

Article

Effect of the Surface Treatment Process of Filter Bags on the Performance of Hybrid Electrostatic Precipitators and Bag Filters

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Abstract: Hybrid electrostatic precipitators consisting of electrostatic precipitation (ESP) and a bag filter are potential devices for ultralow emissions. The ESP captures and charges the particles; subsequently, the charged particles that escape enter the bag filter. The charged particles can cause the electric field of the filter bag to develop, thereby enhancing the filtration efficiency due to the force of the electric field. Experiments based on the coupling-reinforced electrostatic–fabric integrated precipitator system were conducted to investigate the outlet total dust concentration, dust removal efficiency, pressure drop, energy consumption of bag filter, and hybrid electrostatic precipitators with various filter bags. The measured results demonstrate that the removal performance of filter bags with smaller fiber diameters was superior. However, the pressure drop and energy consumption were high due to the increased filtration resistance. Compared to bag filters, hybrid electrostatic precipitators had lower total and grade dust mass concentrations at the outlet, higher total and grade dust removal efficiencies, a minor average pressure drop variation per minute, and lower total energy consumption. Consequently, the quality factor was utilized to comprehensively evaluate the overall performance of dust collectors. The hybrid electrostatic precipitators had a significant greater quality factor; their overall performance was superior to that of bag filters. Overall, a smaller filter bag’s fiber diameter resulted in more effective dust removal capabilities. Hybrid electrostatic precipitators with various filter bags were significantly better than bag filters in terms of dust removal performance, cycle life, and energy consumption.

Keywords: particle; precipitator; filter bags; efficiency; energy consumption; comprehensive performance



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1. Introduction

Large volumes of particulate matter emissions, especially PM_{2.5}, causing air pollution and serious diseases, have raised the bar for dust removal technology [1–5]. The most widely used dust removal devices are bag filters, electrostatic precipitators (ESP), and hybrid electrostatic precipitators [6,7]. The bag filter works on mechanisms such as diffusion, interception, and impaction to capture dust, and it is highly efficient at removing particles, particularly fine particles [8–10]. However, the pressure drop of the bag filter is considerable, and the life of the filter bag depends on various factors and the performance of different filter bags [11,12]. The ESP has a low pressure drop but has relatively low efficiency in removing particles of 0.1–1 µm [7]. Hybrid electrostatic precipitators consisting of ESP and bag filters perform better than the individual dust collectors. Particles are charged and partially removed in the ESP, after which the charged particles enter the bag filter and are recaptured. The filtration efficiency of the bag filter can be improved by the electric field force between the charged particles and bag filter without increasing the pressure drop, and the cleaning cycle and filter bag life can be extended [7,13–16].

The filter bag is the core component of bag filters and an essential component of the hybrid electrostatic precipitators. The performance of different types of filter media varies considerably, and electrostatic precipitation can enhance the performance of the

filter bag. Zíková et al. [17] developed a new device for testing the penetration and calculating the penetration particle size, penetration maximum, and the pressure drop of 20 fiber filter pieces of various materials. The results revealed that the penetration curve shapes, penetration particle size, and penetration maxima of different fiber filters were vastly different. Moreover, the pressure drop was variable, and the linear relationship between pressure drop and surface velocity was also verified. Bao et al. [18] investigated the effect of fibers with different parameters on the filtration efficiency of a bag filter. Their findings indicated that a bag filter with a smaller fiber diameter and Young's modulus had higher efficiency, while fibers with a triangular cross-section had higher dust removal efficiencies than those with a circular cross-section. Liu et al. [8] evaluated various filter types with varying filter pore sizes and fiber diameters. They found that the depth filtration medium has higher efficiency and filtration resistance when the filter medium's average pore size and fiber diameter are small. Bortolassi et al. [12] evaluated the performance of HEPA (high-efficiency particulate air filter) filters with three types of filter media. They concluded that the filter medium with a smaller fiber diameter had a lower permeability. Humphries et al. [19] examined the effect of charged particles on the filtration efficiency of fiber filters. Their results indicated that the efficiency of the fiber filter could be effectively improved, and its operating pressure drop was also effectively reduced due to the charged particles. Huang et al. [20] and Tu et al. [6] found that charged conditions are advantageous for particle trapping on the filter medium. In addition, a higher particle charge resulted in a higher dust removal efficiency and lower pressure drop. Feng et al. [7,21–23] used experiments, theoretical calculations, and numerical methods to explore and evaluate the performance of a hybrid electrostatic air filter with various filters. The study revealed that the electrostatically enhanced efficiency of the fibrous filter was evident, and different filter media could be selected from a variety of vantage points on the basis of their unique characteristic parameters. Tian et al. [24,25] designed and conducted experiments on the compact electrostatically assisted air (cEAA) coarse filter and electrostatically assisted metal foam (EAMF) coarse filter. The authors concluded that charged particles could enhance the filtration efficiency, and that the filter material with a higher relative dielectric constant or larger tortuosity had a higher filtration efficiency. Lyu et al. [26] investigated the collection efficiency and pressure drop of PPS fibrous filter for unipolarly charged fly ash particles, and they indicated that the unipolar charge could improve the filtration performance of bag the filter. Jaworek et al. [27] found that the filtration efficiency of the hybrid electrostatic filtration system could be greatly improved compared to the individual ESP or bag filter, in addition to prolonging the average cleaning interval of bags while extending the filter bag lifetime. Bruno et al. [28] introduced and compared the features of the compact hybrid particulate collector (COHPAC) and the advanced hybrid particulate collector (AHPC). Their conclusions suggested that the evaluation of filter bag characteristics was more important for the development of dust collectors. However, there is still very little research on the effect of different filter bags produced using different surface treatment processes on the performance of hybrid electrostatic precipitators and bag filters.

