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Optimizing Particulate Matter Filtration: Evaluating the Efficacy of Electrode Spacing in Corona Discharge Dust Removal Systems

***Abstract**. This comprehensive study delves into the efficiency of an electrode-based dust removal system, with a specific focus on its capability to filter various sizes of particulate matter: PM1, PM2.5, and PM10. Employing an innovative Corona discharging technology, the research critically evaluates how different electrode spacings influence the efficacy of particle removal. Conducted in a controlled environment, the experiments encompassed a range of electrode distances to ascertain their impact on reducing particle sizes commonly found in indoor air. The methodology involved systematic testing of electrode spacings at 2 cm, 3 cm, and 6 cm, across different particulate matter concentrations. The research utilized a combination of natural sedimentation in control scenarios and active filtration in experimental setups to measure the effectiveness of the dust removal system. Key parameters such as particle charge, airflow dynamics, and the strength of the electrical field across the electrodes were meticulously observed and analyzed. The results of this investigation reveal that electrode spacing is a critical factor in optimizing the removal efficiency of particulate matter. Particularly, the 3 cm electrode spacing emerged as the most effective across all particle sizes, indicating its potential as an optimal configuration for air purification systems. This finding underscores the necessity of a balanced approach in the design of such systems, where both the electric field strength and airflow dynamics are harmoniously aligned. This study contributes significantly to the field of environmental health and indoor air quality control. The insights gleaned from the research provide a foundation for developing more efficient air purification systems, tailored to varying environmental conditions and particulate compositions. The findings also pave the way for future research, exploring the impact of other environmental variables on the performance of electrode-based dust removal systems.*

Streszczenie.
*To kompleksowe badanie zagłębia się w efektywność systemu usuwania kurzu opartego na elektrodach, ze szczególnym uwzględnieniem jego zdolności do filtrowania różnych rozmiarów cząstek stałych: PM1, PM2.5i PM10. Wykorzystując innowacyjną technologię ładowania Coronadish, badanie krytycznie ocenia, jak różne odległości między elektrodami wpływają na skuteczność usuwania cząstek. Przeprowadzone w kontrolowanym środowisku eksperymenty obejmowały szereg odległości elektrod, aby ustalić ich wpływ na redukcję rozmiarów cząstek powszechnie występujących w powietrzu w pomieszczeniach. Metodologia obejmowała systematyczne testowanie odstępów między elektrodami o wartościach 2 cm, 3 cm i 6 cm, w różnych stężeniach cząstek stałych. Badanie wykorzystywało połączenie naturalnej sedymentacji w scenariuszach kontrolnych i aktywnej filtracji w układach eksperymentalnych, aby zmierzyć skuteczność systemu usuwania kurzu. Kluczowe parametry, takie jak ładunek cząstek, dynamika przepływu powietrza i siła pola elektrycznego na elektrodach, były dokładnie obserwowane i analizowane. Wyniki tego dochodzenia ujawniają, że odstęp między elektrodami jest kluczowym czynnikiem w optymalizacji efektywności usuwania cząstek stałych. Szczególnie odstęp elektrod 3 cm okazał się najskuteczniejszy we wszystkich rozmiarach cząstek, wskazując na jego potencjalne zastosowanie jako optymalnej konfiguracji dla systemów oczyszczania powietrza. Wynik ten podkreśla konieczność zrównoważonego podejścia w projektowaniu takich systemów, gdzie zarówno siła pola elektrycznego, jak i dynamika przepływu powietrza są harmonijnie dostosowane. To badanie znacząco przyczynia się do dziedziny zdrowia środowiskowego i kontroli jakości powietrza w pomieszczeniach. Wnioski płynące z badania stanowią podstawę do opracowania bardziej efektywnych systemów oczyszczania powietrza, dostosowanych do różnorodnych warunków środowiskowych i składów cząstek stałych. Wyniki te również otwierają drogę do przyszłych badań, badających wpływ innych zmiennych środowiskowych na wydajność systemów usuwania kurzu opartych na elektrodach. (**Optymalizacja filtracji cząstek stałych: ocena skuteczności odstępu między elektrodami w systemach usuwania pyłu za pomocą wyładowań koronowych**)*

