

Article

Innovative Electrostatic Precipitator Solutions for Efficient Removal of Fine Particulate Matter: Enhancing Performance and Energy Efficiency

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Abstract: The removal of particulate matter (PM) from air streams is essential for advancing environmental technologies and safeguarding public health. This study explores the performance of an electrostatic precipitator (ESP) in eliminating fine and ultra-fine PM under varied experimental conditions. It uniquely examines the influence of PM size and feed rate on ESP removal efficiency. The system's use of low voltages enhances energy sustainability, while its innovative design improves corona discharge, leading to significant reductions in fine and ultra-fine PM emissions. Plants using electrical devices are increasingly being incorporated into material processing lines to reduce pollution in the surrounding work area, as well as to collect particle emissions in the atmosphere. It is also possible to recycle some raw materials in this way with low energy consumption. This cleaning technology increases the added value of industrial equipment, which affects its competitiveness and its impact on sustainable manufacturing. The experimental results indicate a steady electrostatic field voltage of 15.1 kilovolts, with an airflow maintained at 0.8 m/s through a doser at 2.5 bar, eliminating the need for a fan. The PM feed rate varied between 2 and 20 mm/h, with six trials conducted to ensure the data were consistent. Preliminary studies devoid of ESP intervention demonstrated little PM removal, since buildup on the chamber walls distorted the results. The installation of the ESP markedly enhanced the removal efficiency, achieving up to 95.5%. Further analysis revealed that ESP performance depended on PM concentration in the agglomeration chamber, achieving a clearance rate exceeding 98% under optimal conditions. Fine PM (0.35 to 8.7 µm) was more efficiently removed than ultra-fine PM (0.2 to 0.35 µm). The highest removal efficiency was observed at a feed rate of 0.962 mg/s, while the lowest occurred at 0.385 mg/s. A strong positive correlation between particle concentration and removal efficiency (Pearson value up to 0.829) was observed, particularly at feed rates of 0.128, 0.641, and 1.283 mg/s. The study's findings confirm that the ESP is highly effective in removing particulate matter, particularly fine and ultra-fine particles, with an optimal feed rate, significantly enhancing the system's performance.

Keywords: electrostatic precipitator; tooth-shaped spike; fine and ultra-fine particulate matter; air filtration; feed rate



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1. Introduction

Considering the declaration made by the Ministers of the European Region of the World Health Organisation (WHO) regarding the health risks posed by environmental factors [1,2], it is evident that there is a need to conduct extensive research and advance

sustainable technologies to mitigate air pollution [3,4]. Cyclones are a kind of device that may efficiently eliminate particulate matter from air streams in industrial and urban settings [5,6]. Conducting research in this field is crucial for the development and enhancement of sustainable air purification methods that align with the objectives outlined in the WHO declarations [7]. These objectives include guaranteeing the right to a clean, healthy, and sustainable environment, lessening the impact of diseases, and enhancing global public health [8].

Sustainability is crucial in attaining enduring and efficient resolutions to environmental issues [9]. The objective of developing sustainable technologies, such as cyclones, is twofold: to diminish air pollution and to guarantee their economic viability, ecological efficiency, and durability [10]. By engaging in sustainable research, we may create technologies that minimise environmental harm, save resources, and foster a circular economy [11]. Furthermore, these programmes align with the Sustainable Development Goals, established by the WHO and the United Nations (UN), which prioritise the significance of a robust and sustainable environment for the overall welfare and health of the people. By incorporating the concepts of sustainability, scientific research aims to attain enduring and all-encompassing advantageous outcomes [12].

In the field of material processing, technologies for maintaining the necessary environmental quality during the processes are increasingly applicable [13], both to avoid negative conditions for the health of workers and to prolong the operation of the equipment to avoid various impurities and clots, and thereby increase energy consumption, the loss of products, and the wear and tear of technical components [14,15]. The most widespread are the equipment used for handling bulk substances, which can include raw materials for food, the construction industry, medicines, and other sectors of production. Therefore, environmentally friendly processing lines have great prospects for development and application in various spheres, and the use of steady electrostatic field allows us to achieve a qualitative collection of solid particles, the characteristics of which significantly affect traces of pollution in the production of the final product.

The electrostatic precipitator (ESP) or filter is considered to be among the most efficient pieces of technology for the precipitation of particulate matter (PM), including the most harmful fine particles smaller than $1\text{ }\mu\text{m}$ [16–18]. Also, due to a sufficiently high throughput system in the working chamber of the technology, no pressure drops are created compared to other filters, such as HEPA, even at relatively high particle concentrations [19–22]. Such characteristics make electrostatic filters more acceptable in terms of sustainability [23–25]. Also, the regeneration of this principle of technology is carried out by simple pneumoimpulse methods and through the recovery of the raw material, as well as being used for liquid cleaning, but it is much more economical and environmentally friendly than the constant replacement of fibre filters or cartridges in known cleaning technologies [26,27].

By improving the ESP, results have been achieved in which the removal efficiency of PM of a wide enough range is indicated, among which are nanoparticles and various aerosols [28]. Consequently, this technology is applicable for the basic and precise purification of gas streams, and can also be used for the purification of indoor air and other spaces of human activity [29]. Due to the bactericidal effect of the electrostatic field on the gas stream, it is possible to carry out partial sterilisation, as well as electroporation to eliminate viruses, as well as experimentally, for example, using the positive potential for corona discharge, to achieve low concentrations of ozone, which also has a positive effect on the human body [30].

The shape of the electrode is given special attention in order to concentrate the energy of the discharge [16,31,32]. In [33], several planar electrodes with apertures and triangular plates in them were investigated. The results show that this design reduces the ion wind resistance and increases the charge transfer to the PM. It was also found that the symmetry of the edges helps to distribute the discharge voltage uniformly, and that the case where the triangular plates are oriented closer to the deposition electrode allows for the highest removal efficiency [34].

In the study [35], a tube-tip type deposition electrode was tested by varying the geometrical parameters. Numerical simulations showed that longer electrode lengths and more uniform electrode spacing lead to higher deposition efficiencies. It has also been shown that the bending angle of the deposition electrode wires has an influence on the deposition performance and can increase by 15% for a bending angle of $\alpha = 160^\circ$, while the energy loss and ozone generation remain similar.

One paper [36] tested an ESP for high gas flow rates in the duct, above 2 m/s, with relatively low pressure drops of up to 100 Pa. Polarising electrodes with a zigzag shape were used for this purpose. A folded fibre filter between the electrodes was used for additional pre-filtration. The angle of folding was found to change the nature of the steady electrostatic field, with the best results in terms of removal efficiency and energy loss being obtained at $0\text{--}45^\circ$ when PM up to $0.3\text{--}0.5\text{ }\mu\text{m}$ was deposited with up to 80% removal efficiency.

The electrostatic deposition system in combination with a combined agglomeration-precipitation technology was investigated in [37]. The influence of the sprayed sorbent prior to the agglomeration step on the particle resistance was investigated. A unipolar electrostatic agglomerator was used for particle aggregation consisting of two discharge electrodes with spiked plates and two grids of vertically oriented rods. The electrostatic precipitator, meanwhile, consisted of ionisation electrodes with spiked rods mounted on the side walls and one deposition electrode in the axis of the unit. The removal efficiency of this system technology was up to 90% for PM of about $10\text{ }\mu\text{m}$ and about 60% for PM of $1\text{ }\mu\text{m}$.

An ESP system in the form of a “cup-shaped W-type” is investigated in [38]. The results show that such sub-tubular electrodes produce a more uniform space charge density on the collector surface than conventional flat electrodes. This type of design also has lower particle shedding, and the removal efficiency increases more rapidly with increasing voltage. A cup-shaped electrode discharges a higher number of ions or a steadier electrostatic field than a conventional tubular electrode. When a w-type electrode and a cup-type electrode are applied together, the ionisation and collection area is increased, resulting in a higher ESP removal efficiency.

All the work disclosed demonstrates the advantages of planar electrodes compared to tubular or wire electrodes. Also, it can be clearly seen that the ribbing of the electrode shape allows for the concentration of the electrical discharge, or in other words, a greater number of ions, which are able to affect the PM more strongly and more quickly, and to impart the right charge to them, thus improving the ESP removal efficiency. Also, electrodes with a larger surface area allow for a greater volumetric spread of charges in the channel to reach the PM, thus reducing their shedding without deposition [39–44].

