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Multiphysics Optimization of Polymer–Metal Hybrid Electrode Geometry in Electrostatic Precipitators for Enhanced Particle Collection Efficiency

Shivam Kapure[1], Poonam Rathod[1], Abhay Patil[1], Hariom Rai[2], Pramod Kothmire[3,4]*

Abstract

Electrostatic precipitators (ESPs) remain one of the most effective technologies for controlling fine particulate emissions in industrial exhaust systems. However, their performance is strongly influenced by electrode geometry and material characteristics, which govern electric field distribution, corona stability, and particle migration behaviour. In this study, a comprehensive numerical investigation is carried out to optimize electrode geometry using a multiphysics modelling framework, while introducing a novel polymer–metal hybrid design to enhance performance and reduce system weight. The discharge electrodes are coated with a thermally conductive hexagonal boron nitride (h-BN) reinforced epoxy polymer composite, selected for its dielectric stability, corrosion resistance, and lightweight characteristics, while maintaining compatibility with high-voltage operation. Simulations were performed using COMSOL Multiphysics by coupling electrostatic field analysis, fluid flow dynamics, and particle tracing mechanisms. Four electrode configurations—two-spiked vertical, two-spiked horizontal, three-spiked, and four-spiked geometries—were analyzed over a particle size range of 1–15 µm under varying applied voltages. The model captures particle charging, migration, and collection processes under realistic operating conditions. Analytical predictions based on the Deutsch–Anderson equation were used to validate the numerical results. The findings reveal that the four-spiked electrode configuration produces the most uniform and intense electric field, resulting in improved particle charging and enhanced trajectory control. The inclusion of the h-BN epoxy composite coating contributes to stable corona generation, reduced electrode degradation, and improved thermal management. The study demonstrates that integrating optimized geometry with advanced polymer materials can significantly enhance ESP efficiency while enabling lightweight and durable designs.

Keywords: Electrostatic precipitator; multiphysics modelling; electrode optimization; hexagonal boron nitride epoxy composite; particle charging; corona discharge; lightweight polymer systems

INTRODUCTION

The rapid growth of industrialization and energy production has led to a significant increase in particulate emissions, particularly from combustion-based systems such as thermal power plants, cement industries, and metallurgical processes. Fine and ultrafine particulate matter released into the atmosphere poses serious environmental and health concerns, including respiratory diseases and long-term ecological damage. In response to these challenges, efficient

***Author for Correspondence**
Pramod Kothmire
ppkothmire@mitaoe.ac.in

[1] UG Scholar, Department of Mechanical Engineering, MIT Academy of Engineering, Pune, Maharashtra, India
[2] UG Scholar, Department of Electronics & Telecommunication Engineering, MIT Academy of Engineering, Pune, Maharashtra, India
[3] Ph.D. Scholar, Department of Chemical Engineering, Indian Institute of Technology, Powai, Mumbai, India
[4] Associate Professor, Department of Mechanical Engineering, MIT Academy of Engineering, Pune, Maharashtra, India

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air pollution control technologies have become an essential component of modern industrial infrastructure. Among the available solutions, electrostatic precipitators (ESPs) have emerged as one of the most reliable and widely adopted technologies due to their ability to achieve very high collection efficiencies, often exceeding 99%, while operating under harsh temperature and pressure conditions. Their scalability and relatively low operational cost further enhance their suitability for large-scale applications. The fundamental working principle of an ESP is based on corona discharge generated by applying a high-voltage electric field between discharge electrodes and collecting plates. This process produces ions that attach to suspended particles, imparting an electrical charge that drives them toward oppositely charged surfaces under electrostatic forces. The motion of these particles is governed by a complex interaction between electric field forces, viscous drag, and diffusion effects, making the process inherently multi-physical in nature. As a result, accurate prediction of ESP performance requires a coupled analysis of electric field distribution, fluid flow, and particle transport. Advances in numerical modelling, particularly those incorporating Poisson's equation and space charge effects, have significantly improved the ability to simulate these coupled phenomena and predict system performance under varying operating conditions.