Using a coupled electric bag filter experimental system, this paper investigated the performance (dust removal performance, running conditions, and energy consumption) of bag filters and hybrid electrostatic precipitators with different filter bags. The novelty of this study is that the filter bags were obtained using different surface treatment processes: anti-static, ordinary laminated, and anti-static laminated. In addition, quality factors were used to evaluate the overall performance of the dust collectors with different filter bags.

2. Experimental System and Methods

2.1. Experimental Setup

The experimental system, as depicted in Figure 1, consisted of four key sections: the particle generator section, the power supply section, the hybrid electrostatic precipitators, and the measurement systems. In the particle generator section, particles fell into the inlet duct driven by the spiral rod rotation, where they were then mixed with clean compressed

air and introduced into the dust collector at a flow rate of $407 \text{ m}^3/\text{h}$. The DC high-power voltage source (Tessmann TD2202N20-400-20 kV to 0 kV, 400 W) provided negative voltage to the discharge wires. The hybrid electrostatic precipitators consisted of two sections, the front and the back areas, measuring 1590 mm in width and 2300 mm in height. Due to the arrangement of the air distribution plate at the inlet of hybrid electrostatic precipitators, the air entered and flowed uniformly; the air was then cleaned in the front and back areas of the dust collector. Four discharge wires and two collection plates constituted the front area. Corona discharge wires of 8 mm in diameter and 120 mm in length were placed in the channel consisting of two collection plates measuring 1000 mm by 835 mm. The wire-to-wire and the plate-to-plate distances were 200 mm each, while the wire-to-plate distance was 100 mm. The back areas consisted of three cloth bag units, each containing three bags organized in a single row. The filter bags were 130 mm in diameter and 1000 mm in length. For the concentration measurement, the electrical low-pressure impactor (ELPI) was used to measure the particle concentration upstream and downstream of the hybrid electrostatic precipitators; the classification and total removal efficiency could be computed using the particle concentration. The hybrid electrostatic precipitator's pressure drop was determined using a wireless mini pressure drop sensor (testo 510i) and the testo smart probes app. Readings from the high-voltage power supply could be used to determine the discharged current.

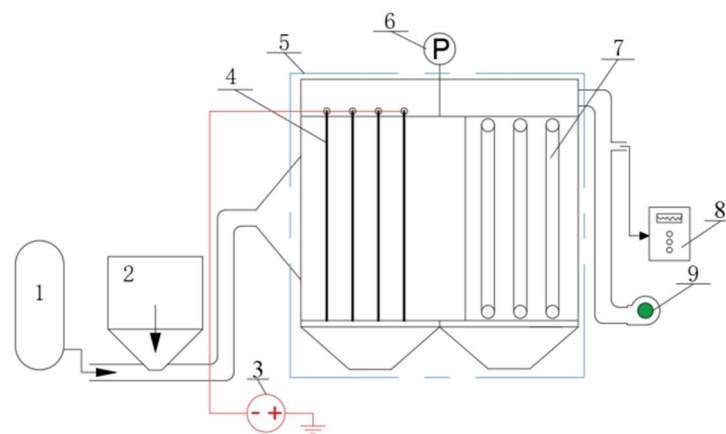


Figure 1. Schematic diagram of the experimental setup: 1. compressed air; 2. particle generator; 3. high-voltage power source; 4. discharge wires; 5. hybrid electrostatic precipitators; 6. pressure meter; 7. filter bag; 8. ELPI; 9. induced draft fan.

2.2. Filter Bags and Test Particles

The performances of three polyester-made filter bags produced using different surface treatment processes from China Pengbo Environmental Protection Equipment Co., Botou, China, were studied. Three types of filter bags were evaluated: anti-static filter bags, ordinary laminated filter bags, and anti-static laminated filter bags, hereafter referred to as filter bag 1, filter bag 2, and filter bag 3, respectively. Their SEM images are shown in Figure 2. The SEM magnification of filter bag 1 was $500\times$, while that of filter bags 2 and 3 was $2000\times$. It can be seen that filter bag 1 had relatively uniform fiber diameters, whereas filter bags 2 and 3 had many small nodules, possibly due to the laminating process. All three types of filter media had microscale diameters, which made them very effective in removing particles [12], and filter bags 2 and 3 had substantially smaller fiber diameters than filter bag 1. The thickness of each of the three filter bags was 1.8 mm. Parameters related to the three filter bags are listed in Table 1.