Keywords: Electrode Spacing, Particulate Matter Filtration, Corona discharging Technology, Air Purification Systems
Słowa kluczowe: Odstęp Elektrod, Filtracja Cząstek Stałych, Technologia Ładowania Coronadish, Systemy Oczyszczania Powietrza

1. Introduction

Air pollution has emerged as a critical environmental and public health concern, especially with the rising levels of fine particulate matter, including PM1, PM2.5, and PM10. These tiny particles, invisible to the naked eye, pose a significant threat due to their ability to penetrate deep into the respiratory system, enter the bloodstream, and potentially impact various organs. The human nasal filters are largely ineffective against these minuscule particles, thereby underscoring the necessity for efficacious strategies to prevent and mitigate their harmful effects[1-3]. Prolonged exposure to such particulates is linked to a decline in lung function, the development of non-smoker emphysema, and an increased risk of lung cancer [4-6]. Moreover, these particles often harbor additional hazardous substances like cadmium, mercury, and carcinogens, further contaminating the air with a variety of unseen germs and pollutants [7-8]. High concentrations of these particulates can impair visibility, leading to fog formation and negatively impacting both indoor and outdoor air quality [9-10].

The primary contributors to fine particle pollution include direct emissions from activities such as open burning, transportation, electricity generation, and various industrial processes. These sources release not only particulate matter but also noxious gases like sulfur dioxide (SO2) and nitrogen oxides (NOx), along with other toxins such as mercury, cadmium, arsenic, and polycyclic aromatic hydrocarbons (PAHs). The burning of diesel, particularly in areas of heavy traffic congestion, and the use of non-environmentally friendly fuels like coal exacerbate the problem, emitting substantial quantities of SO2 and NOx [11-14].

In the face of this growing challenge, numerous methods have been developed to reduce small particle pollution. Conventional approaches, such as water spraying, have limitations in their effectiveness on fine particles and are resource-intensive [15-16]. Air purifiers with High-Efficiency Particulate Air (HEPA) filters, while capable of trapping these particles, face constraints due to their dense structure, which can lead to reduced airflow and increased energy consumption or decreased efficiency [17-

18]. These filters also necessitate regular maintenance and environmentally responsible disposal [19-20]. Electrostatic precipitators, particularly those incorporating a two-stage system with a precharger and an electrostatic accumulator, have demonstrated enhanced efficiency in particle collection [21-22]. Additionally, recent advancements in plasma technology, including Multipin Corona Discharge (MCDP) and Dielectric Barrier Discharge (DBD) plasma generators, have shown promise in dust removal. Studies indicate that both types can effectively reduce dust levels, with MCDP generators exhibiting higher efficiency and faster operation [23-25]. The generation of plasma can be achieved by energizing an emitter to create a high-intensity electric field. The architecture of energy emitters has evolved, incorporating various designs for diverse applications, including the use of induction coils applicator [26-28] and curved plate applicator [29-30]. This study explores both plate-type and pointed-shape power release models [31-39]. It is discerned that the pointed tip configuration is particularly conducive for applications involving plasma energy sources, due to its efficient energy release pattern. This insight underscores the significance of emitter design in optimizing plasma generation for specific applications.

This article introduces the innovative Coronadish charging technology, a novel approach designed to remove fine particles using energy emitted through strategically placed copper electrodes. The focus of this study is to explore the effectiveness of this technology in eliminating PM1, PM2.5, and PM10 particles, paving the way for its application in addressing air pollution challenges. The development and implementation of such advanced solutions like Coronadish charging are crucial in the ongoing battle against air pollution. These technologies represent significant strides toward effectively managing the issue of fine particulate matter, thereby helping to mitigate the profound impact of air pollution on human health and the environment

2. Materials and Methods

This segment delineates the constituents utilized, along with the testing strategies implemented. It encompasses comprehensive explications of the power emitter's attributes, the protocols for installation and assessment procedures, the fundamental tenets of plasma dust eradication, and the techniques for quantifying the efficacy of dust removal. These subjects will be expounded in the ensuing sub-sections.