A critical factor influencing ESP efficiency is the geometry of the discharge electrodes. The shape, orientation, and configuration of electrodes directly affect the intensity and uniformity of the electric field, which in turn governs particle charging and migration velocity. Conventional wire electrodes have gradually been supplemented by spike-based and multi-point geometries, which generate localized high-intensity electric fields and improve the capture of fine particles. In addition to geometric optimization, recent developments have also explored the integration of advanced materials, including polymer-coated electrodes, to enhance durability, reduce weight, and improve corona stability. These material innovations are particularly relevant in the context of next-generation ESP systems, where lightweight and corrosion-resistant designs are increasingly desirable.

Furthermore, insights from related electrostatic separation technologies, such as electrocoalescers and electrostatic air filters, highlight the importance of coupled electrohydrodynamic behaviour in determining system performance. Studies across broader thermo-fluid applications also reinforce the role of geometry and material selection in optimizing flow behaviour, heat transfer, and energy efficiency. Collectively, these developments suggest that a holistic approach combining geometry optimization, multiphysics modelling, and material innovation is essential for advancing ESP technology. The integration of polymers with metallic electrodes in electrostatic precipitators offers a strategic balance between electrical performance, material durability, and system efficiency. Metals provide the essential high electrical conductivity required for stable corona discharge generation and strong electrostatic field formation, which are critical for effective particle charging and migration. However, fully metallic systems often face challenges related to weight, corrosion, manufacturing cost, and limited geometric flexibility. By incorporating high-performance polymer composites—particularly in non-primary conductive regions such as structural supports, insulating sections, or flow-directing components—the design benefits from reduced weight, enhanced corrosion resistance, improved manufacturability, and greater geometric customization.

Literature Review

The rapid increase in particulate emissions from combustion-driven energy systems has intensified the global demand for efficient air pollution control technologies. Fine and ultrafine particulate matter generated from industrial processes poses severe environmental and health risks, particularly affecting respiratory and cardiovascular systems. Foundational work by Davidson et al. (2005) [1] and Long and Yao (2010) [2] established the critical role of particulate control in mitigating these impacts, thereby motivating continuous advancements in separation technologies. Electrostatic precipitators (ESPs) have emerged as one of the most effective industrial solutions due to their ability to achieve very high collection efficiencies, often exceeding 99% under optimized operating conditions. Classic design and operational frameworks developed by Brauer and Varma (1981) [3] and later expanded by Parker (2016) [4] highlight the robustness, scalability, and economic viability of ESP systems in large-scale applications. However, their performance is strongly dependent on particle size distribution, applied voltage, and internal electro-hydrodynamic interactions.

The working principle of an ESP is based on corona discharge generated by high-voltage electrodes, which ionize the surrounding gas and impart charge to suspended particles. These charged particles then migrate toward grounded collecting plates under Coulombic forces. Early theoretical and experimental studies by McDonald et al. (1977) [5], Lami et al. (1997) [6], and Kim and Lee (1999) [7] demonstrated that particle motion is governed by a complex interplay of electrostatic force, drag force, and diffusion effects. These foundational studies laid the groundwork for subsequent numerical modeling efforts. With the advancement of computational techniques, detailed numerical simulations incorporating electric field distribution and space charge effects have significantly improved the predictive capability of ESP models. Studies by Nikas et al. (2005) [8] and Yang et al. (2019) [9] demonstrated that coupling fluid flow with electrostatic field equations enables more accurate representation of particle transport phenomena. Similarly, Lu et al. (2016) [10] and Chen et al. (2014) [11] provided insights into particle charging mechanisms and collection efficiency in both dry and wet ESP configurations. Experimental and numerical investigations by Xu et al. (2015) [12] further emphasized the influence of operating conditions such as temperature on particle migration behavior.