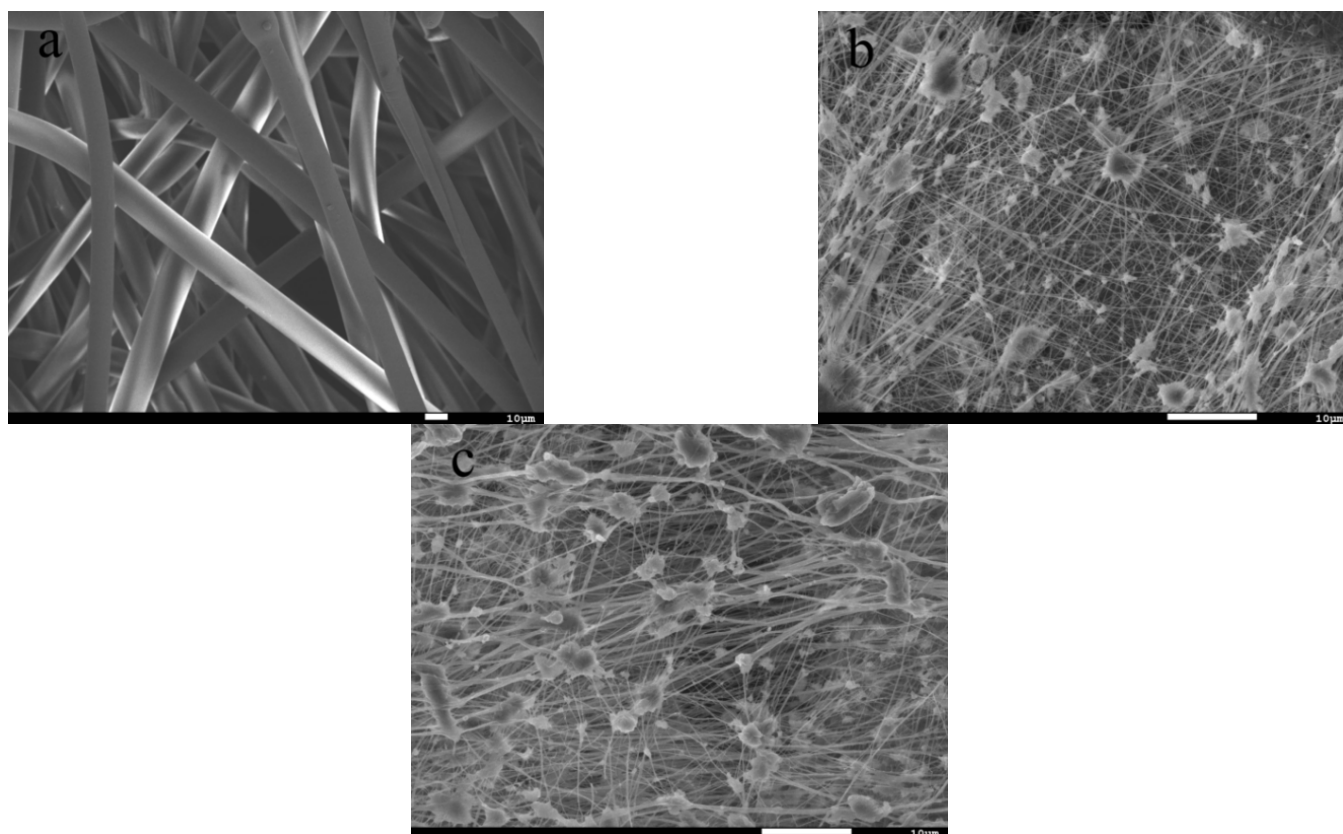


Figure 2. SEM micrographs of three types of filter bags: (a) filter bag 1; (b) filter bag 2; (c) filter bag 3.

Table 1. The testing parameters of the three filter bags.

	Material	Thickness (mm)	Fiber Diameter (μm)	Dielectric Constant	Surface Treatment Process
Filter bag 1	Polyester	1.8	14	1.20	Anti-static
Filter bag 2	Polyester	1.8	0.16	1.22	Ordinary laminated
Filter bag 3	Polyester	1.8	0.18	1.31	Anti-static laminated

The experimental particles used were fly ash particles with a bulk density of 1000 kg/m^3 from a coal-fired power plant in China. The inlet fly ash mass concentration measurement range of ELPI was narrow and was only for PM_{10} , and it needed to be combined with a laser particle size analyzer (Malvern Mastersizer 3000) to determine the overall inlet fly ash concentration mass distribution. The results are shown in Figure 3, with a more significant mass concentration in the range of $66.00\text{--}163.00 \mu\text{m}$; the trend was similar to the particle size distribution of fly ash. The particle size distribution can also be seen in Figure 3, revealing a bimodal distribution with a median particle size of $32.93 \mu\text{m}$. The particle size distribution was broad.

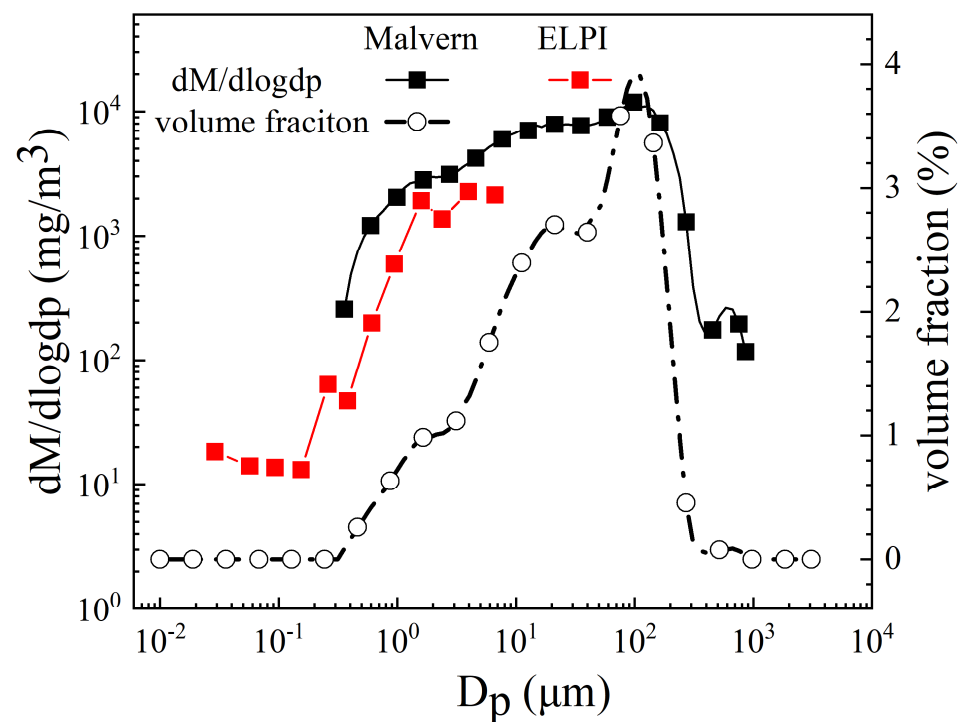


Figure 3. Fly ash particle mass concentration distribution at the dust collector's inlet and particle size distribution.

