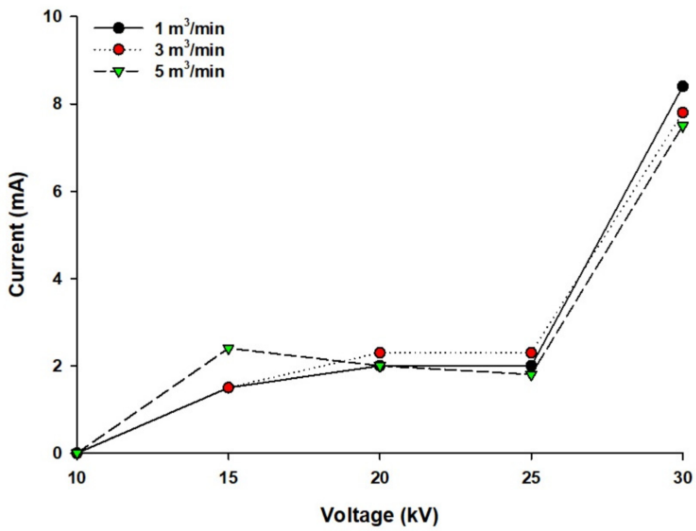

Figure 4. Voltage–current relationships at different flow rates.

The electrode current in a WESP is known to depend upon its contours, the voltage supply, and the current efficiency of the voltage supplier [28]. In addition, the shape of the discharge electrode can directly affect the current, so different currents can be generated under the same applied voltage. Thus, the choice and shape of the discharge electrode play important roles in PM collection efficiency and operating cost. Karwat et al. [28] revealed that a spike-type electrode showed the highest current among vane-edged and wire-, square-, and ribbon-shaped electrodes. According to Yang et al. [27], the pin-shaped electrode showed the highest current among pin-, sawtooth-, and rod-shaped electrodes. However, similar particle collection efficiencies were achieved regardless of the electrode shape when the applied current was higher than 2.0 mA. Even though our novel WESP had a rod-shaped discharge electrode, higher collection efficiencies at various flow rates could be expected since currents higher than 2 mA were observed at more than 15 kV of applied voltage.

3.2. PM Collection Efficiency

A thimble filter was used to evaluate the PM collection efficiency. As seen in Figure 5, a significant visual difference was observed after the application of the novel WESP. The PM collection efficiency ranged from 97.3 to 99.67% at a flow rate of 1–5 m^3/min and applied voltages of 15–30 kV, as shown in Figure 6. The highest PM collection efficiency (99.67%) was achieved at a flow rate of 5 m^3/min and an applied voltage of 30 kV. The achievement of a higher PM collection efficiency at a higher flow rate, except at an applied voltage of 25 kV, was unexpected. Given that the PM collection efficiency can be commonly explained by the current function, the current in the WESP was 8.4 mA, 7.8 mA, and 7.5 mA at flow rates of 1 m^3/min, 3 m^3/min, and 5 m^3/min, respectively, under an applied voltage of 30 kV. In addition, an increase in flow rate led to a decrease in residence time and might cause a substantial decrease in the collision probability between PM and ions. Similar results were reported by Steiner et al. [29] showing better collection efficiency of particle sizes between 300 nm and 350 nm at 1.2 m/s than at 1.0 m/s. The results indicated that the PM collection efficiency was not a simple function of the relationship between the applied voltage and the current, but that other factors need to be considered for optimizing a WESP. As stated by Oliveira and Guerra [30], "the existence of several operational and geometric parameters makes electrostatic precipitation a highly complex process, so it is difficult to compare the results of different studies in this field." The PM concentrations in the WESP outlet ranged from 8.17 to 0.16 mg/m^3 at various operating conditions, as shown in Figure 7, and the lowest PM concentration was achieved at a flow rate of 5 m^3/min and an applied voltage of 30 kV. These results demonstrated the promising performance of the novel WESP, which met the exhaust emission standard (<15 mg/Sm^3) in South Korea. Similarly, Yang et al. [27] reported the reduction in PM concentration to 1.18 mg/m^3 using a WESP, and further significant reductions up to 0.43 mg/m^3 were achieved by the combination of a WESP and a pre-charger in a full-scale coal-fired power plant. To guarantee PM concentrations of less than 1.0 mg/m^3 in a full-scale plant, our novel WESP should consider the installation of a pre-charger in the case of a performance drop after scaling-up.