The possibility of using an electrode that has a few more zones of high curvature at the same voltage as the ESP is the idea discussed in this paper. In addition to this, we discuss the feasibility of using a different plane to increase the active surface area. The positive results of the removal efficiency of this electrode design provide a basis for further more in-depth studies of limited voltage values and the effect on particulate matter. Also, one of the tasks is to analyse the efficiency of this electrode at different levels of gas flow; therefore, the particulate matter feed modes were taken as a variable parameter. In addition, the improved design of the electrode has a higher rigidity and a degree of resistance to external forces, which can be a clear advantage in comparison with traditionally shaped electrodes. Thus, the equivalent removal efficiency level of the electrode studied in this paper with a traditional electrode has every reason to be an object of further analysis, for example, for the possibility of using these electrodes in high-pressure flows, etc.

The removal efficiency of an ESP depends on the discharge voltage generated at the ionising electrode. However, the concentration of the charge on the electrode surface and the transfer of the charge to the PM, which ultimately increases the deposition of the PM on the counter-potential deposition electrode, has a much greater influence. This also improves the energy efficiency of the filtration system, since the excess electric current is no longer used to generate a discharge voltage, and the increase in the area of the active surface for ionisation reduces the probability of particle precipitation [42,44–47]. The novelty of

this work lies in the use of newly developed specifically shaped ionisation electrodes for the filtration of the gas stream by the precipitation of fine PM. This electrode consists of tooth-shaped edges in two perpendicular planes, which are repeated along the length of the electrode. The height of the tooth edges, and thus the radius of curvature of the tooth-shaped elements, increases the charging of the most difficult to deposit smallest PM of 0.3–0.5 μm , and thus the removal efficiency of this PM in the electrostatic precipitator, since this shape allows for a higher concentration of charge on the tip of each edge of the tooth. Also, the two perpendicular planes allow a larger volume to be covered in the precipitator channel, so that the probability of particle trapping for the charge transfer is higher compared to other shaped electrodes. This system allows a lower voltage to be applied to generate a proper discharge, which significantly reduces energy losses and reduces the emission of fine PM more efficiently.

2. Methods and Methodology

The experimental bench (Figure 1) consists of a vertical pipe with a top feeding the PM and a reproducible generator of aerosol for solid particles, unit Palas RGB 1000 (Palas, Germany), to generate the adjustable mass flow of the test aerosols. An ESP is installed at the bottom at the outlet of the PM.

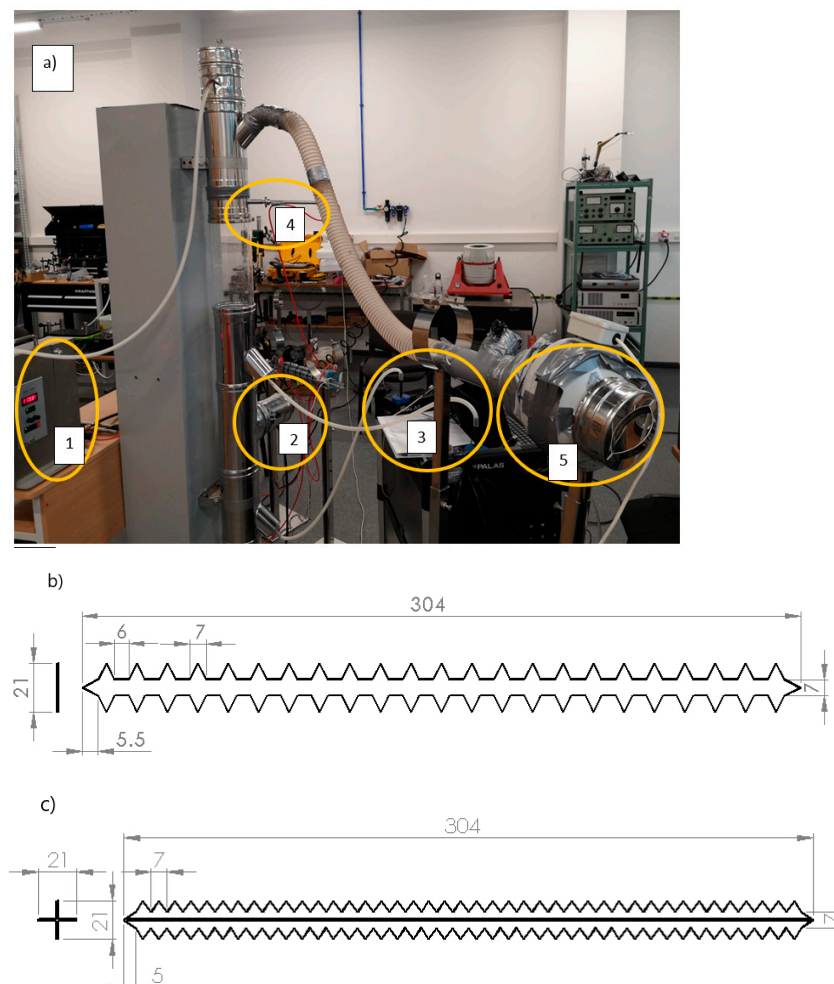


Figure 1. View of the experimental bench for the study of fine and ultra-fine PM in the ESP (a): 1—Palas RGB 1000 particulate dosimeter; 2—electrostatic precipitator with a control unit (view of the electrode used in this study is shown in part (b) of the figure); a typical electrode as comparable (c); 3—Welas digital 3000 fine particle number measuring equipment; 4—MKA880 flow velocity meter; 5—ventilator.

The electrode used in this study differs from a typical electrode (shown in Figure 1c) in its geometry, in which the number of spikes has been increased from 48 to 170, i.e., 3.54 times. In addition, the new electrode consists of 2 planes connected in a plus shape, which makes the electrode structure more rigid, preventing the electrode from entering resonance caused by the ion wind. Such an electrode design has not been found in the reviewed literature.

The flow velocity is measured by an air velocity meter, MKA880 (Newsigar, China), with an output signal of 4–20 mA/0–5 V/0–10 V/RS485, a measuring range of 0.1 to 30 m/s, and an error of no more than FS 0.02%. The air velocity meter is positioned downstream of the air flow inlet. The PM measuring equipment Welas digital 3000 H (Palas, Germany) is installed before and after the ESP.

A vertical tube was constructed for the experimental setup, which included a PM (known as a particle classifier) and an RBG 1000 (Palas, Germany) (a device used for low-concentration solid particle aerosols produced from powders and for injecting a gas flow as an imitated source of emission) at the top. This arrangement was used to provide a controlled flow. The ESP was positioned at the lowermost part of the tube. The air velocity was quantified via an MKA880 air flow meter, which boasts a precision of FS 0.02%. The concentrations of PM were quantified using the Welas digital 3000 H instrument both before and after using the ESP. The removal efficiency of the technology was studied based on the concentration of particulate matter. The mass concentration was only used to determine the dosage, i.e., the number of particles delivered to the inlet air duct. Laser sensors were used in the pre- and post-cleaning sections to capture samples and quantify the particle size composition. The PM source consisted of quartz sand with a fraction size of up to 0.2 mm. A detailed grain composition of the tested particulate matter is presented in Table 1. The overall density of the sample was 2550 kg/m³, and the bulk density was 1500 kg/m³. Both silica and silica sand have a high resistivity, which makes the use of an ESP somewhat inefficient. However, at low relative humidity (7% to 11%), condensation occurs on the silica particles, and the use of ESP becomes effective. The resistivity of the particles of quartz powder is equal to $7 \times 10^8 \Omega \cdot \text{cm}$.

Table 1. Composition of the tested particulate matter.

PM diameter, μm	0.5	1	3	5	8	10
% under for full sample	1.1	5.1	19.5	29.7	39.2	44.6

For the tests, silica sand up to a fraction of 0.2 mm was used as a PM source. During the experiment, a constant ESP voltage of 15.1 kV was maintained. The tests were carried out at a constant air velocity of 0.8 m/s. The measurements were carried out at different particle concentrations. The PM concentration was varied by means of a metering device with particle feed modes of 2, 4, 6, 8, 10, 15, and 20 mm/h (corresponding to a silica sand feed per unit time (particle flow rate), it corresponds to 0.128 mg/s, 0.257 mg/s, 0.385 mg/s, 0.513 mg/s, 0.641 mg/s, 0.962 mg/s, and 1.283 mg/s). During the tests, particle concentrations were measured before and after the application of the electrostatic precipitator. Measurements before and after were recorded for 30 s each, with the sequences occurring consecutively. System flushing, including electrode cleaning, was performed before each test unless particulate matter was not introduced into the system (Figure 2). Six measurements were taken for each mode, and the average experimental values were taken for comparison. The Meteorological conditions in the laboratory during the tests were maintained, at 50–60% relative humidity and 18° C temperature.