2.3. Experimental Conditions

The room temperature was maintained at 5–9 °C, and the room's relative humidity ranged from 20% to 23%. The velocity of the flue was 10 m/s at the dust collector's outlet, controlled by keeping the induced draft fan frequency consistent. The gas velocity was 0.56 m/s in the ESP and 1.85 m/min in the bag filter, as shown in Table 2. The performance of the three filter bags was determined in two experimental conditions: (1) bag filter (with uncharged electrodes); (2) hybrid electrostatic precipitators (with charged electrodes and an applied voltage of −16 kV).

Table 2. The experimental conditions.

Room Temperature (°C)	Humidity (%)	Particle Concentration (g/m³)	Flow Rate (m³/h)	Filtration Velocity	
				Gas Velocity inside ESP (m/s)	Filtration Velocity of Bag Filter (m/min)
5–9	20–30	16.00 ± 0.80	407	0.57	1.85

3. Results and Discussion

3.1. Dust Removal Performance

Figure 4a depicts the particle mass concentration distribution of fly ash at the outlet of the dust collector. The results show that the variation curves for particle mass concentration distribution under various experimental conditions were comparable. The maximum values were within the particle size range of 1.00–3.97 μm, mainly because the mass concentration distribution at the inlet was higher. For both bag filters (the electrodes were not charged) and hybrid electrostatic precipitators (the electrodes were charged), filter bag 3 had the lowest outlet mass concentration of particulates, with essentially little or no difference when using filter bags 1 and 2. In addition, the particle mass concentration distribution of a large particle size range was substantially smaller in hybrid electrostatic precipitators than in the bag filter. Thus, charged particles could effectively reduce the fly ash outlet concentration.

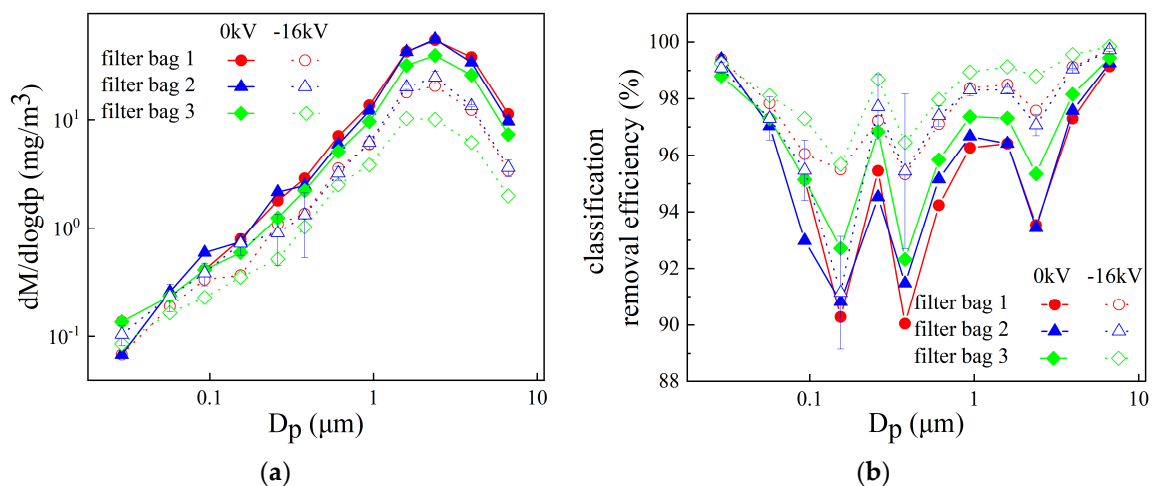


Figure 4. Classified dust removal performance of the dust collectors: (a) classified particle mass concentration; (b) classification removal efficiency.

Figure 4b presents the classification removal efficiency of bag filter (uncharged electrodes) and the hybrid electrostatic precipitators (charged electrodes) with various filter bags. It was observed that all three types of filter bags had the same penetration windows for particulates under different experimental conditions, $0.09\text{--}0.26\text{ }\mu\text{m}$, $0.26\text{--}0.61\text{ }\mu\text{m}$, and $1.59\text{--}3.97\text{ }\mu\text{m}$, respectively. However, the penetration window of hybrid electrostatic precipitators with filter bag 3 in the range of $1.59\text{--}3.97\text{ }\mu\text{m}$ was not readily apparent. As particle size increased beyond $1.00\text{ }\mu\text{m}$, the removal efficiency of hybrid electrostatic precipitators and bag filters with filter bag 1 and filter bag 2 varied little. The hybrid electrostatic precipitators with filter bag 1, filter bag 2, and filter bag 3 were superior to bag filters in terms of the classification removal efficiency, which improved by 4.40%, 3.90%, and 4.46%, respectively, in the penetration window of $1.59\text{--}3.97\text{ }\mu\text{m}$.