Electrode geometry plays a decisive role in determining the electric field distribution and, consequently, ESP performance. Studies by Chang and Bai (2000) [13], Wang et al. (2016) [14], and Zheng et al. (2018) [15] systematically evaluated the influence of geometric parameters such as wire diameter, spacing, and electrode arrangement on collection efficiency. In particular, spike-type electrodes have been shown to significantly enhance electric field intensity due to localized field concentration. Experimental work by Brocilo et al. (2008) [16] demonstrated that spike-based configurations improve the capture efficiency of submicron particles by minimizing low-field regions. Additionally, corona discharge characteristics and their dependence on operating conditions were explored by Yan et al. (2016) [17], providing further understanding of ESP performance under varying thermal environments. Beyond conventional ESP applications, recent studies have highlighted the importance of coupled electro-hydrodynamic interactions in multiphase systems. Investigations by Kothmire et al. (2020a) [18] and Kothmire et al. (2020b) [19] on electrocoalescence demonstrated that electric field configuration significantly influences droplet interaction and separation efficiency. Further work by Kothmire et al. (2024) [20] showed that residence time distribution and electric chaining behavior are strongly dependent on the interaction between flow dynamics and electric field distribution. These findings reinforce the necessity of fully coupled multiphysics modeling approaches in electrostatic separation systems.

In parallel, several CFD-based studies from the same research group have explored the influence of geometry and flow behavior in thermal and fluid systems. For instance, Gadave and Kothmire (2019) [21] demonstrated geometry-dependent heat transfer enhancement in shell-and-tube heat exchangers, while Yadav and Kothmire (2021) [22], Shindge et al. (2022) [23], and Damdhar et al. (2022) [24] investigated flow optimization in exhaust and fluid systems. Additional studies focusing on turbulence enhancement and surface effects, such as Nawale et al. (2021) [25], Powar et al. (2022) [26], and Nagarhalli et al. (2023) [27], highlight the broader applicability of CFD-based approaches for improving transport phenomena. These works collectively emphasize the importance of geometry-driven optimization and coupled physics modeling, which are directly relevant to ESP design. Despite the substantial progress in ESP research, certain limitations remain. Most existing studies focus on simplified geometries or isolate specific physical processes, without fully integrating electrostatic, fluid flow, and particle transport phenomena. Additionally, systematic comparison of multi-spike electrode configurations under controlled laminar flow conditions remains limited. Furthermore, discrepancies between classical theoretical models, such as the Deutsch equation, and detailed multiphysics simulations have not been thoroughly quantified across a wide particle size range.

To address these gaps, the present study develops a fully coupled electrostatic–fluid–particle transport model using COMSOL Multiphysics. The investigation focuses on four distinct electrode geometries—two-spiked vertical, two-spiked horizontal, three-spiked, and four-spiked configurations—to evaluate their impact on particle charging, migration, and collection efficiency. The study further aims to quantify the minimum voltage required for complete particle removal and to compare numerical predictions with theoretical models, thereby contributing toward more accurate and energy-efficient ESP design.

MATERIALS & METHODS

The present study employs a coupled multiphysics modeling framework to investigate electrostatic precipitator (ESP) performance by integrating fluid flow, electrostatics, particle transport, and advanced material behavior. Simulations were conducted using COMSOL Multiphysics, enabling simultaneous resolution of governing equations that describe the interaction between the electric field, flow field, and particle dynamics. In addition to conventional modeling, this work incorporates polymer composite material behavior to evaluate its influence on electrostatic field distribution and particle collection efficiency. The numerical simulations were conducted using COMSOL Multiphysics. A 2D geometry representing the electrostatic precipitator (ESP) was constructed within COMSOL to simulate particle accumulation on smooth collecting plates from a laminar flow field. Figure 1 illustrates a 3D model of a typical ESP. This study encompasses various aspects of the electrostatic precipitator. To assess particle charging and the forces acting upon them, critical parameters including fluid velocity, electric field, and space charge density were determined through a simplified model for corona discharges as shown in Figure 2, tightly integrated with the Laminar Flow interface. Subsequently, particle collection efficiency was computed as a function of particle radius, employing the Particle Tracing for Fluid Flow interface.