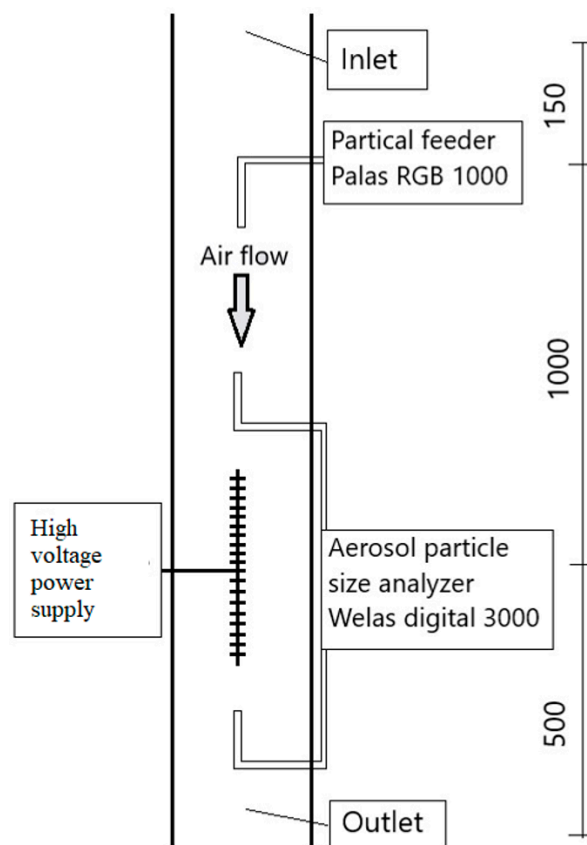


Figure 2. Diagram of the experimental stand.

The number of PM deposited on the walls of the experimental bench was not assessed, as it was negligible compared to the total particulate concentration [6].

Electrostatic precipitator design description

The electrostatic precipitator consists of two parts: a control unit with a high-voltage power supply and a precipitator unit. A stream of untreated air is supplied to the inlet of the precipitator unit. The control unit should contain a high-voltage power supply producing the 20 kV positive voltage current required to power the ionisation and deposition electrode, as well as the control and indication elements necessary for the operation of the unit. A single-base electrostatic precipitator was designed, in which a single electrode was used for ionisation and particulate deposition. The geometry and dimensions of the electrode should be chosen so that the residence time of the solid particle in the ionisation–deposition zone is sufficient to achieve a charge close to the threshold charge and deposit it on the outer surface of the deposition zone. The ionisation–deposition electrode is placed in the deposition unit parallel to the direction of air flow.

The control unit is connected to the deposition unit by a special 3 m long plastic sheathed non-removable cable. The control unit must be connected to the household power supply via a three-pin connector (with a separate ground contact).

If the filter control unit is connected to the 220VAC mains, the 24VDC power supply unit converts the 220VAC AC voltage into 24VDC DC voltage. In this way, the electrical circuits of the device are separated from the mains. The de-energising voltage of the power supply used is 4500 V. The power supply has a short-circuit protection of 1.9 A.

3. Results

Experimental bench measurements (Figure 3) indicate that the ESP is very efficient in eliminating PM from the air flow. However, the removal efficiency may vary under certain feed rate regimens. This research examined the effectiveness of ESP in utilising several

PM dose regimens to identify the most appropriate ESP performance regimen. The graph displays the PM removal efficiency data obtained from several dosage regimens, enabling a thorough evaluation of the efficacy of each regimen.

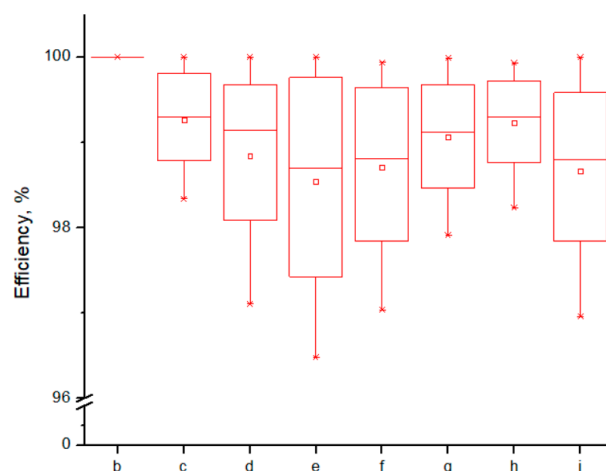


Figure 3. Dependence of the removal efficiency for PM from 0.35 μm to 9.3 μm for different system operations; b—with electrostatic precipitator switched on without the use of a doser; c–i with electrostatic precipitator switched on and with the use of a different particle flow rate from the doser. Special symbols: a mode as a square, a variance as a rectangle, a mediana as a line in the rectangle and limits of error bars as a star.

In the absence of particle feeding, the first mode (b) exhibits an ESP removal efficiency of almost 100% at a voltage of 15.1 kV. A value of the electric field intensity [48] is equal to 2.34 kV/cm at the spike of the electrode level and 2.32 kV/cm at the sub-root level.

This suggests that when air flow is optimised, the ESP has the ability to efficiently eliminate PM from the air flow. The mean removal efficiency value exhibited a very high level, but the variation remained low, suggesting a consistent and dependable performance with little oscillations in PM concentration.

The second mode (c), where the ESP was used with a dosage of 2 mm/h PM, exhibits a broader range of removal efficiency fluctuation. The removal efficiency spans from around 98.8% to 99.9%, suggesting a wider range of values and a few exceptional situations. The findings indicate that using low particle dosage rates might result in unpredictable outcomes, albeit the overall (all PM fractions) removal efficiency remains significantly high.

The third mode (d), using a 4 mm/h PM dosage, exhibited even higher dispersion, with removal efficiency values ranging from 98% to 99.8%. This mode also exhibited several instances of severe occurrences, which served as indications of instability in the particle removal process. However, the median value remained very high at around 99.2%, suggesting that a large proportion of the measurements had positive results.

The fourth regimen (e), with a dosage of 6 mm/h PM, had comparable outcomes to the other regimens. However, the variability in effectiveness was much more noticeable, ranging from a minimum of 97.2% to a maximum of 100%. The mean removal efficiency value was about 99.9%, with several exceptional instances displaying fluctuation in this concentration. The findings of this study validate that the stability of removal efficiency decreases as the rate of particle dosage rises.

The fifth regime (f), which used a feed rate of 0.513 mg/s PM, exhibited reduced dispersion compared to the preceding regimes, achieving an average removal efficiency value of around 98.8%. While there were a few instances below 97.9%, the findings indicate that the effectiveness of this dosage schedule is quite consistent. This implies that increasing the dosage of particles may slightly contribute to achieving more consistent outcomes in the elimination of PM.

The sixth mode (g), when administered with a dosage of 10 mm/h PM, exhibits a consistent removal efficiency of around 99.1%, characterised by little variability and a scarcity of exceptional instances. The findings of this study indicate that increasing the particle feed rate improves the stability of the ESP performance. Additionally, the removal efficiency values demonstrate that this particular regime is well-suited for maintaining steady PM removal activity.

The seventh mode (h), when administered with a dosage of 15 mm/h PM, exhibited a broader range of removal efficiency distribution, spanning from 98.9% to 99.8%. However, the average value consistently hovered around 99.4%. The high variation and several severe examples suggest that outcomes may be unpredictable at this concentration. However, the majority of the experiments yielded positive results, demonstrating the superior effectiveness of the ESP when exposed to greater particle dosage rates.

The eighth regime (i), which had a dosage of 20 mm/h PM, had the greatest variation compared to all other trials. The removal efficiency exhibits a broad distribution, with the mean value hovering around 99.7%. Instances when the value is below 97.9% are considered severe and suggest a significant level of volatility, while the overall removal efficiency remains high. This suggests that when PM is administered at very high rates, the efficacy of the ESP may vary, but it may still effectively remove a significant amount of PM.

The measurement results show that the concentrations of particles with and without ESF exposure can be divided into three groups (Figure 4): For particles with diameters between 0.2 and 0.35 μm , the first group; for particles with diameters between 0.35 and 8.7 μm , the second group; and for particles with diameters between 8.7 and 9.3 μm , the third group.