2.1 Characteristics Of The Power Emitter

The corona energy emitter, fabricated from copper, manifests an electrical conductivity quantified at 59.6 x 10^6 Siemens per meter [40]. Its dimensions are precisely 20 millimeters in width, 200 millimeters in length, and 0.5 millimeters in thickness, conforming to the conventional dimensions of a standard HEPA filter. The emitter's design integrates a triangular apex, each measuring 5 millimeters in both height and base length, with a total of 30 such apices distributed along the length of the copper plate. This plate is strategically positioned at a distance of 15 millimeters from the electrode on either side. The electrode itself is characterized by dimensions of 2 millimeters in thickness, 200 millimeters in width, and 300 millimeters in length, as delineated in Figure 1. The experimental apparatus comprises three sets of pointed plates, each set containing 5, 10, and 15 plates, with inter-plate spacings within each set being 20 millimeters, 30 millimeters, and 60 millimeters, respectively, as depicted in Figure 2. A high-voltage circuitry, rated at 15 kilovolts, energizes the generator set for the electrode test configuration.

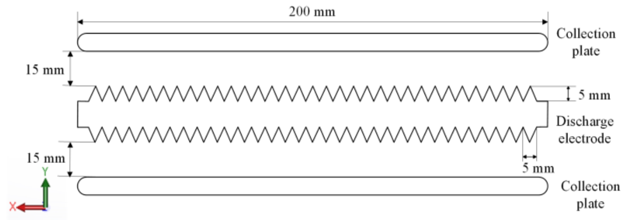

Fig.1 The power emitter's architecture is characterized by a tapered plate composed of copper.

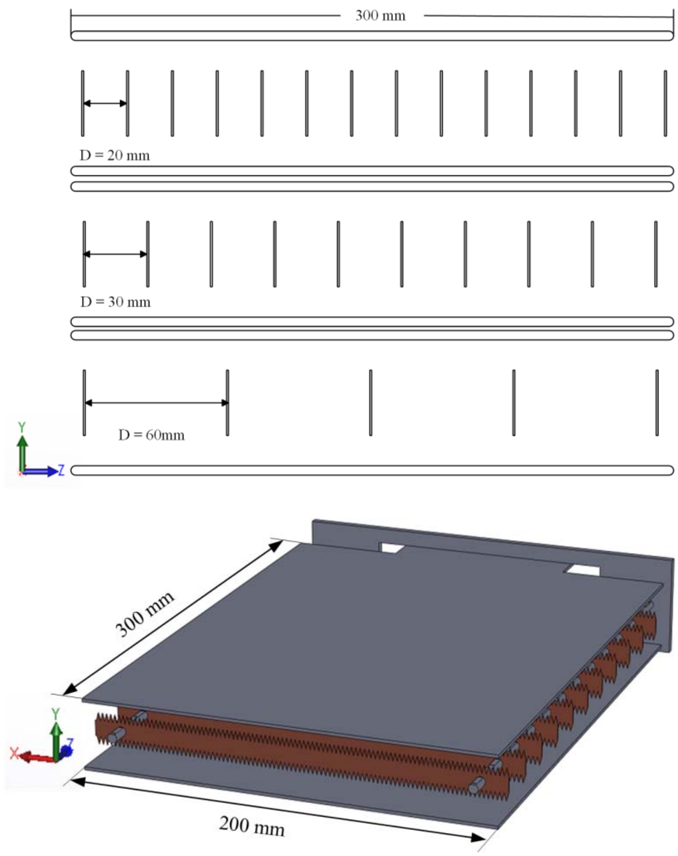

Fig. 2 The experimental apparatus comprises three sets of pointed plates.

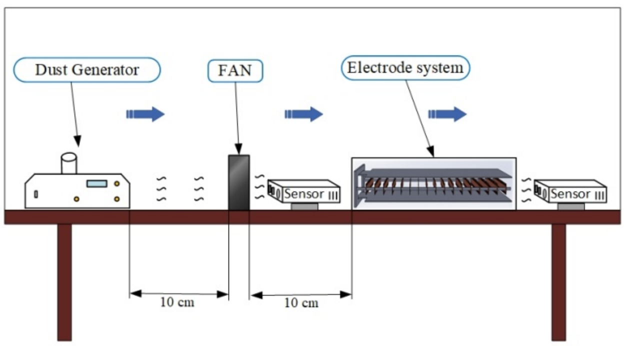

Fig. 3 Methodology for Installation and Evaluation Procedures.