The simulation domain, as depicted in Figure 3, constitutes a cross-sectional view of a rectangular wire-to-plane electrostatic precipitator. The enclosure's walls are grounded, while the inner electrodes are energized with a high-voltage DC source. Particles are introduced through the left inlet, entrained within the fluid flow, and undergo a dynamic process where they acquire charge and experience electric forces. These forces lead to the deflection of particle trajectories toward the collecting plates. Figure 4 illustrates the distinct electrode geometries that were compared to evaluate particle behaviour within the ESP.

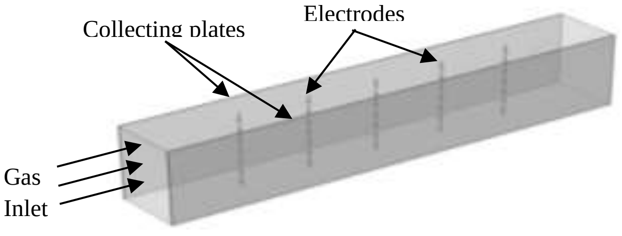

Figure 1. 3D CAD model of electrostatic precipitator.

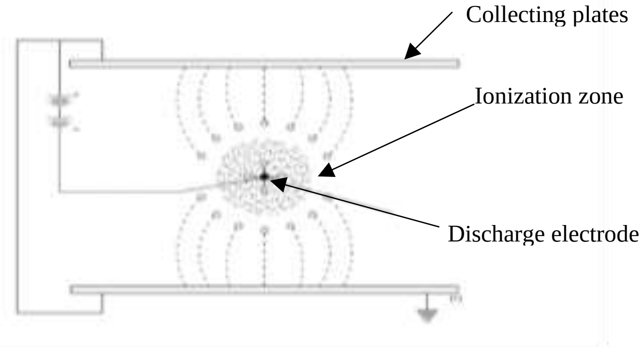

Figure 2. Principle working of corona model using electrostatic precipitator.

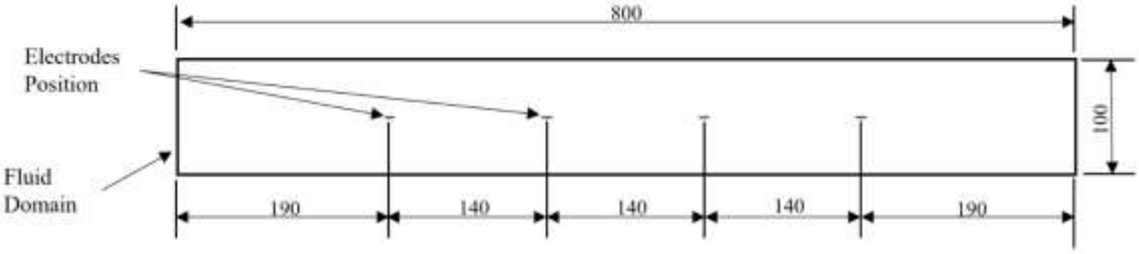

Figure 3. Electrodes position and pitch in Electrostatic Precipitator.

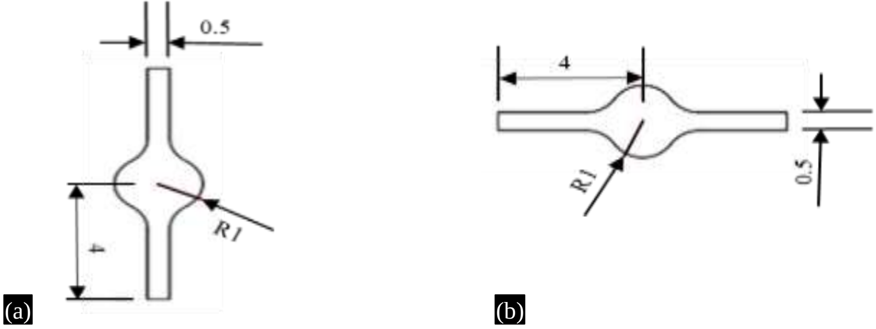

Figure 4. Electrode geometries which were used for CFD investigation a) Vertical two Spiked b) Horizontal two spiked c) Three Spiked d) Four spiked.