Figure 5a depicts the total dust concentration at the outlet of dust collector with various filter bags. The bag filter or the hybrid electrostatic precipitators with filter bag 3 had a lower outlet particle concentration than the other two filter bags. Moreover, the total particle concentration at the outlet of a bag filter with filter bag 2 was lower than that of a bag filter with filter bag 1. In contrast, the corresponding experimental results were the opposite for hybrid electrostatic precipitators. The total particle concentrations at the outlet of hybrid electrostatic precipitators with different filter bags were reduced by $22.03\text{ mg}/\text{m}^3$, $19.67\text{ mg}/\text{m}^3$, and $18.01\text{ mg}/\text{m}^3$, respectively, when compared to bag filters with filter bags 1, 2, and 3.

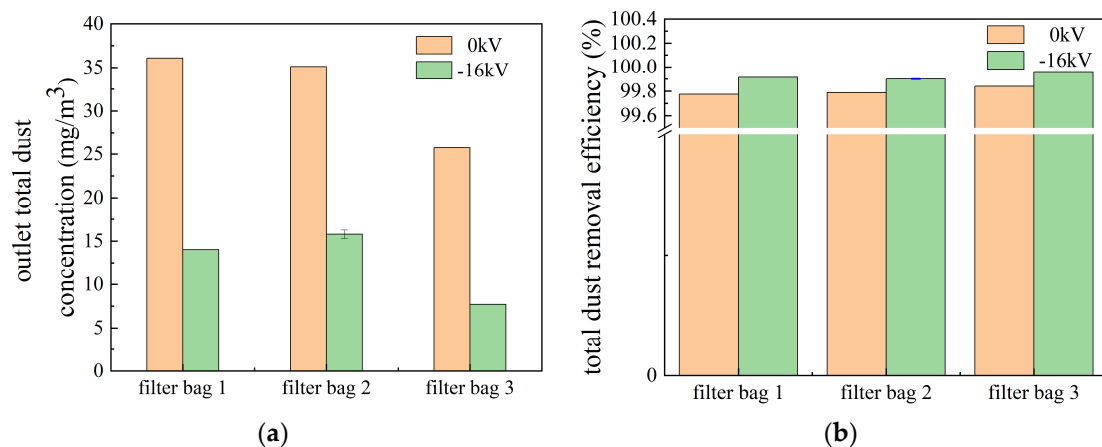


Figure 5. Total dust removal performance of the dust collectors: (a) total dust concentration; (b) dust removal efficiency.

Figure 5b presents the dust removal efficiency of dust collectors with various filter bags. The hybrid electrostatic precipitators with filter bag 3 had higher efficiency than those with the other two filter bags. The total dust removal efficiency of the bag filter with filter bag 1 was higher than that of the bag filter with filter bag 2. Nevertheless, the corresponding experimental results for hybrid electrostatic precipitators were the opposite due to different surface treatment process. The dust removal performance of hybrid electrostatic precipitators was significantly superior to that of bag filters. Compared to bag filters, the overall dust removal efficiencies of hybrid electrostatic precipitators with filter bag 1, filter bag 2, and filter bag 3 were increased by 0.14%, 0.11%, and 0.11%, respectively. Moreover, the dust collectors' total dust removal efficiency with various filter bags exceeded 99%.

In summary, the hybrid electrostatic precipitators were significantly more effective than the bag filter in terms of dust removal performance. This is because charged particles caused the electric field of the filter medium to develop, thereby increasing the filtration efficiency [21]. The dust removal performance of filter bag 3 was superior to that of the other two filter bags, due to its relatively small fiber diameter and relatively large dielectric constant [8,18,24,25]. Moreover, the surface treatment process of filter bag 3 was the organic combination of filter bag 1 and filter bag 2, revealing the better dust removal performance of the filter bag after anti-static lamination treatment.

Figure 6 presents SEM micrographs of the front and sides of different filter bags. The fly ash accumulation of filter bags was different due to surface treatment processes, and the surface and internal fly ash accumulation of filter bag 2 and filter bag 3 was greater than that of filter bag 1, because of the laminated treatment, relatively small fiber diameter, and relatively large dielectric constant. Moreover, filter bag 3 was subjected to anti-static treatment in addition to the ordinary laminated treatment of filter bag 2, and it had better dust removal performance. In summary, the fiber size, structure, and dielectric constant played an important role in the dust removal performance of filter bags, as did the anti-static laminated treatment process.