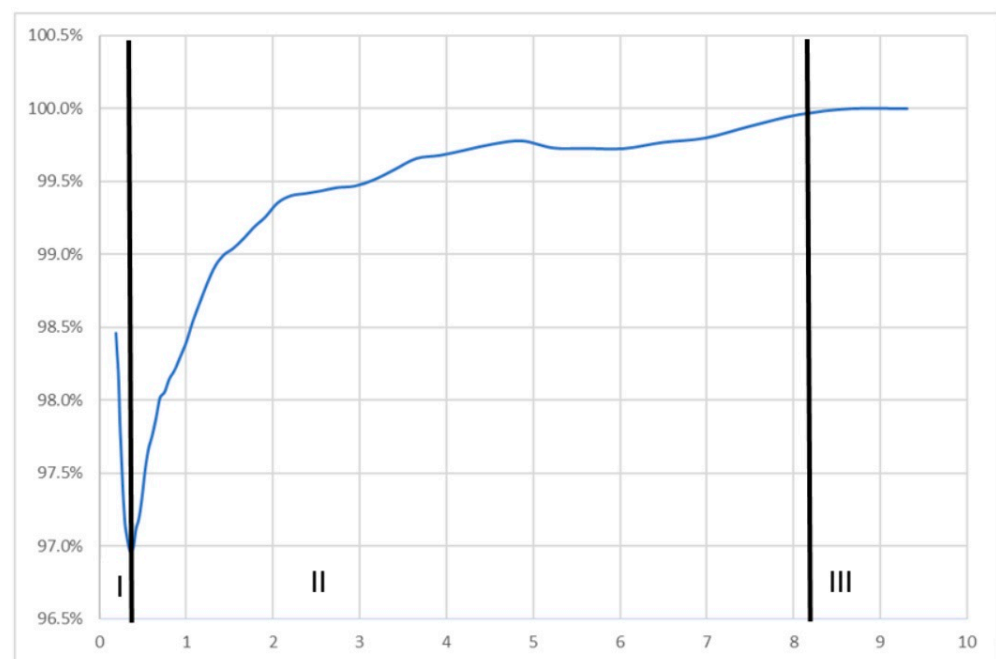


Figure 4. Particle removal efficiency curve at a feed rate of $3.08 \text{ cm}^3/\text{h}$ divided into three groups: group I from 0.2 to 0.35 μm , group II from 0.35 to 8.7 μm , and group III from 8.7 to 9.3 μm .

Table 2 displays the percentage decrease in the concentration of PM based on particle size and dosage schedule. This table presents a comprehensive assessment of the effectiveness of the ESP at different PM dose rates. The overall PM removal efficiency stays consistently high for all feed rate regimens, ranging from 98.69% to 99.35%. A maximum removal efficiency of 99.35% was attained when the dosage rate was 15 mm/h, while a minimum removal efficiency of 98.69% was observed at a feed rate of 0.385 g/s. This

implies that the effectiveness of ESP may vary according on the dosage schedule, but it remains very high.

Table 2. Percent reduction in particulate concentration by diameter.

PM Diameter μm /Feed mm/h	2	4	6	8	10	15	20
Overall removal efficiency	99.33	98.93	98.69	98.94	99.23	99.35	98.84
Removal efficiency when the diameter of PM is up to 0.35 μm	98.6	97.68	97.29	97.83	98.53	98.72	97.66
Removal efficiency when PM diameter ranges from 0.35 to 8.7 μm	99.4	99.1	98.79	98.89	99.17	99.34	98.86
Removal efficiency when PM diameter ranges from 8.7 to 9.3 μm	100	100	100	100	100	100	100

Table 2 categorises PM sizes into three groups: less than 0.35 μm , between 0.35 and 8.7 μm , and between 8.7 and 9.3 μm . The efficacy of each group is also contingent upon the prescribed feeding schedule. The effectiveness for PM with a size of up to 0.35 μm varies between 97.29% (at a feed rate of 0.385 mg/s) and 98.72% (at a feed rate of 0.962 mg/s). The lowest removal efficiency (97.29%) suggests that smallest PM provides a somewhat greater challenge to remove at medium dosage rates. The best effectiveness, which reached 98.72%, was seen when the dosage rate was set at 15 mm/h. This indicates that adjusting the feed rate to an ideal level may significantly enhance the removal of fine and ultra-fine PM.

The effectiveness of PM ranging from 0.35 to 8.7 μm in this group is high, with a range of 98.79% (at a feed rate of 0.385 mg/s) to 99.4% (at a feed rate of 0.128 mg/s). The removal efficiency of 98.79% suggests that the feed rate may have some detrimental impact on the removal of PM of this particular size. The optimal removal efficiency of 99.4% is achieved at a feed rate of 0.128 mg/s, suggesting that reducing the dosage rate may enhance the removal of PM of this size.

The removal efficiency of PM ranging from 8.7 to 9.3 μm is at its highest in this group, achieving a maximum of 100% in all feed rate modes. The findings demonstrate that ESP is efficient in eliminating fine PM, irrespective of the dosage rate. Given the limited amount of PM in this category compared to the overall PM concentration, it is not unexpected that it is effectively removed.

Consistent findings were documented in the research conducted by other writers. For instance, the study conducted by Badran and Mansour [49] demonstrates that electrostatic precipitators are very efficient in eliminating upper fraction of fine PM (>1 μm), typically obtaining a level of effectiveness between 99% and 100%. The smallest fine PM and ultra-fine PM, particularly with a diameter less than 0.3 μm , may be eliminated with somewhat reduced effectiveness. However, the overall removal efficiency remains quite high, often ranging between 97% and 98%. The investigations conducted by Jena et al. [50] yielded comparable findings, indicating that both particle size and concentration have an impact on precipitator performance. However, it is worth noting that the overall removal efficiency stays consistently over 98%.

The results demonstrate that the ESP exhibits a very high removal efficiency throughout all PM dosage regimens. However, it is worth noting that the removal efficiency outcomes may differ in certain regimes. The maximum removal efficiency was attained with a feed rate of 0.962 mg/s, while the lowest removal efficiency was seen at a dosage rate of 6 mm/h. The removal efficiency of ESP for ultra-fine PM is somewhat decreased compared to fine PM; however, the overall removal efficiency remains very high. These results corroborate the conclusions of previous research conducted by other authors, which demonstrate that ESP is a very successful approach for eradicating PM, particularly when the most suitable dosage schedule is used.

Figure 5 illustrates the efficacy of an ESP in eliminating PM with sizes ranging from 0 to 0.35 μm , using different feed rate methods. Upon analysing each mode, it becomes

evident that the removal efficiency and stability exhibit variations that are contingent upon the particle feed rate.

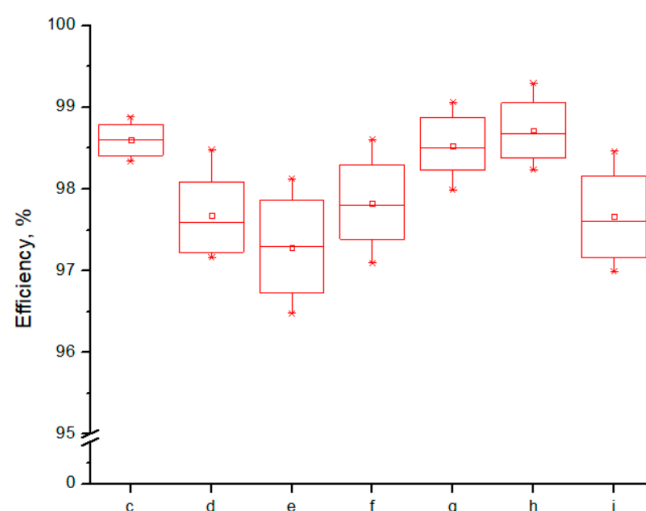


Figure 5. Removal efficiency dependence for PM smaller than $0.35\ \mu\text{m}$ for different system operations; c–i with the electrostatic precipitator switched on and with different particle fluxes from the doser. Special symbols: a mode as a square, a variance as a rectangle, a mediana as a line in the rectangle and limits of error bars as a star.

The removal efficiency in mode “c” (15.1 kV, 2 mm/h) is very high, ranging around 98.5%. The average removal efficiency value is almost 98.6%, as shown by a tightly clustered boxplot that demonstrates little variation in the data. A limited number of exceptional instances falling below 98.4% indicate that the outcomes are very consistent and dependable.

Under the “d” mode, which operates at a voltage of 15.1 kilovolts and a precipitation rate of 4 millimetres per hour, the removal efficiency experiences a reduction and fluctuates between about 96.5% and 99%. The mean removal efficiency number is almost 98%, but there is a wider range of values and more severe situations, suggesting a higher level of volatility in the findings. This setting indicates that higher particle feed rate may diminish the effectiveness of the ESP for ultra-fine PM.