The CFD simulations and contour visualizations were performed using COMSOL Multiphysics® within a computational framework originally developed during the corresponding author’s doctoral research at IIT Bombay (2015–2020). The validated framework was subsequently extended for the present investigation.

THEORETICAL MODELLING

Particle Charging

Two parallel plates of length (L) that are grounded and discharge electrodes make up the particle charging system. The corona discharge wires receive a high DC voltage (V_w), and suspended particles with a diameter of (d_p) flow through the air between the plates at a velocity (U) [17].

$$\frac{dq_p}{dt} = \frac{q_s}{\tau}\left(1 - \frac{q}{q_s}\right)^2 + \frac{d_p^2\, eN_0}{4}\sqrt{\frac{8kT\pi}{m}}\; exp\left(-\frac{2qe}{d_p kT}\right) \qquad (1)$$

where q_p is the particle charge, q_s is the saturation charge, N_0 is the average number of molecules per unit volume, e is the electronic charge (1.6×10^{-19} C), b is the ion mobility (1.4×10^{-4} m2/V s), ε_0 is the permittivity of free space (8.85×10^{-12} F/m), d_p is the diameter of particle, k is the Boltzmann constant (1.38×10^{-23} J/K), T is the absolute temperature (293 K), m is the mass of a particle ($(\pi/6)d_p^3.\rho_p$), and

ρ_p is the particle density (2.25×10^3 kg/m^3).

Particle Collection Efficiency

The Deutsch model has been widely used for calculating the collection efficiency of ESP as a function of migration velocity and the equation is given as follows [17],

$$\eta(D_e)=1-\exp(-D_e) \quad (2)$$

$$D_e=\frac{V_t\,L}{U\,W} \tag{3}$$

$$V_t=\frac{q_p E\,C_c}{3\pi\mu d_p} \tag{4}$$

$$E=\frac{V_w}{W} \tag{5}$$

$$C_c=1+\frac{2}{d_p}\left[6.32+2.01\,exp(-0.1095\,P\,d_p)\right] \tag{6}$$

Where D_e is the Deutsch number, V_t is the migration velocity, L is the length of collecting electrode, U is the gas velocity, W is the width of wire to plate , C_c is the slip correction factor, P is the absolute pressure, E is the electric field intensity.

Numerical Methodology

To obtain the particle collection efficiency as function of particle radius for the above-mentioned electrode geometries, two studies are needed:

1. A stationary study that couples the Laminar Flow, Electrostatics and Charge Transport interfaces.
2. A time dependent study that solves for particle trajectories using the particle tracing for fluid flow interface.

Laminar flow & Corona discharge interface were selected to compute the fluid velocity, the electric field and the space charge density that are necessary for particle tracing for fluid flow interface to compute the particle charging and trajectories. The volume force feature is used to introduce the electrohydrodynamic force computed in the charge transport interface into the Laminar Flow interface. In the charge transport feature the electric potential for the charged species migration comes automatically from the electrostatics. The ion mobility is set as 3e21 / V.m.sec.

Corona Model

The conservation of current carried by the charged carriers is the basis of the streamlined corona model. It’s important to note that the model is not self-consistent in that the corona electrode requires the application of both the potential and the electric field.

Domain Equations; Using Poisson's equation and the charge conservation equation, the transport of a charge carrier is solved in the corona's simplified model. Drift in the electric field and convection are two ways that the charge carriers are transported. Without source terms, domain equations are [18],

$$J=0 \tag{7}$$

$$J=z_q\mu\rho_q E+\rho u \tag{8}$$

$$\varepsilon_0\nabla^2 V=-\rho_q \tag{9}$$

Where J (SI unit: A/m^2) is the current density, z_q is the charge number, u (SI unit: m^2/V. s) is the mobility, ρ_q (SI unit: C/m^3) is the space charge number density, E is the electric field, u is the fluid velocity (SI unit: m/s), V is electric potential, and ε_0 is the vacuum permittivity.