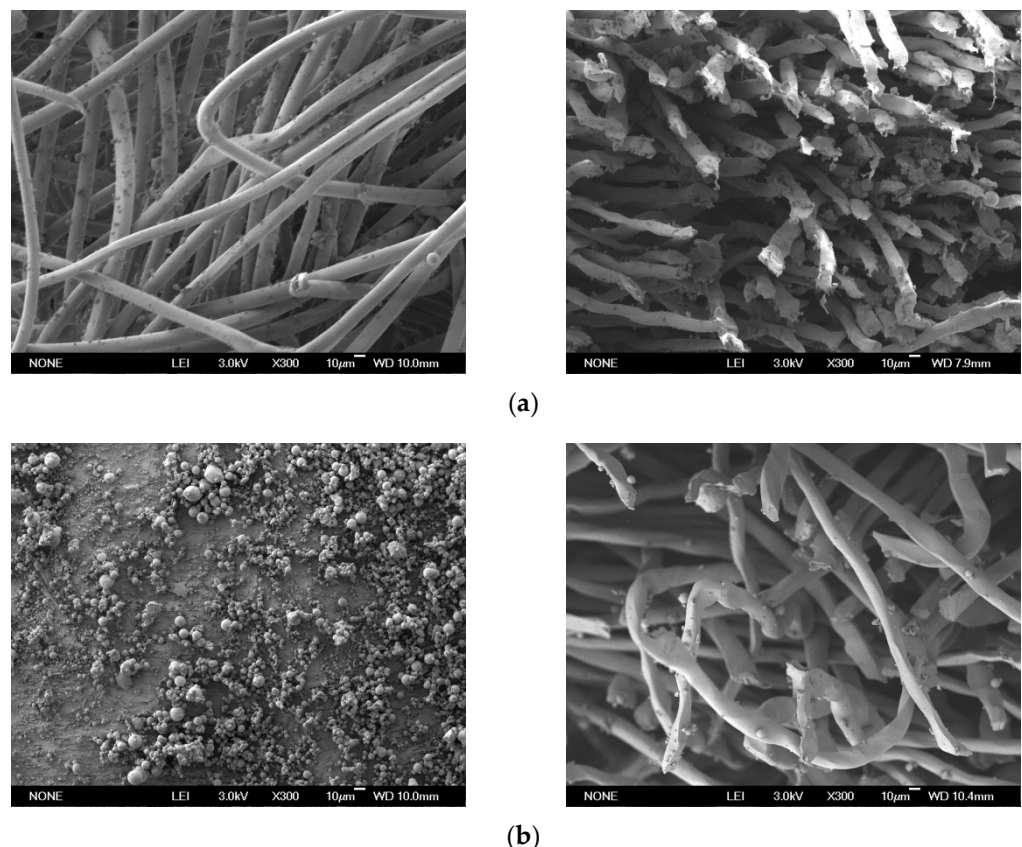


Figure 6. Cont.

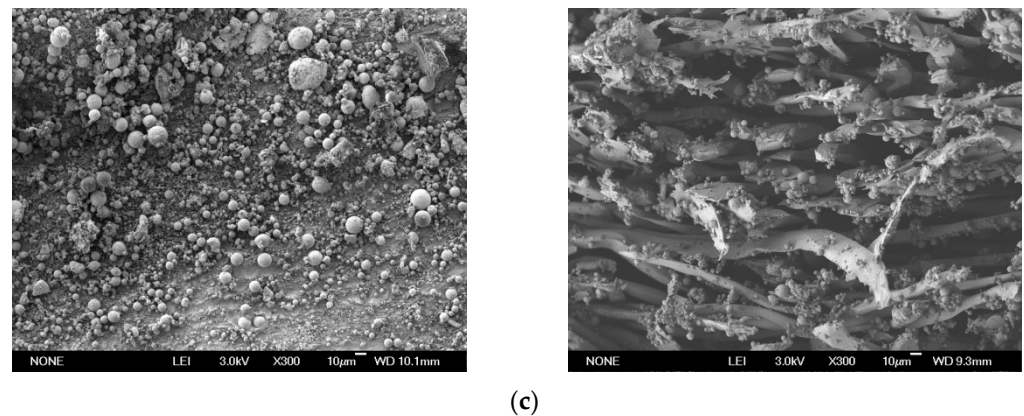


Figure 6. SEM micrographs of three types of filter bags after the experiment: (a) filter bag 1; (b) filter bag 2; (c) filter bag 3.

3.2. Running Conditions

The variation of dust collectors' pressure drop, measured in real time using a wireless mini pressure drop sensor (testo 510i) and the testo smart probes app, is shown in Figure 7. The pressure drop of the dust collectors with different filter bags increased sharply at the beginning of the experiment. It then increased relatively slowly in a linear trend as the investigation progressed over 10 min. The pressure drop of the hybrid electrostatic precipitators increased much more slowly than that of the bag filters, because the larger particles were precipitated in the electrostatic precipitator stage, and the fly ash entering the bag area decreased. In addition, the deposit built from charged particles is a porous dendrite-like structure [27,29]. Therefore, charged particles could efficiently reduce the total dust concentration at the outlet of dust collectors with a minor increase in pressure drop. The cleaning cycle for the dust collector was extended, suitable for long-term operation. The difference between the final and initial pressure drops for hybrid electrostatic precipitators with filter bags 1, 2, and 3 was reduced by 166 Pa, 274 Pa, and 246 Pa, respectively, as compared to bag filters.

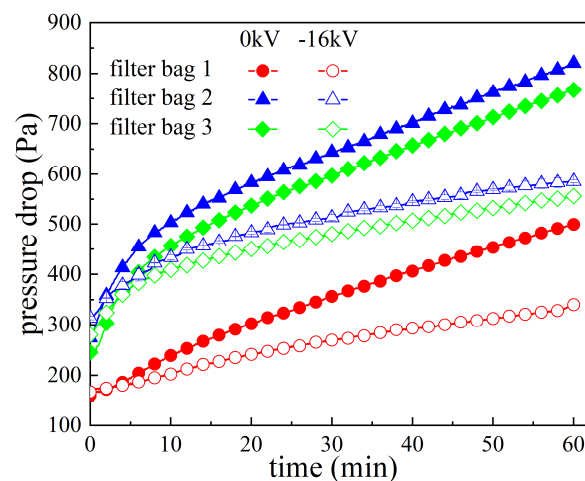


Figure 7. Variation in pressure drop for dust collectors with different filter bags.

Since the starting pressure drop of dust collectors with different filter bags is inconsistent, some studies used theoretical calculations and models to analyze the cleaning cycle, the mass density of the cake, and the pressure drop of filter bag according to its coefficient [30,31]. Accordingly, we estimated the average pressure drop variation per minute to evaluate the operating performance of dust collectors with various filter bags, as shown in Figure 8. The hybrid electrostatic precipitators with filter bag 3 had an average pressure

drop variation per minute of 4.60 Pa/min, which was more than that with filter bags 1 and 2. The bag filter with filter bag 2 had an average pressure drop variation per minute of 9.10 Pa/min, which was higher compared to filter bag 1 and filter bag 3. The average pressure drop variation per minute of bag filters and hybrid electrostatic precipitators with filter bag 1 was small, at 5.65 Pa/min and 2.88 Pa/min, respectively. Overall, the operational performance of hybrid electrostatic precipitators was superior to that of bag filters. The average pressure drop variation per minute of filter bag 1 was smaller than that of the other two filter bags. This is because the filter bag with a smaller average fiber size has higher resistance [8], and filter bag 1 had a bigger fiber diameter than the other two filter bags.