2.2 Installation and Evaluation Procedures

The experiment dedicated to dust removal will be executed within a confined environment, incorporating three separately delineated experimental protocols, each with a duration of one hour. An airflow velocity of 2.4 meters per second will be employed for the procedure. In order to synthesize fine dust particulates, the smoke from burning incense will be utilized, confined within a polymer containment unit. A ventilation device, specifically modified to draw the incense smoke through strategically placed perforations in the container, will facilitate the transport of the smoke into the dust removal apparatus. Instrumentation for measuring particulate concentrations will be strategically located at both the ingress and egress points of the system,thereby enabling a comprehensive evaluation of the system's proficiency in filtering fine dust particulates. This configuration is illustrated in Figure 3.

2.3 The Principles of Plasma Dust Removal

Plasma generation entails the application of a high direct current (DC) voltage across two electrodes, with the inter-electrode spacing typically ranging from approximately 1 millimeter to 10 millimeters, although this gap may be adjusted to suit specific applications. For example, establishing a voltage differential (e.g., 10 kilovolts) relative to the ground potential between these electrodes leads to the ionization of the gas traversing this gap. This ionization process is initiated as the elevated voltage energizes the gas ions, augmenting their energy states and consequently diminishing the gas's electrical resistance. When the resistance decreases sufficiently, a substantial potential difference induces an electrical arc from the higher to the lower potential side, a phenomenon recognized as spark discharge. In instances where thepotential difference is not exceedingly high, no spark occurs; rather, a soft luminescence is observed, manifesting in various forms such as corona discharge, gliding arc discharge, and others. The introduction of a dielectric barrier between the two electrodes results in what is known as Dielectric Barrier Discharge (DBD). These diverse discharge manifestations constitute the fundamental mechanisms of plasma, with the dimly lit zone signifying the plasma region, capable of attaining temperatures ranging from 10,000 Kelvin to 100,000 Kelvin. [41-42]

In the context of the dust removal experiment, incense smoke was introduced through all three variations of electrode assemblies. The levels of particulate matter (PM1, PM2.5, and PM10) were quantitatively assessed using a specialized instrument at both the entry (C_{in}) and exit (C_{out}) points of the electrode configuration. The experiment involved the systematic recording of C_{in} and C_{out} data to facilitate the computation of particulate removal efficiency, as delineated in Equation 1 [43].

(1) $$\text{Removal efficiency} = \left[\frac{(C_{in} - C_{out})}{C_{in}}\right] \times 100\%$$

3. Results and discussions

3.1 Experimental results

During the control experiment, the natural sedimentation of particulate matter was observed in the absence of any active filtration mechanisms. The initial concentration of fine particulate matter (PM1) was quantified at 400 micrograms per cubic meter. Over time, this concentration exhibited a gradual decrement, descending to 250 micrograms per cubic meter after 10 minutes, and ultimately stabilizing at 50 micrograms per cubic meter post an hour. This observed decrease can primarily be ascribed to the intrinsic settling of particles coupled with minor passive filtration within the containment chamber.

Upon activation of the dust removal system, a pronounced enhancement in particulate reduction efficacy was noted. The incorporation of electrodes substantially augmented the system's capability to filter out PM1 particles. For electrodes spaced at 2 centimeters, the initial PM1 concentration of 220 micrograms per cubic meter reduced to 140 micrograms per cubic meter after 10 minutes, and significantly, to 20 micrograms per cubic meter following an hour, indicating a high efficiency of this configuration. In the setup with electrodes spaced at 3 centimeters, a similar trend was observed, starting from a PM1 level of 200 micrograms per cubic meter and mirroring the results observed with 2-centimeter spacing. For electrodes spaced at 6 centimeters, the PM1 level, initially at 250 micrograms per cubic meter, declined to 150 micrograms per cubic meter in 10 minutes, eventually reaching 17 micrograms per cubic meter after an hour. While effective, this arrangement demonstrated a marginally lower particle reduction rate compared to the other configurations.