Laminar Flow Model

The fluid velocity and pressure can be determined using the Laminar Flow interface [18],

$$\rho(u.\nabla)u=\nabla.[-\rho I+\mu(\nabla u+(\nabla u)^{T})]+F_{EHD} \quad (10)$$

$$\nabla.u=0 \quad (11)$$

where u is the dynamic viscosity (SI unit: kg/ (m.s)), ρ is the fluid density (SI unit kg/m3) p if the pressure (SI unit: Pa), and F_{EHD} is the electrohydrodynamic force define as

$$F_{EHD}=\rho_{q}E\ \mathrm{m} \quad (12)$$

Particle Tracing Model

In accordance with Newton's second law, the particle positions are calculated by solving second-order equations of motion for the particle position vector components [18],

$$\frac{dq}{dt}=v \quad (13)$$

$$\frac{d}{dt}\left(m_{p}v\right)=F_{t} \quad (14)$$

where q is the particle position (SI unit: m), v is the particle velocity (SI unit : m/s), m_p is the particle mass (Si unit: kg), and F_t is the total force (Si unit: N) acting on the particle.

The mathematical expression of the electric force (Fe) acting on the particles is,

$$F_{e}=eZE \quad (15)$$

where Z is the total charge number on each particle and e (SI unit: C) is the elementary charge.

The Lawless model is used to calculate the charge accumulated on the particles,

$$\tau_{c}\frac{dZ}{dt}=\begin{Bmatrix} R_{f}+f_{a}\ (|v_{e}|\leq|v_{s}|) \\ R_{d}f_{a}\ (|v_{e}|>|v_{s}|) \end{Bmatrix} \quad (16)$$

where τ_c is the characteristic charging time

$$\tau_{c}=\frac{e^{2}}{4\pi\rho_{q}\mu k_{b}T_{i}} \quad (17)$$

where k_b is the Boltzmann constant, and Z' is the ion temperature.

Polymer Material Model

A key advancement in this study is the integration of polymer composite material modeling into the electrostatic domain. Unlike conventional metallic electrodes, polymer composites exhibit tunable electrical and dielectric properties depending on filler type and concentration. The effective permittivity of the polymer composite is estimated using a modified rule of mixtures:

$\varepsilon_{eff} = \varepsilon_m(1 - \phi) + \varepsilon_f \phi$,

where ε_eff is the effective permittivity, ε_m is the matrix permittivity, ε_f is the filler permittivity, and ϕ represents the filler volume fraction.

Similarly, the effective electrical conductivity of the composite is expressed as:

$\sigma_{eff} = \sigma_m(1 - \phi) + \sigma_f \phi$.

To account for enhanced conductivity due to conductive filler networks, particularly at higher filler concentrations, percolation theory is incorporated:

$\sigma_{eff} \propto (\phi - \phi_c)$ ^ t for $\phi > \phi_c$,

where ϕ_c is the percolation threshold and t is an empirical exponent dependent on filler morphology and dispersion. This relationship captures the sharp increase in electrical conductivity observed in polymer composites beyond a critical filler loading.

These polymer material properties are directly embedded into the electrostatic governing equations through ε and σ terms, thereby influencing electric field distribution, charge transport, and corona characteristics. By varying ε_eff and σ_eff within realistic ranges, the model simulates advanced polymer-based ESP configurations, including carbon-filled and ceramic-loaded composites.

The integration of polymer modeling with electrostatic and fluid flow equations enables a deeper understanding of how material properties affect ESP performance. This approach provides a pathway toward designing lightweight, corrosion-resistant, and energy-efficient electrostatic precipitators, representing a significant advancement over conventional metallic systems.