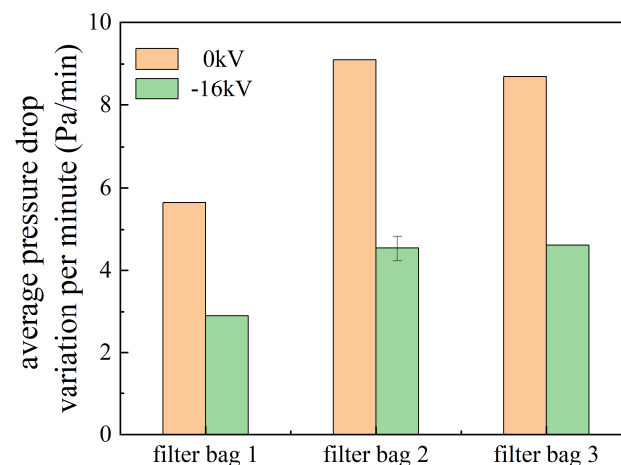


Figure 8. Dust collectors' average pressure drop variation per minute with different filter bags.

Figure 9 illustrates the variation in current for hybrid electrostatic precipitators with various fiber bags. The measurement was derived according to the high DC voltage power. The current initially decreased rapidly before the rate slowed. The current measurements showed an overall decreasing trend, mainly because the fly ash adhered to the corona electrode and the dust collection plate, which increased the overall resistance. Moreover, the dust layer thickened over time, which could have also increased the overall resistance. The difference between the final and initial current values of the hybrid electrostatic precipitators with filter bags 1, 2, and 3 was 0.31 mA, 0.33 mA, and 0.27 mA, respectively.

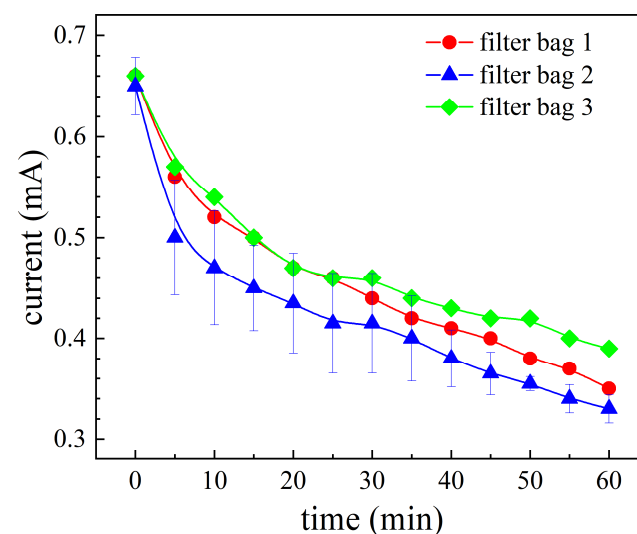


Figure 9. Variation in current of the hybrid electrostatic precipitators with different fiber bags.

3.3. Energy Consumption

For bag filters, the total energy consumption is represented by the bag pressure drop consumption; for hybrid electrostatic precipitators, it is the sum of the bag pressure drop consumption and the electrical energy. Equations (1) and (2) can be used to determine the energy consumption [32].

$$E_{charge} = UIt, \quad (1)$$

$$E = \Delta P(t) \cdot A_{filter} \cdot t, \quad (2)$$

where E_{charge} is the electrical energy, E is the bag pressure drop consumption, and U is the applied voltage (V). I is the experimental current (A), $\Delta P(t)$ is the pressure drop of the filter bag (Pa), A_{filter} is the filtration area (m^2), and t is the operating time (s). The experimentally applied voltage was -16 kV, and the total experiment time was 60 min.

Figure 10 depicts the total energy consumption of bag filters and hybrid electrostatic precipitators with three types of filter bags. The total energy consumption of the bag filter with filter bags 1, 2, and 3 was 0.043 kW·h, 0.077 kW·h, and 0.072 kW·h, respectively. The total energy consumption of the hybrid electrostatic precipitators with filter bags 1, 2, and 3 was 0.041 kW·h, 0.070 kW·h, and 0.066 kW·h, respectively. Moreover, the current of the hybrid electrostatic precipitators with filter 3 dropped slowly in the later stage and was slightly higher than that of other filters, and the total electrical energy consumption of the three bag filters was 0.0079 kW·h, 0.0077 kW·h, 0.0082 kW·h, respectively. The deviation between the value with filter 3 and that with filters 1 and 2 was 3.80% and 6.49%, indicating that the deviations were small and acceptable.

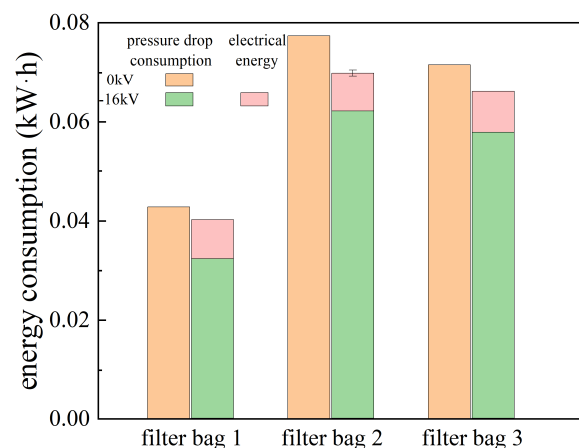


Figure 10. Comparison of energy consumption of three types of filter bags under different experimental conditions.