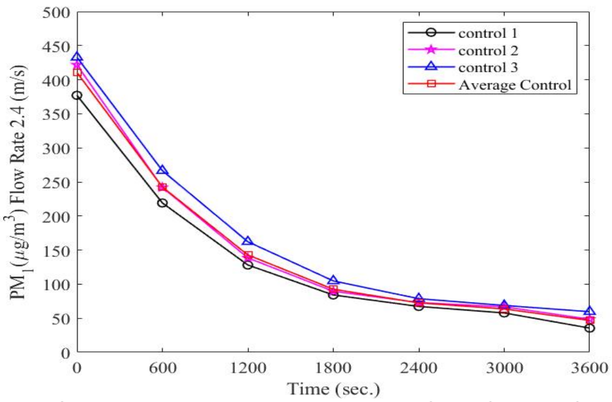

Fig. 4 Cumulative Findings Pertaining to the Quantification of PM1 Particulate Matter in the Control Apparatus.

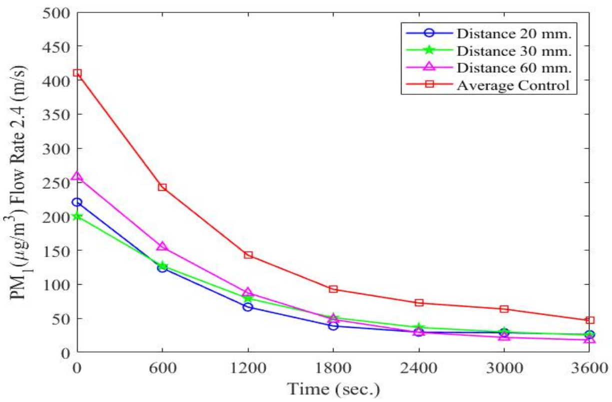

Fig. 5 Results of PM1 Particulate Matter Removal at Varied Electrode Distances.

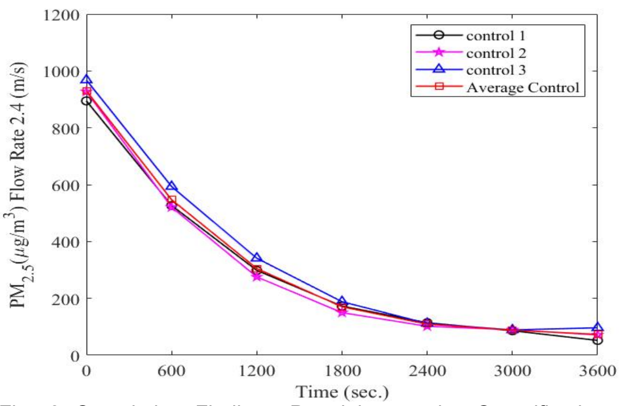

Fig. 6 Cumulative Findings Pertaining to the Quantification of PM2.5 Particulate Matter in the Control Apparatus.

These findings underscore the efficacy of the electrode-based dust removal system in diminishing PM1 concentrations, significantly surpassing the natural settling observed in the baseline tests. Among the electrode configurations examined, the 3-centimeter spacing exhibited the most consistent and effective results in PM1 reduction, suggesting an optimal inter-electrode distance for maximizing electrostatic particle attraction while maintaining efficient airflow.

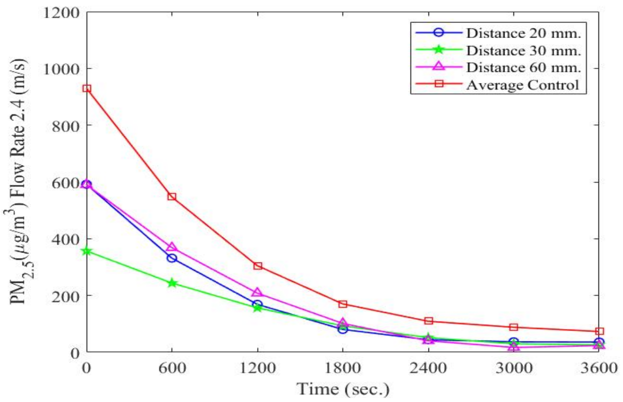

Fig. 7 Results of PM2.5 Particulate Matter Removal at Varied Electrode Distances.