To control the odor of exhaust gas, wet scrubbers were installed and operated in our pilot-scale bio-drying-assisted SRF generation plant. Diluted sulfuric acid (H_2SO_4) and sodium hypochlorite (NaClO) were mainly used to neutralize and oxidize the basic exhaust gas, respectively. After the installation of the novel WESP, the average chemical consumption was roughly halved (data not shown), suggesting that the novel WESP not only enabled PM collection, but also reduced odorous gas via water spraying, thereby achieving cost-effective operation.

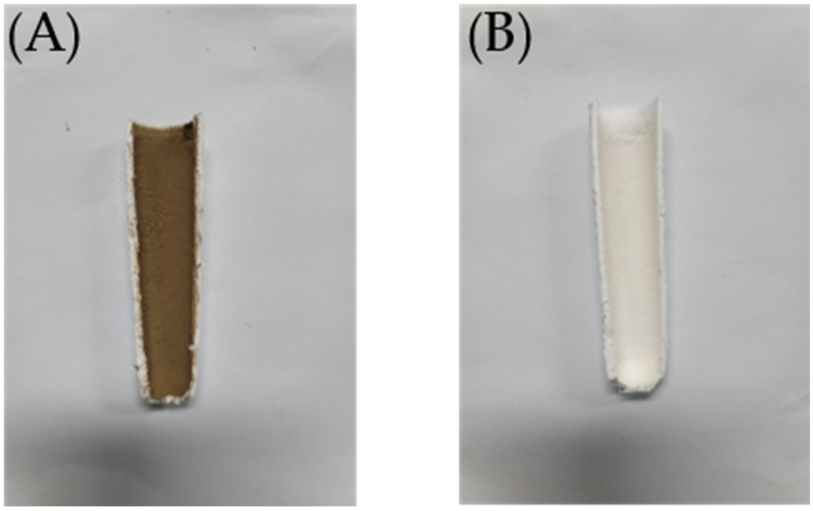

Figure 5. Picture of a thimble filter tested with the novel WESP (**A**) at the inlet and (**B**) at the outlet.

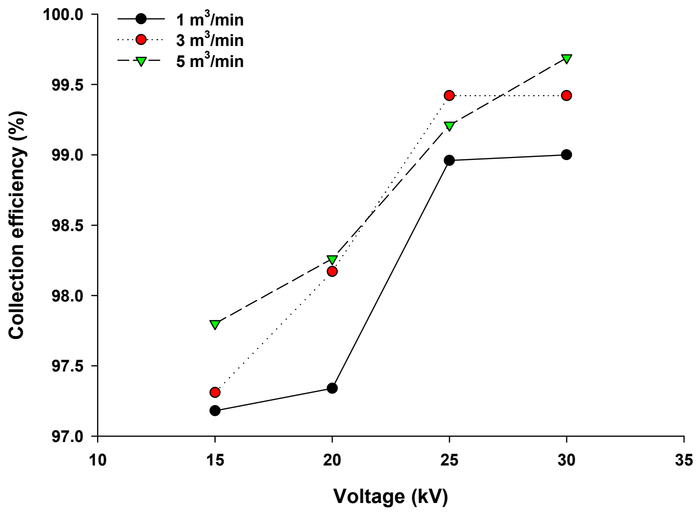

Figure 6. PM collection efficiency at various operating conditions.