Both dust collectors equipped with filter bag 1 significantly reduced the total energy consumption compared to the other two filter bags. The hybrid electrostatic precipitators consumed less energy than the bag filters due to the removal of the front area electric field for particles, which reduced the number of particles entering the bag area. In addition, the porous structure of the charged particles deposited on the filter bag due to the inter-particle electric field force could further decrease the energy consumption of hybrid electrostatic precipitators. In terms of cycle life, hybrid electrostatic precipitators were superior to bag filters [33]. The bag pressure drop was the primary determinant of the total energy consumption of bag filters and hybrid electrostatic precipitators.

3.4. Comprehensive Evaluation

Different filter bags have different properties (such as pressure drop, fiber diameter, and dielectric constant) [22]; as a result, they perform differently. The quality factor (QF) is a parameter that combines pressure drop and dust removal efficiency, which can be used to comprehensively evaluate the dust collectors with different filter bags. As the QF increases,

the overall performance of the dust collector improves. QF is calculated using the following equation [22,34]:

$$QF = \frac{-Ln(1 - E_T)}{\Delta P Q / \eta + UI'} \quad (3)$$

where QF is the quality factor, E_T is the particle collection efficiency of the dust collector, ΔP is the pressure drop of the filter bag (Pa), Q is flue gas flow rate (m^3/s), and η is the efficiency of the fan.

Figure 11 shows the quality factors of the three distinct types of filter bags under different experimental conditions. Both dust collectors with filter bag 1 had a higher quality factor than those with filter bags 2 and 3 due to the much lower pressure drop increase per minute, total energy consumption, and marginally smaller difference in total dust removal efficiency among the three filter bag types. The quality factor of hybrid electrostatic precipitators with different filter bags was significantly higher than that of bag filters. Despite the electric energy consumption, the outlet total dust concentration and dust removal efficiency of the hybrid electrostatic precipitators demonstrated a noticeable improvement, resulting in a higher quality factor. The filter bag selection for the dust collector can vary on the basis of practical requirements. The dust collector with filter bag 1 had a lower pressure drop and total energy consumption but a higher outlet particulate mass concentration and a lower dust removal efficiency. In contrast, the dust collector with filter bag 3 had a lower outlet particulate mass concentration, a higher dust removal efficiency, and a higher pressure drop and total energy consumption.

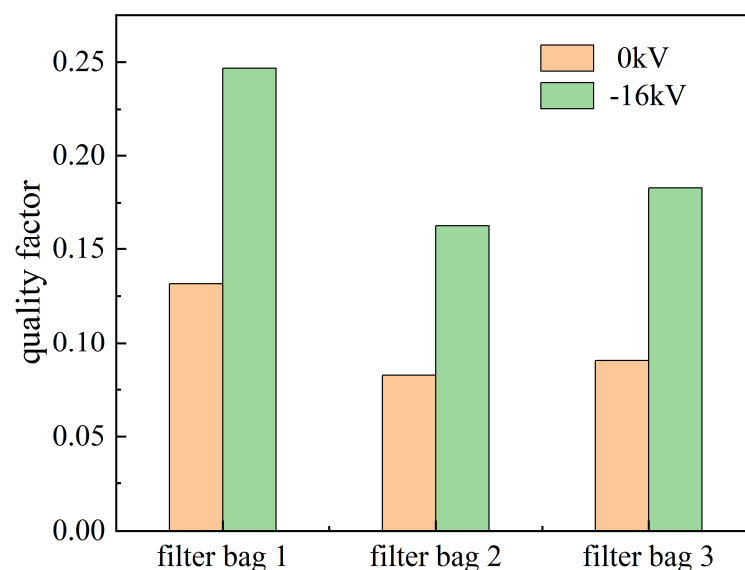


Figure 11. The quality factor of different filter bags under different experimental conditions.

4. Conclusions

Using a coupling-reinforced electrostatic–fabric integrated precipitator experimental system, experiments were conducted to investigate the performance (dust removal performance, operating conditions, and energy consumption) of bag filters and hybrid electrostatic precipitators with different filter bags produced using different surface treatment processes (anti-static filter bags, ordinary laminated filter bags, and anti-static laminated filter bags). Furthermore, the quality factor was used to comprehensively evaluate the overall performance of the filter bags under various experimental conditions. The conclusions of the study are as follows:

- (1) The selection of filter bags for dust collectors was influenced by various practical considerations. The dust removal efficiencies were highest for filter bag 3. The pressure drop and energy consumption were the lowest for filter bag 1. Regarding

the quality factor, the dust collectors with filter bag 1 performed the best; hence, the overall performance of filter bag 1 was likely the best. In addition, the removal performance of filter bags with smaller fiber diameters was better, despite the pressure drop and elevated energy consumption, because of the higher filtration resistance.

- (2) Due to electrostatic force, the hybrid electrostatic precipitators with different filter bags were superior to the bag filters in terms of dust removal performance, long cycle operation, and energy consumption. Their quality factor was significantly higher than that of bag filters. The total particle concentrations at the outlet of the hybrid electrostatic precipitators with different filter bags were reduced by 2.03 mg/m³, 19.67 mg/m³, and 18.01 mg/m³, and the dust removal efficiencies were increased by 0.14%, 0.11%, and 0.11%, respectively.

Research is in progress on the theoretical calculation model of dust collector efficiency, and the experimental data will be used to verify the accuracy of the model.

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