In the baseline scenario, the initial concentration of particulate matter PM2.5 was noted to be 900 micrograms per cubic meter. Over the duration of an hour, a gradual decline was observed, culminating at 70 micrograms per cubic meter, attributable to natural sedimentation and minor passive filtration within the test chamber. When the dust removal system was operational, the reduction in PM2.5 levels was markedly more pronounced. With electrodes spaced at 2 centimeters, the initial PM2.5 concentration of 600 micrograms per cubic meter decreased to 360 micrograms per cubic meter after 10 minutes and further to 28 micrograms per cubic meter post an hour, indicative of a substantial filtration efficiency improvement. The 3-centimeter electrode spacing began with a PM2.5 level of 360 micrograms per cubic meter, reducing to 200 micrograms per cubic meter in 10 minutes, showcasing performance comparable to the 2-centimeter spacing. For the 6-centimeter spacing, the initial PM2.5 level of 600 micrograms per cubic meter declined to 400 micrograms per cubic meter in 10 minutes, reaching 20 micrograms per cubic meter after an hour, though exhibiting a slightly lower reduction rate compared to the other setups.

These results emphasize the considerable impact of the electrode-based dust removal system in curtailing PM2.5 levels, with the active filtration significantly outshining the natural settling noted in the baseline scenario. The 3-centimeter electrode spacing demonstrated the most consistent and effective reduction in PM2.5 levels, suggesting an optimal equilibrium between electrostatic attraction and airflow efficiency.

In the baseline tests, the mean initial concentration of PM10 was documented at 1600 micrograms per cubic meter. Over the course of an hour, a natural reduction in PM10 levels was recorded, settling at 90 micrograms per cubic meter, a decline attributed to natural sedimentation and minor passive filtration. The activation of the dust removal system led to a more pronounced reduction in PM10 levels. With electrodes spaced at 2 centimeters, the initial PM10 levels of 1000 micrograms per cubic meter decreased to 600 micrograms per cubic meter in 10 minutes, ultimately reducing to 35 micrograms per cubic meter after an hour, showcasing a considerable amelioration in the system’s efficiency. The 3-centimeter electrode spacing started with a PM10 concentration of 250 micrograms per cubic meter, dropping to 200 micrograms per cubic meter in 10 minutes, exhibiting a consistent reduction rate akin to the 2-centimeter electrode spacing. For the 6-centimeter spacing, the initial PM10 level of 600 micrograms per cubic meter fell to 400 micrograms per cubic meter after 10 minutes, and ultimately to 20 micrograms per cubic meter after an hour, indicating significant filtration capability, albeit slightly less efficient than the other configurations.

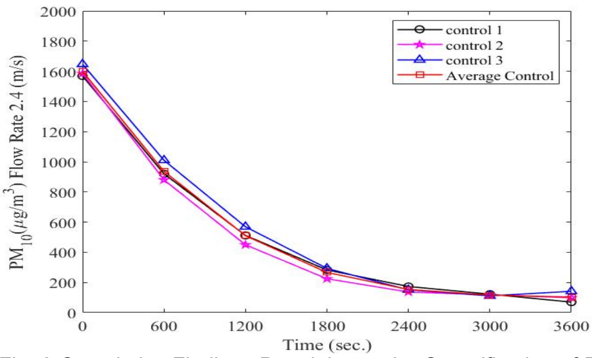

Fig. 8 Cumulative Findings Pertaining to the Quantification of PM10 Particulate Matter in the Control Apparatus.

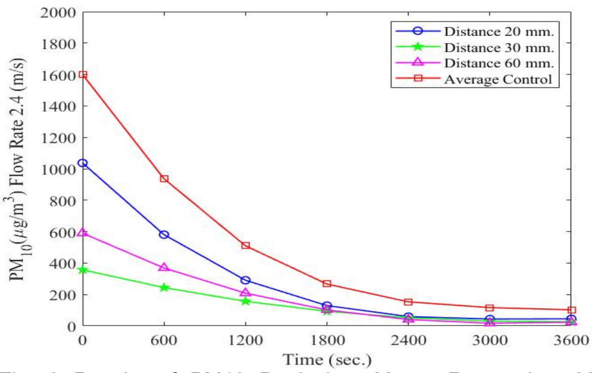

Fig. 9 Results of PM10 Particulate Matter Removal at Varied Electrode Distances.