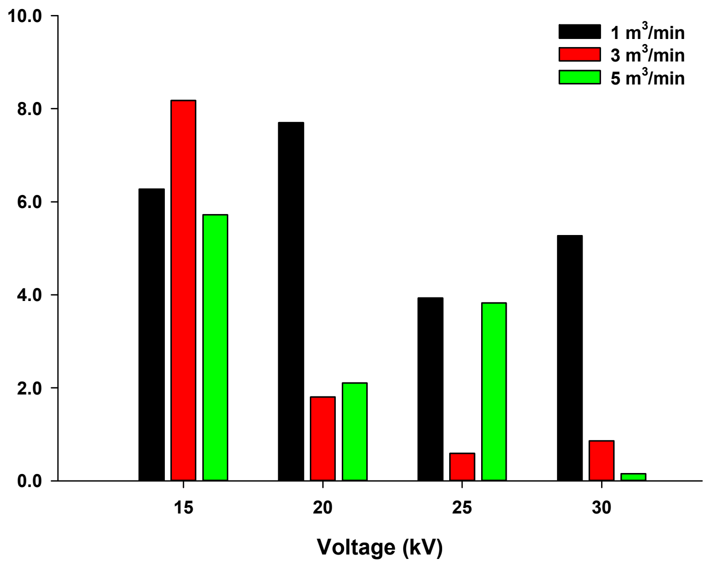

Figure 7. PM concentration in WESP outlet at various operating conditions.

3.3. PM_{10} Collection Efficiency

The overall PM_{10} collection efficiency showed different trends compared with PM collection efficiency, as seen in Figure 8. Similar to the PM collection efficiency, however, the highest PM_{10} collection efficiency of approx. 91% was achieved at a flow rate of 5 m^3/min and an applied voltage of 30 kV. Reportedly, smaller-sized PM was more toxic and could be transferred farther and deposited to the lower lung lobes, possibly causing respiratory issues [31]. To monitor changes in PM size distribution after the novel WESP application, a particle size analysis was conducted. Given that most PM concentrations in the WESP outlet were in the PM size range smaller than 2.5 µm ($PM_{2.5}$) [32], the particle number distribution was presented based on three ranges (<0.1 µm, 0.1–2.5 µm, and >2.5 µm), as shown in Figure 9. The particle number distribution analysis showed the effectiveness of the novel WESP for various PM ranges. However, the amount of PM with particle sizes smaller than <0.1 µm ($PM_{0.1}$) was dramatically increased after the application of the novel WESP. This phenomenon could presumably be explained by the break-up theory suggested by Kim and Dunn [33], dealing with the generation of progeny droplets by an external electric field. They found that numerous smaller droplets were generated from a 2.24 mm-diameter parent drop under an applied electric field (~10 kV/cm). Similarly, in this study, $PM_{0.1}$ could be generated via the breaking-up of $PM_{2.5}$ during a 30 kV application. It could also be explained by the generation of nanoparticles through binary homogenous nucleation and ion-induced nucleation in corona discharge [34]. In this theory, components of the exhaust gas such as SO_x and NO_x affect the generation of nano-sized particles during electrode discharge. A high proportion of SO_x and NO_x was observed in exhaust gas from the co-combustion of forest biomass and sewage sludge [35] and the majority seemed to originate from sewage sludge. Thus, SO_x and NO_x generated during bio-drying and heat-drying in this study possibly affected the generation of $PM_{0.1}$. Even though our novel WESP showed 99.67% PM collection efficiency and met the exhaust emission standard at optimal operating conditions, further research is needed to increase the collection efficiency of $PM_{0.1}$ for better future applications. Economic analysis should also be conducted considering increased electric usage for the novel WESP and reduced chemical usage in wet scrubbers.

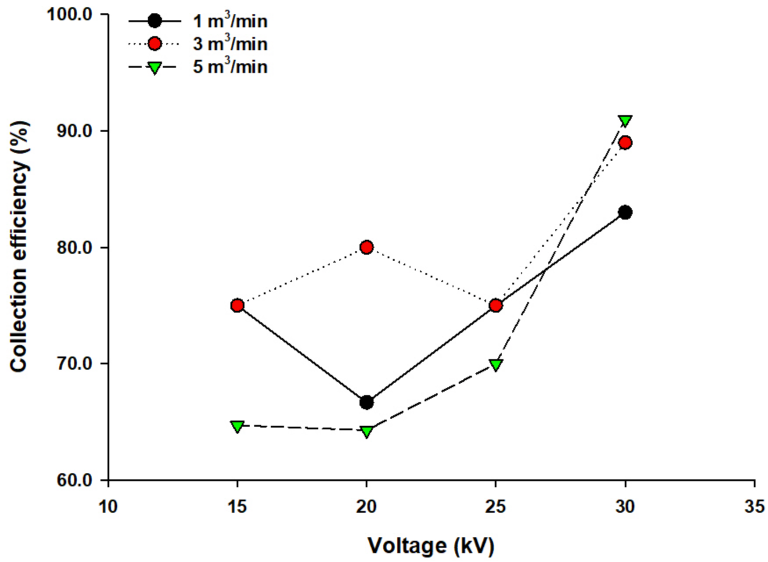

Figure 8. PM_{10} collection efficiency at various operating conditions.