When operating in mode “e” with a voltage of 15.1 kV and a precipitation rate of 6 mm/h, the removal efficiency experiences a further decrease, varying between about 96% and 99%. The mean removal efficiency rating is around 97.5%, exhibiting a large interquartile range and several outliers. At a feed rate of 0.385 mg/s, the findings indicate a decrease in ESP effectiveness and an increase in the variability of the results.

When operating in mode “f” with a voltage of 15.1 kV and a precipitation rate of 8 mm/h, the removal efficiency experiences a little rise, varying between about 97% and 99%. The mean removal efficiency score is around 98%, with a smaller range than the prior regime, indicating less variability and fewer instances of extreme occurrences. This mode demonstrates that increasing the feed rate may enhance the stability of the ESP’s function.

Under the “g” mode, which operates at 15.1 kilovolts and 10 millimetres per hour, the removal efficiency consistently stays within a high range of around 97.5% to 99%. The mean removal efficiency score is around 98%, exhibiting less variability and fewer outliers. According to the findings, when the dose is 10 mm/h, the ESP performs consistently and effectively.

When operating in mode “h” with a voltage of 15.1 kV and a precipitation rate of 15 mm/h, the removal efficiency is very high, ranging from around 97.5% to almost 100%. The mean removal efficiency score is around 99%, with a small range and little instances of extreme values, suggesting low variability. At a dose of 15 mm/h, this mode demonstrates the highest and consistently steady ESP removal efficiency.

Under the “i” mode (15.1 kV, 20 mm/h), the removal efficiency experiences a reduction and varies between about 96% and 99%. The mean removal efficiency value is around 98%; however, there is a wider range of values and more instances of severe situations. The findings indicate that administering very large doses may diminish the effectiveness of ESPs in capturing fine and ultra-fine PM.

Figure 6 illustrates the efficacy of an ESP in eliminating PM with sizes ranging from 0.35 to 8.7 μm , using different feed rate methods. Upon analysing each mode, it becomes evident that the removal efficiency and stability exhibit variations based on the particle feed rate.

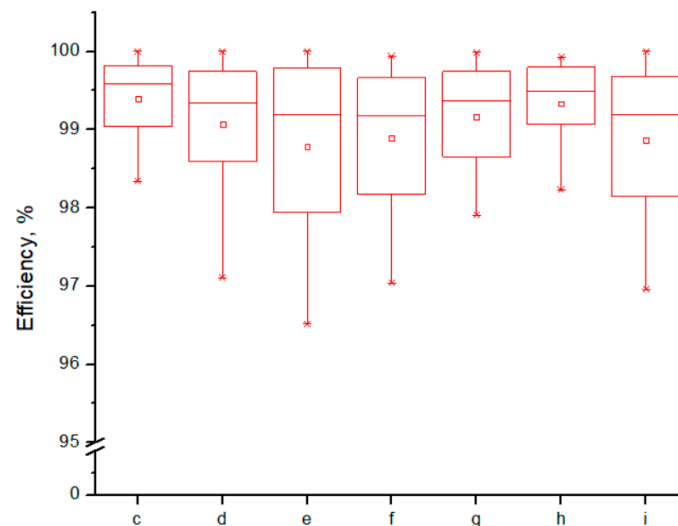


Figure 6. Dependence of the removal efficiency for PM from 0.35 μm to 8.7 μm for different system operations; c–i with the electrostatic precipitator switched on and with the use of a different particle flow rate from the doser. Special symbols: a mode as a square, a variance as a rectangle, a mediana as a line in the rectangle and limits of error bars as a star.

The removal efficiency in mode “c” (15.1 kV, 2 mm/h) is very high, ranging from around 98% to almost 100%. The mean removal efficiency value is around 99.4%, and the data exhibits little variation, as shown by a narrow boxplot. A limited number of exceptional instances falling below 98% demonstrates the high level of stability and dependability of the outcomes.

Under the “d” mode (15.1 kV, 4 mm/h), there is a little decrease in removal efficiency, which varies between about 97% and almost 100%. The mean removal efficiency number is around 99.1%, but there is a wider range of values and more severe situations, suggesting a higher level of volatility in the findings. This mode demonstrates that higher particle feed rate may decrease ESP removal efficiency while still maintaining a very high level.

When operating in mode “e” with a voltage of 15.1 kV and a precipitation rate of 6 mm/h, the removal efficiency experiences a further decline, varying between approximately 96% and 100%. The mean removal efficiency rating is around 98.79%, characterised by a large interquartile range and several outliers. At a feed rate of 0.385 mg/s, the ESP effectiveness is reduced, and the results are less consistent.

When operating in mode “f” with a voltage of 15.1 kV and a precipitation rate of 8 mm/h, the removal efficiency experiences a modest rise, ranging from around 97% to 99.5%. The mean removal efficiency score is around 98.89%, with a smaller range compared to the prior regime, indicating less variability and fewer instances of extreme occurrences. This mode demonstrates that increasing the feed rate may enhance the stability of the ESP’s function.

When operating in mode “g” with a voltage of 15.1 kV and a precipitation rate of 10 mm/h, the removal efficiency consistently remains at a high level, ranging from around 97.5% to almost 100%. The mean removal efficiency value is around 99.17%, exhibiting

lower variability and fewer instances of extreme values. According to the findings, when the dose is 10 mm/h, the ESP performs consistently and effectively.

The removal efficiency in mode “h” (15.1 kV, 15 mm/h) has a very wide range, often spanning from around 97.5% to almost 100%. The mean removal efficiency score is around 99.34%, with a small range and few outliers, suggesting a low level of variability. At a dose of 15 mm/h, this mode demonstrates that the ESP removal efficiency is at its highest level and remains consistently steady.

In the “i” mode, which operates at 15.1 kV and 20 mm/h, the removal efficiency ranges from around 96% to almost 100%, but is somewhat lower compared to other modes. The mean removal efficiency value is around 98.86%; however, there is a greater variability and occurrence of extreme situations. The findings indicate that administering very large doses may diminish the effectiveness of the ESP.

The analysis of the graph indicates that the effectiveness of ESP in eliminating PM ranging from 0.35 to 8.7 μm in size is very high and may vary based on the pace at which PM is introduced. Feed rates of 0.128 mg/s and 0.962 mg/s exhibit consistently high and stable removal efficiency, but a feed rate of 0.385 mg/s demonstrates more variability in outcomes and lower removal efficiency.

Figures 5 and 6 show the effectiveness of an ESP in eliminating PM within the size range of 0.2 to 0.35 μm and 0.35 to 8.7 μm , using different feed rate methods.

The removal efficiency levels for both particle groups remain very high, with fine and ultra-fine PM (0.35–8.7 μm) exhibiting somewhat higher average removal efficiency levels compared to 0–0.35 μm . The average removal efficiency rates are high in both groups. However, in the fraction group of ultra-fine PM, there is a minor drop in removal efficiency at higher feed rates. This suggests that ESP is extremely efficient for both categories of PM, but the removal efficiency may differ based on particle size and dosage schedule.

The dispersion is more pronounced for PM with a size range of 0–0.35 μm compared to PM with a size range of 0.35–8.7 μm . Significant differences in findings are detected at the 6 mm/h dosage rate in both groups, suggesting a higher level of variability. A low feed rate (e.g., 0.128 mg/s) and high rate (e.g., 0.962 mg/s) result in reduced dispersion and increased stability.

Extreme situations exhibit heightened volatility in the efficacy of removing fine and ultra-fine PM. Both ultra-fine and fine PM exhibit extreme situations, while ultra-fine PM has more pronounced extremes, particularly at moderate feed rates (e.g., 0.385 mg/s). This suggests that the removal of ultra-fine PM becomes more challenging at certain dosage rates, but the overall effectiveness remains high.

When examining the efficacy of removing PM of varying sizes, it is evident that fractions of the smallest fine and fine PM (0.35–8.7 μm) are removed with somewhat higher removal efficiency and less dispersion compared to that of 0.2–0.35 μm . Both groups exhibit the largest volatility and lowest removal efficiency when feed rates are modest, such as 0.385 mg/s. High and steady removal efficiency is a characteristic of lower feed rates (0.128 mg/s) and higher feed rates (0.962 mg/s).

Overall, the ESP demonstrates high efficacy in eliminating PM across both particle size categories. Optimal removal efficiency and stability are attained at lower (2 mm/h) and higher (15 mm/h) dosage rates, but a medium feed rate (0.385 mg/s) exhibits more volatility and reduced removal efficiency. This validates the efficacy of ESP as a dependable agent for the eradication of PM, particularly when appropriate dosage regimens are used.