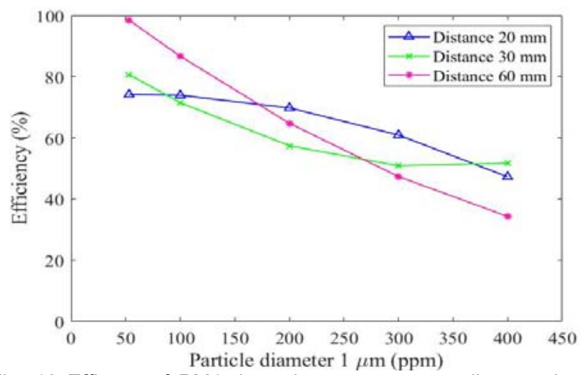

Fig. 10 Efficacy of PM1 dust abatement across diverse electrode spacings.

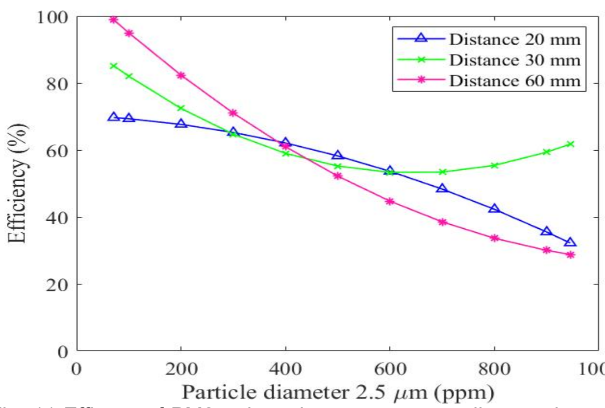

Fig. 11 Efficacy of PM2.5 dust abatement across diverse electrode spacings.

The experimental outcomes elucidate the effectiveness of the electrode-based dust removal system in substantially diminishing PM10 particle concentration, notably out performing the natural reduction observed in the baseline scenario. Among the tested configurations, the 3-centimeter electrode spacing emerged as the most efficient in PM10 reduction, indicating an optimal balance between particle attraction and airflow dynamics.

3.2 Removal efficiency

The outcomes delineate a differential efficacy in the removal of PM1 particles contingent upon the inter-electrode spacing and varying PM1 concentration spectra. The 2-centimeter spacing exhibited heightened efficiency within the median concentration range (300 parts per million to 200 parts per million), whereas the 6-centimeter distance demonstrated augmented efficiency in the lower concentration spectrum (200 parts per million to 50 parts per million). The 3-centimeter inter-electrode distance seemed to offer an equilibrium between these divergent scenarios.

These observations imply that the distance between electrodes is a pivotal factor in determining the efficiency of PM1 particle removal. The observed variations in efficiency across different concentration brackets may be attributable to aspects such as the charge of the particles, the dynamics of the airflow, and the strength of the electrical field established between the electrodes.

The experimental data reveal disparate efficiencies in the removal of PM2.5 particles across varied electrode spacings and concentration ranges. Notably, the 3-centimeter spacing was observed to be more efficacious in the initial concentration range (940 parts per million to 600 parts per million), while the 2-centimeter distance proved to be more effective within the mid-range (600 parts per million to 400 parts per million). The 6-centimeter distance displayed increased efficiency in the lower concentration range (400 parts per million to 70 parts per million).

Such variations intimate that the spacing between electrodes significantly influences the efficiency of particle removal. The differences in efficiency across the concentration ranges could be ascribed to factors including the behavior of particles under varying electrical fields, patterns of airflow, and the intrinsic physical properties of the particles.

The findings elucidate varied efficacies in the removal of PM10 particles across different electrode distances and concentration spectrums. The 3-centimeter distance manifested superior efficiency across all examined concentration ranges, denoting its optimal balance for the removal of PM10 particles. The observed variations in efficiency might be owing to factors such as the intensity of the electric field, the charge properties of the particles, and the dynamics of airflow in the vicinity of the electrodes.

3.3 Discussions

The comprehensive analysis of this study yields critical insights into the efficacy of an electrode-based dust removal system, examining a range of particle sizes (PM1, PM2.5, and PM10) and electrode spacings. These insights are instrumental in elucidating the mechanisms of particulate matter filtration and the significance of electrode configurations in enhancing air purification systems.