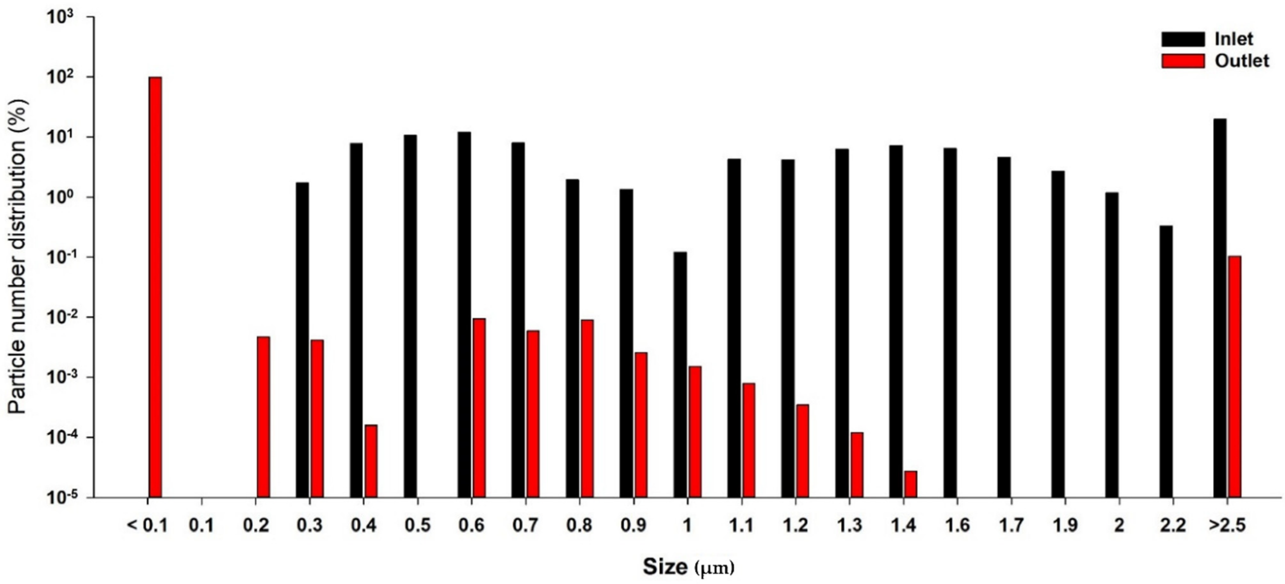

Figure 9. Particle number distribution based on size in the inlet and outlet at a flow rate of 5 m^3/min and an applied voltage of 30 kV.

4. Conclusions

The novel pilot-scale WESP developed in this study was installed in a pilot-scale bio-drying-assisted SRF generation plant for the first time. To investigate the performance of the novel WESP, PM and PM_{10} collection efficiencies were evaluated and demonstrated promising performances. Under optimal operating conditions (flow rate of 5 m^3/min and an applied voltage of 30 kV), 99.76% PM and 91% PM_{10} collection efficiencies were achieved, and the PM concentration was 0.16 mg/m^3, which met the exhaust emission standard in South Korea. However, a dramatic increase in $PM_{0.1}$ was observed, which could be explained by the break-up theory, binary homogenous nucleation, and ion-induced nucleation. To enhance the novel WESP, further research needs to focus on increasing $PM_{0.1}$ collection efficiency and economic analysis of the novel WESP applications.

Author Contributions: Investigation, H.J., Y.P. and U.H.; Resources, K.K., D.H.C. and G.J.P.; Writing—original draft, M.-S.K. and A.T.; Writing—review & editing, S.-K.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministry of Trade, Industry, and Energy's "Plan-ministerial Linked Technology Commercialization Research Project", and we appreciate the contribution (task number: P0018244).

Conflicts of Interest: The authors declare that they have no conflict of interest.

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