4. Discussion

The scatterplot matrix (Figure 7) illustrates the correlations among several experimental settings used to quantify the effectiveness of PM removal. The graphs illustrate the correlation between each condition (a, b, c, d, e, f, g, h, i) in terms of particle removal effectiveness. The red outlines around the ellipse depict the concentration of the data and the characteristics of their distribution. Conversely, the diagonal matrix presents the same experimental data, illustrating the distribution of the data based on the relevant condition.



Figure 7. The correlation matrix is constructed from the calculated incoming and outgoing numerical particle concentrations of different particle sizes, giving the removal efficiency of the electrostatic precipitator for the different cases of system operation, a—background level of PM in the gas stream, b—electrostatic precipitator activation without feeding, c–i—electrostatic precipitator activation with the use of the different particle flux from the generator of aerosol.

The distribution of PM becomes more uniform when electrostatic precipitator “b” is activated, as opposed to the scenario where the PM level in air stream “a” is at its natural background level. The fine dispersion particles are scattered most uniformly in the higher portion of the fraction. At the basal level “a”, there is no discernible pattern of division across fractions over the whole range for all replicates.

Condition “a” (with just air) exhibits a significant scattering of the data together with a low level of concentration. The presence of wide ellipses in the data indicates a significant dispersion, suggesting that the removal efficiency without the ESP is both extremely low and unpredictable. The condition labelled “b” (15.1 kV air alone) has little data variation and displays thinner ellipses, suggesting a high level of stability and removal efficiency. The substantial inter-relationships seen when correlating with other circumstances demonstrate that activating the ESP leads to a considerable gain in removal efficiency.

Condition “c” (15.1 kV 2 mm/h) exhibits a greater dispersion in the data compared to “b”; however, it remains relatively narrow, suggesting a consistent removal efficiency with a small, elevated level of variability. Condition “d” (15.1 kV 4 mm/h) has a greater degree of data dispersion and fluctuation, suggesting a higher level of volatility in the experimental outcomes. The condition “e” (15.1 kV 6 mm/h) has a higher degree of data dispersion, as seen by the presence of large ellipses that indicate substantial volatility and reduced stability in removal efficiency. Condition “f” (15.1 kV 8 mm/h) exhibits a reduced range of data compared to conditions d and e, but larger than conditions “b” and “c”. This suggests that the removal efficiency is more consistent at a feed rate of 0.257 mg/s, while there is still some degree of variance. Condition “g” (at 15.1 kV and a feed rate of 0.641 mg/s) has a small range and consistent effectiveness, displaying robust associations with other conditions. The condition “h” (15.1 kV 15 mm/h) exhibits a restricted range of data and good consistency, with data points that are closely clustered and minimum variability. Condition “i” (15.1 kV 20 mm/h) has a greater degree of dispersion compared to condition “h”, while it remains relatively narrow. This suggests that although the removal efficiency is good, there is a slightly higher level of fluctuation compared to the feed rate of 0.962 mg/s.

When comparing the various situations, it is evident that lower and higher feed rates (e.g., 0.128 mg/s, 0.962 mg/s) result in higher removal efficiency and less variation in the data. On the other hand, medium feed rates (e.g., 0.257 mg/s, 0.385 mg/s) lead to more dispersion and variation. The presence of strong correlations among conditions “b”, “c”, “f”, “g”, and “h” suggests that these circumstances exhibit more stability and reliability in terms of PM removal. On the other hand, conditions d and e demonstrate higher volatility and less consistent outcomes, making them perhaps less suitable for successful PM removal.

The graph analysis reveals that the effectiveness of the electrostatic precipitator is closely tied to the pace at which PM is introduced. Feed rates of 0.128 mg/s and 0.962 mg/s provide superior stability and removal efficiency, with little data variation. Conversely, feed rates of 0.257 mg/s and 0.385 mg/s demonstrate more variability in outcomes and a larger range of data dispersion. These findings suggest that in order to obtain the highest possible effectiveness in removing PM, it is crucial to choose a suitable feed rate that guarantees the consistent and dependable functioning of the ESP.

Table 3 displays the Pearson correlation coefficients between different test settings and the effectiveness of removing PM.

Table 3. The Pearson correlation coefficients between different test settings and the effectiveness of removing PM.

Condition Tag	a	b	c	d	e	f	g	h	i
Pearson coefficient	−0.485	0.292	0.822	0.782	0.792	0.797	0.829	0.793	0.810

Conduct an experiment to examine the properties of air. The correlation coefficient is −0.485. A negative correlation coefficient suggests a substantially inverse association between PM concentration and clearance effectiveness. As the concentration of PM rises, there is a corresponding drop in removal efficiency. Given the absence of an ESP, it is not unexpected to obtain this outcome.

The correlation coefficient is 0.292 in Test “b” (15.1 kV air only). A positive correlation coefficient indicates a slightly positive association between PM concentration and clearance effectiveness. This indicates that when the concentration of PM rises, there is a modest improvement in removal efficiency, although the correlation is not significant.

Test “c” was conducted at a voltage of 15.1 kilovolts and a speed of 2 millimetres per hour. The correlation coefficient obtained from the test is 0.822. A correlation coefficient with a high positive value shows a robust positive association between PM concentration and clearance removal efficiency. This indicates that the removal efficiency of the process improves dramatically as the concentration of PM rises, suggesting an ideal method for removing PM.

Test “d” (15.1 kV 4 mm/h) shows the correlation value is 0.782. Additionally, it demonstrates a robust positive correlation between the concentration of PM and the effectiveness of removal, but significantly less pronounced than in test “c”. The removal efficiency also exhibits a substantial rise with a higher PM concentration.

Test “e” conducted at a voltage of 15.1 kilovolts at a rate of 6 millimetres per hour resulted in a correlation value of 0.792. The robust positive correlation demonstrates that the effectiveness of the ESP improves as the concentration of PM rises. This suggests that the ESP operates well in this circumstance, but with a somewhat lesser degree of correlation compared to Tests “c” and “d”.

The correlation coefficient for Test “f”, conducted at a voltage of 15.1 kV and a speed of 8 mm/h, is 0.797. A robust positive correlation suggests that the effectiveness of the ESP improves as the concentration of PM rises, demonstrating a consistent performance of the ESP under these circumstances.

Test “g”, conducted at a voltage of 15.1 kV at a rate of 10 millimetres per hour, resulted in a correlation value of 0.829. These data demonstrate a robust positive correlation between

PM concentration and removal efficiency, suggesting that the removal efficiency notably improves as the PM concentration rises, making it an ideal condition.

Test “h” (15.1 kV, 15 millimetres per hour) describes how the correlation coefficient is 0.793. A robust positive correlation suggests that removal efficiency rises as PM concentration increases, showing consistent and dependable ESP performance in this scenario.

Test “i”, conducted at a voltage of 15.1 kV and a speed of 20 millimetres per hour, yielded a correlation value of 0.810. A strong positive correlation coefficient suggests that when the concentration of PM grows, the effectiveness of the ESP also increases dramatically, showing a favourable performance of the ESP in this particular circumstance.

Table 3 displays Pearson correlation coefficients indicating a substantial association between electrostatic precipitator removal efficiency and PM concentration in the majority of experiments. Test “a” demonstrates a negative correlation, indicating that there is a negative association between the concentration of PM and removal efficiency when the ESP is not used. The experiments (b–i) show a significant positive correlation, suggesting that when the concentration of PM rises, the ESP removal efficiency also increases. The tests “c” (2 mm/h), “g” (10 mm/h), and “i” (20 mm/h) exhibit the greatest correlation coefficients, suggesting that these dosage rates are ideal for achieving optimum ESP effectiveness. Tests “d”, “e”, “f”, and “h” exhibit robust positive correlations, but with coefficients somewhat lower than those of the ideal tests.

The comprehensive findings indicate that the electrostatic precipitator functions well across different aerosols feed rate regimes. However, some regimes, namely those with feed rates of 0.128 mg/s, 0.641 mg/s, and 1.283 mg/s, exhibit superior levels of removal efficiency and stability.

The experimental investigation of electrostatic precipitator technology using a new geometric electrode with high-curvature-radius edges has demonstrated the effectiveness of this type of design for the deposition of particulates. The geometry of the electrode requires further scientific investigation and the identification of possible limitations in terms of installation in the duct, the maintenance of such a system, and mechanical resistance to gas flow and electric current. It would therefore be appropriate for future scientific understanding to investigate the limitations of the possible length of the electrode by using an analogous tooth-shaped electrode with two perpendicular planes. It would also be useful to determine the variation in energy losses with electrode length, as well as the amount of ozone formation as a by-product of the pollutant, under different scenarios.