Baseline Observations and Inherent Particle Dynamics: In the baseline assessments for each particle size category, a consistent decline in concentration over time was noted. This reduction is predominantly ascribed to gravitational settling and modest passive filtration within the test chamber. Understanding these innate reduction processes is essential for comprehending the fundamental behavior of particulate matter in confined spaces, thereby establishing a

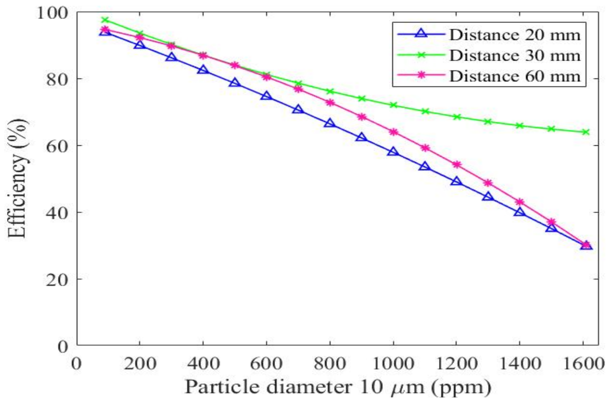

Fig. 12 Efficacy of PM10 dust abatement across diverse electrode spacings.

PM1 Particle Removal Analysis: The study revealed a differential removal efficiency for PM1 particles across various electrode spacings. The 2 cm spacing proved more effective in mid-range concentrations, while the 6 cm spacing exhibited heightened efficiency at lower concentration levels. This suggests that smaller particles, such as PM1, which are more prone to Brownian motion and less influenced by gravitational forces, exhibit distinct responses to variations in the electric field produced by different electrode distances. The 3 cm spacing offered a more uniform efficiency across a wider concentration spectrum, indicating its applicability in environments with fluctuating PM1 levels.

PM2.5 Particle Filtration Efficacy: The efficiency in removing PM2.5 particles also varied with electrode spacing. The enhanced efficiency at 3 cm in the initial concentration phase implies that this spacing ideally balances electric field intensity and particle interaction, especially for larger particles compared to PM1. The efficacy of the 2 cm spacing in mid-range concentrations can be linked to a more intense localized electric field, facilitating particle entrapment. The improved performance of the 6 cm spacing at lower concentrations hints at a more pronounced role of airflow dynamics, potentially less restricted at wider spacings.

PM10 Particle Reduction Dynamics: In the case of PM10 particles, the 3 cm electrode spacing was identified as the most efficient across all concentration brackets. This observation is critical, indicating that larger particles, such as PM10, which are more substantially affected by gravity and less by Brownian motion, necessitate an optimized equilibrium of electric field strength and airflow for effective filtration. The diminished efficiency at narrower and wider spacings suggests that extremes in electric field intensity and airflow dynamics may not be optimal for PM10 particle removal.

Electrode Spacing and Particle Dynamics: The pivotal role of electrode spacing in influencing removal efficiency is apparent across all particle sizes. This can be attributed to various factors, including the charge of the particles, the dynamics of airflow, and the intensity and distribution of the electric field. The interaction of these elements with particulate matter of varying sizes underscores the complexity inherent in designing efficient air purification systems.

Implications for Air Purification System Design: The outcomes of this investigation hold substantial implications

for the conceptualization and deployment of electrode-based dust removal systems. Grasping the interrelation between electrode spacing and particle size efficiency is critical in crafting air purifiers capable of adapting to diverse environmental conditions and particulate compositions.
benchmark for evaluating the performance of active filtration systems. [44-46]

Future Research Directions: Future investigations should delve into the influence of other variables such as ambient humidity, temperature, and the presence of additional pollutants. Studies focused on real-world applications would be invaluable in understanding the efficacy of these systems in various indoor and outdoor settings.

This experiment highlights the intricate interplay between electrode spacing, electric field dynamics, airflow, and particle characteristics within the realm of air purification. The results provide a foundational basis for forthcoming advancements in air purification technology, tailored to meet a spectrum of environmental requirements and particle profiles.

4. Conclusions:

The experimental outcomes demonstrate that electrode spacing plays a crucial role in the efficiency of particulate matter removal in an electrode-based dust removal system. The study revealed that a 3 cm electrode spacing is generally the most effective across all particle sizes, striking a balance between electric field strength and airflow dynamics. These results offer valuable implications for the design and optimization of air purification systems, emphasizing the need for tailored approaches based on particle characteristics and environmental conditions. Future research should explore additional variables such as humidity, temperature, and other pollutants, to further enhance the understanding and efficiency of these systems in diverse settings.

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