5. Conclusions

1. This investigation demonstrated the high efficacy of the electrostatic precipitator in eliminating particulate matter from the air flow. Under ideal circumstances, the removal efficiency may exceed 98%. In some experiments, such as those conducted at feed rates of 0.128 mg/s, 0.641 mg/s, and 1.283 mg/s, removal efficiency limits of even 99% or higher are attained.
2. PM with a size range of 0.2–0.35 μm provides a greater challenge for removal compared to PM with a size range of 0.35–8.7 μm . The removal effectiveness of the biggest ultra-fine PM is mostly influenced by the feed rate, while a fraction of fine PM and upper fraction exhibiting consistent and greater removal efficiency regardless of the feed rate.
3. Feed rates of 0.128 mg/s and 0.962 mg/s exhibit excellent stability and removal efficiency, resulting in little data deviation. The mean dosage rates (4 mm/h and 6 mm/h) exhibit more variability in the outcomes and a broader distribution of data.
4. Using the dual-plane electrode geometry with spike parts at voltages of no more than 15 kV is significantly sustainable due to reducing the energy demand during the purification of gas stream of fine PM at dosage from 0.308 cm^3/h to 3.08 cm^3/h .
5. Most experiments show a robust positive association between PM concentration and removal efficiency, suggesting that the effectiveness of the precipitator improves as

the PM concentration rises. The tests with the greatest correlation coefficients are “c” (2 mm/h), “g” (10 mm/h), and “i” (20 mm/h).

6. Experiments conducted with a voltage of 15.1 kV and higher feed rates, particularly at 0.641 mg/s and 0.962 mg/s, demonstrate a significant level of stability in the removal efficiency. These tests exhibit reduced variances and a decreased number of extreme situations, suggesting more consistent and reliable outcomes.
7. Varying experimental settings, such as the absence of a precipitator, the presence of merely air flow, or variable dosage rates, have a significant impact on the effectiveness of particulate matter removal. The highest removal efficiency may be attained by using feed rates of 0.128 mg/s, 0.641 mg/s, and 0.962 mg/s under optimum circumstances.
8. The electrostatic precipitator system has shown its reliability and removal efficiency in many settings, but certain feed rates may enhance the precipitation process. Tests demonstrate that the system can function well even when exposed to high levels of PM.
9. To enhance the effectiveness of the electrostatic precipitator, it is advisable to do more research including varying particle sizes and feed rates. Additionally, it would be beneficial to broaden the scope of the research by including other air flow rates and particle compositions in order to obtain a more comprehensive understanding of the system’s performance limitations and possibilities.

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References

1. UN General Assembly Declares Access to Clean and Healthy Environment a Universal Human Right. *UN News*. 28 July 2022. Available online: <https://news.un.org/en/story/2022/07/1123482> (accessed on 13 July 2024).
2. Pichler, M.; Krenmayr, N.; Schneider, E.; Brand, U. EU industrial policy: Between modernization and transformation of the automotive industry. *Environ. Innov. Soc. Transit.* **2021**, *38*, 140–152. [CrossRef]
3. Borucka, A.; Wiśniowski, P.; Mazurkiewicz, D.; Świdorski, A. Laboratory measurements of vehicle exhaust emissions in conditions reproducing real traffic. *Measurement* **2021**, *174*, 108998. [CrossRef]
4. Baltrėnas, P.; Chlebnikovas, A. The investigation of the structure and operation of a multi-channel cyclone, separating fine solid particles from an aggressive dispersed gas and vapour flow. *Powder Technol.* **2018**, *333*, 327–338. [CrossRef]
5. Maghrour Zefreh, M.; Torok, A. Theoretical Comparison of the Effects of Different Traffic Conditions on Urban Road Traffic Noise. *J. Adv. Transp.* **2018**, *2018*, 7949574. [CrossRef]
6. Fuc, P.; Lijewski, P.; Kurczewski, P.; Ziolkowski, A.; Dobrzynski, M. The analysis of fuel consumption and exhaust emissions from forklifts fueled by diesel fuel and liquefied petroleum gas (LPG) obtained under real driving conditions. In Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Tampa, FL, USA, 3–9 November 2017.
7. Jaroń, A.; Borucka, A.; Deliś, P.; Sekrecka, A. An Assessment of the Possibility of Using Unmanned Aerial Vehicles to Identify and Map Air Pollution from Infrastructure Emissions. *Energies* **2024**, *17*, 577. [CrossRef]

8. Machnik, R.; Więckowski, Ł. Operational tests of an electrostatic precipitator reducing low dust Indexed by: Emission from solid fuels combustion. *Ekspluat. I Niezawodn. Maint. Reliab.* **2021**, *23*, 569–574. [\[CrossRef\]](#)
9. Jadaan, K.; Khreis, H.; Török, Á. Exposure to Traffic-related Air Pollution and the Onset of Childhood Asthma: A Review of the Literature and the Assessment Methods Used. *Period. Polytech. Transp. Eng.* **2017**, *46*, 21. [\[CrossRef\]](#)
10. Chlebnikovas, A.; Selech, J.; Kilikevičius, A.; Przystupa, K.; Matijošius, J.; Vaišis, V. Modeling of Two-Phase Flow Parameters of a Multi-Channel Cylindrical Cyclone. *Energies* **2022**, *15*, 4690. [\[CrossRef\]](#)
11. Jarašūnienė, A.; Čižiūnienė, K.; Petraška, A. Sustainability Promotion by Digitalisation to Ensure the Quality of Less-Than-Truck Load Shipping. *Sustainability* **2022**, *14*, 12878. [\[CrossRef\]](#)
12. Matijošius, J.; Juciūtė, A.; Rimkus, A.; Zaranka, J. Investigation of the concentration of particles generated by public transport gas (CNG) buses. *Cogn. Sustain.* **2022**, 1–5. [\[CrossRef\]](#)
13. Kilikevičienė, K.; Chlebnikovas, A.; Matijošius, J.; Kilikevičius, A. Investigation of the acoustic agglomeration on ultrafine particles chamber built into the exhaust system of an internal combustion engine from renewable fuel mixture and diesel. *Heliyon* **2023**, *9*, e16737. [\[CrossRef\]](#)
14. Marczyk, A.; Caban, J.; Aleshkin, A.V.; Savinykh, P.A.; Isupov, A.Y.; Ivanov, I.I. Modeling and Simulation of Particle Motion in the Operation Area of a Centrifugal Rotary Chopper Machine. *Sustainability* **2019**, *11*, 4873. [\[CrossRef\]](#)
15. Zaranka, J.; Matijosius, J.; Radvilaite, U.; Caban, J.; Dudziak, A. Establishing Emergency Sections on Land Roads in Order to Improve the Quality of Transport Services, Creating Comfortable Conditions for International and Local Traffic. *Adv. Sci. Technol. Res. J.* **2023**, *17*, 75–85. [\[CrossRef\]](#)
16. Lima, F.D.; Medeiros, G.B.; Chagas, P.A.; Aguiar, M.L.; Guerra, V.G. Aerosol Nanoparticle Control by Electrostatic Precipitation and Filtration Processes—A Review. *Powders* **2023**, *2*, 259–298. [\[CrossRef\]](#)
17. Kuzin, A.; Chen, G.; Zhu, F.; Gorin, D.; Mohan, B.; Choudhury, U.; Cui, J.; Modi, K.; Huang, G.; Mei, Y.; et al. Bridging the gap: Harnessing liquid nanomachine know-how for tackling harmful airborne particulates. *Nanoscale* **2023**, *15*, 17727–17738. [\[CrossRef\]](#)
18. Brunekreef, B.; Holgate, S.T. Air pollution and health. *Lancet* **2002**, *360*, 1233–1242. [\[CrossRef\]](#)
19. Da Silva, R.P.; Muniz, E.C.; Medeiros, G.B.; Aguiar, M.L.; Corradini, E. Electrospun Membrane for Media Filters: A Review. *Preprints* **2023**, 2023111682. [\[CrossRef\]](#)
20. Choi, D.Y.; Jung, S.-H.; Song, D.K.; An, E.J.; Park, D.; Kim, T.-O.; Jung, J.H.; Lee, H.M. Al-Coated Conductive Fibrous Filter with Low Pressure Drop for Efficient Electrostatic Capture of Ultrafine Particulate Pollutants. *ACS Appl Mater Interfaces* **2017**, *9*, 16495–16504. [\[CrossRef\]](#)
21. de Castro, B.J.C.; de Lacerda, C.R.; de Melo, B.R.; Sartim, R.; Aguiar, M.L. Performance assessment of a bench scale hybrid filter in the collection of nanoparticles. *Process Saf. Environ. Prot.* **2021**, *154*, 32–42. [\[CrossRef\]](#)
22. Liu, C.-Y.; Tseng, C.-H.; Wang, K.-F. The Assessment of Indoor Formaldehyde and Bioaerosol Removal by Using Negative Discharge Electrostatic Air Cleaners. *Int. J. Environ. Res. Public Health* **2022**, *19*, 7209. [\[CrossRef\]](#)
23. Pushpawela, B.; Jayaratne, R.; Nguy, A.; Morawska, L. Efficiency of ionizers in removing airborne particles in indoor environments. *J. Electrostat.* **2017**, *90*, 79–84. [\[CrossRef\]](#)
24. Othman, M.; Latif, M.T.; Yee, C.Z.; Norshariffudin, L.K.; Azhari, A.; Halim, N.D.A.; Alias, A.; Sofwan, N.M.; Hamid, H.H.A.; Matsumi, Y. PM_{2.5} and ozone in office environments and their potential impact on human health. *Ecotoxicol. Environ. Saf.* **2020**, *194*, 110432. [\[CrossRef\]](#)
25. Kek, H.Y.; Tan, H.; Othman, M.H.D.; Lee, C.T.; Ahmad, F.B.J.; Ismail, N.D.; Nyakuma, B.B.; Lee, K.Q.; Wong, K.Y. Transforming pollution into solutions: A bibliometric analysis and sustainable strategies for reducing indoor microplastics while converting to value-added products. *Environ. Res.* **2024**, *252*, 118928. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Dobrowolski, A.; Strob, R.; Nietfeld, J.; Pieloth, D.; Wiggers, H.; Thommes, M. Preparation of spray dried submicron particles: Part B—Particle recovery by electrostatic precipitation. *Int. J. Pharm.* **2018**, *548*, 237–243. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Afshari, A.; Ekberg, L.; Forejt, L.; Mo, J.; Rahimi, S.; Siegel, J.; Chen, W.; Wargocki, P.; Zurami, S.; Zhang, J. Electrostatic Precipitators as an Indoor Air Cleaner—A Literature Review. *Sustainability* **2020**, *12*, 8774. [\[CrossRef\]](#)
28. de Aquino Lima, F.; Guerra, V.G. Collection of nanoparticles by electrostatic precipitation operating over a wide range of electric fields. *Sep. Sci. Technol.* **2024**, *59*, 848–865. [\[CrossRef\]](#)
29. Zhou, Y.; Liu, Y.; Shi, Z.; Li, X.; Yu, M. Enhanced size-dependent efficiency of removal of ultrafine particles: New solution of two-stage electrostatic precipitator with thermophoresis. *Sep. Purif. Technol.* **2024**, *346*, 127479. [\[CrossRef\]](#)
30. Chen, L.; Gonze, E.; Ondarts, M.; Outin, J.; Gonthier, Y. Electrostatic precipitator for fine and ultrafine particle removal from indoor air environments. *Sep. Purif. Technol.* **2020**, *247*, 116964. [\[CrossRef\]](#)
31. Podlinski, J.; Niewulis, A.; Mizeraczyk, J.; Atten, P. ESP performance for various dust densities. *J. Electrostat.* **2008**, *66*, 246–253. [\[CrossRef\]](#)
32. Shi, Y.; Li, C.; Fang, M.; Cen, J.; Wang, Q.; Yan, K. Numerical investigation of particle re-entrainment mechanism and its suppression strategy in the high-temperature electrostatic precipitator. *Powder Technol.* **2024**, *437*, 119538. [\[CrossRef\]](#)
33. Yanada, H.; Takagi, S.; Mamiya, S. Effects of electrode and filter element shapes on characteristics of charge injection type of electrostatic oil filter. *J. Electrostat.* **2015**, *74*, 1–7. [\[CrossRef\]](#)
34. Vaddi, R.S.; Guan, Y.; Novosselov, I. Behavior of ultrafine particles in electro-hydrodynamic flow induced by corona discharge. *J. Aerosol Sci.* **2020**, *148*, 105587. [\[CrossRef\]](#)

35. Lee, G.H.; Hwang, S.Y.; Cheon, T.W.; Kim, H.J.; Han, B.; Yook, S.J. Optimization of pipe-and-spike discharge electrode shape for improving electrostatic precipitator collection efficiency. *Powder Technol.* **2021**, *379*, 241–250. [\[CrossRef\]](#)
36. Mo, J.; Gu, Y.; Tian, E. Efficiently remove submicron particles by a novel foldable electrostatically assisted air coarse filter. *Sep. Purif. Technol.* **2022**, *288*, 120631. [\[CrossRef\]](#)
37. Krupa, A.; Sobczyk, A.T.; Marchewicz, A.; Jaworek, A. Fly ash and sorbent particles agglomeration and removal in system of electrostatic agglomerator and electrostatic precipitator. *Powder Technol.* **2024**, *431*, 119075. [\[CrossRef\]](#)
38. Pal, A.; Dixit, A.; Srivastava, A.K. Design and optimization of the shape of electrostatic precipitator system. *Mater. Today Proc.* **2021**, *47*, 3871–3876. [\[CrossRef\]](#)
39. Li, K.; Feng, G.; Chen, T.; Zhao, H. Research of electret air filter: A review. *Polym. Adv. Technol.* **2024**, *35*, e6454. [\[CrossRef\]](#)
40. Song, Y.; Zhang, Y.; Zhu, W.; Liu, Y.; Long, W.; Vafai, K. Study on the influence of electrodes on the collection efficiency during the treatment of welding fume in electrostatic precipitators. *J. Electrostat.* **2023**, *123*, 103808. [\[CrossRef\]](#)
41. Wang, Y.; Gao, W.; Zhang, H.; Yang, Z.; Zhao, Z.; Shao, L.; Sun, Z.; Zheng, C.; Gao, X. Significance of ionic wind propulsion on charged particle removal during flue gas purification. *Powder Technol.* **2022**, *410*, 117804. [\[CrossRef\]](#)
42. Fayyad, M.M.B.; González, A.G.A.; Iváncsy, T. Numerical study of wavy collecting electrodes with different shapes of corona electrodes. In Proceedings of the 2022 IEEE 5th International Conference and Workshop Óbuda on Electrical and Power Engineering (CANDO-EPE), Budapest, Hungary, 21–22 November 2022; pp. 000037–000042. [\[CrossRef\]](#)
43. Fayyad, M.B.; González, A.A.; Iváncsy, T. Numerical study of the influence of using crenelated collecting plates on the electrostatic precipitators. *J. Electrostat.* **2023**, *123*, 103811. [\[CrossRef\]](#)
44. Bani Fayyad, M.; Iváncsy, T. Investigation of Three Types of Collecting Plates for a Single-Stage ESP. In Proceedings of the 2023 IEEE 6th International Conference and Workshop Óbuda on Electrical and Power Engineering (CANDO-EPE), Budapest, Hungary, 19–20 October 2023. [\[CrossRef\]](#)
45. Bani Fayyad, M.; Iváncsy, T. Numerical Study of the Influence of Using Semicircular Corrugated Collecting Plate and Inverted Semicircular Corrugated on the Electrostatic Precipitator. *Period. Polytech. Elec. Eng. Comp. Sci.* **2024**, *68*, 124–134. [\[CrossRef\]](#)
46. Chen, Y.-T.; Lu, C.-L.; Lu, S.-J.; Lee, D.-S. Electrostatic Precipitator Design Optimization for the Removal of Aerosol and Airborne Viruses. *Sustainability* **2023**, *15*, 8432. [\[CrossRef\]](#)
47. Gholami, M.; Kazerooni, H. An Investigation on the Effect of Different Discharge Electrode Geometries on the Performance of the Spiked Electrode-Plate Electrostatic Precipitator. *Appl. Electromagn.* **2022**, *10*, 55–68.
48. Parker, K.R. *Applied Electrostatic Precipitation*; Springer: Dordrecht, The Netherlands, 1997; ISBN 978-0-7514-0266-7.
49. Badran, M.; Mansour, A.M. Evaluating Performance Indices of Electrostatic Precipitators. *Energies* **2022**, *15*, 6647. [\[CrossRef\]](#)
50. Jena, M.C.; Mishra, S.K.; Moharana, H.S. Effect of Particle Size on Collection Efficiency of ESP and RABH: A Case Study. *Aerosol Sci. Eng.* **2019**, *3*, 75–87. [\[CrossRef\]](#)

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