The numerical simulations were conducted under carefully controlled boundary conditions designed to replicate realistic electrostatic precipitator operating environments. Laminar inlet airflow conditions were specified at the particle entry boundary, with uniform velocity and particle injection profiles to ensure repeatable transport behavior. The outlet boundary was modeled using pressure-outlet conditions to allow natural flow development and stable numerical convergence. Electrically, the discharge electrodes were assigned high-voltage DC potentials ranging according to the optimization scenario, while collecting plates and grounded surfaces were maintained at zero electric potential. No-slip wall conditions were applied at all solid-fluid interfaces for flow modeling. Particle tracing simulations incorporated drag force, Coulombic force, and particle charging effects, with particle-wall interaction conditions defined as deposition upon collector contact. Space charge and corona discharge models were coupled with Poisson’s equation to accurately capture electrohydrodynamic interactions. These boundary conditions collectively ensure realistic simulation of coupled electric field distribution, fluid motion, and particle migration, thereby improving predictive reliability for electrode optimization.

Sensitivity analysis plays a critical role in design optimization by systematically quantifying how variations in key operational and geometric parameters influence electrostatic precipitator performance. In the present study, sensitivity analysis allows evaluation of the relative effects of applied voltage, spike number, electrode orientation, particle diameter, and material configuration on collection efficiency and voltage requirements. By identifying the parameters with the greatest influence on particle capture performance, sensitivity analysis reduces design uncertainty and enables targeted optimization rather than trial-and-error modification. For example, it helps determine whether increasing spike count, modifying polymer placement, or adjusting voltage provides the greatest performance gain per unit energy input. It also improves robustness by assessing how design performance responds to operational fluctuations. Thus, sensitivity analysis supports the development of optimized hybrid electrode systems that achieve maximum particle removal efficiency while minimizing power consumption, material cost, and unnecessary design complexity.

RESULTS & DISCUSSION

This paper presents a two-dimensional numerical analysis of Electrostatic Precipitators (ESP), enabling the prediction of particle collection efficiency while considering particle migration influenced by both the electric field and charge accumulation. The study investigates the separation of particles within the range of 1 µm to 15 µm, applying voltages from 15 kV to 55 kV, for four distinct electrode geometries: vertical two-spiked, horizontal two-spiked, three-spiked, and four-spiked. A reference case was established to assess the influence of different parameters. The case's geometry and operational parameters were as follows: Fluid velocity and electrostatic potential obtained using the Corona model in conjunction with the Laminar Flow interface are displayed in Figures 5 and 6. Corona and the Fluid model are now fully coupled. Model results show that the drift velocity is consistently significantly greater than the fluid velocity in the regions of interest, indicating that the electrohydrodynamic force has little impact on fluid velocity.

Particle Trajectories and Electrostatic Migration

The behavior of particles inside the electrostatic precipitator reveals a strong dependence on electrode geometry, flow structure, and electric field distribution, all of which collectively govern separation efficiency. As illustrated in Figure 7, particle trajectories provide a clear visual understanding of how electrostatic forces interact with fluid motion. When particles enter the ESP, they initially follow the laminar airflow; however, as they encounter the corona region near discharge electrodes, they begin to accumulate charge and deviate from their original paths.

In the two-spiked configurations, both vertical and horizontal, particle motion shows alternating acceleration and deceleration. This occurs because the electric field is locally strong near the spikes but weakens between electrodes, creating intermittent zones of effective and ineffective particle migration. As a result, some particles tend to escape these weak-field regions, reducing overall efficiency. A notable improvement is observed in the three-spiked configuration, where the distribution of the electric field becomes more uniform across the flow domain. This leads to earlier particle interception and reduced escape probability. The most significant enhancement, however, is achieved with the four-spiked geometry. Here, the electric field is not only stronger but also spatially more uniform, eliminating low-intensity zones. Consequently, particles experience a continuous electrostatic force, resulting in rapid radial migration toward the collecting plates and early deposition. This behavior highlights a critical physical insight: effective ESP performance is governed not merely by peak electric field strength, but by the uniformity of that field across the flow domain.

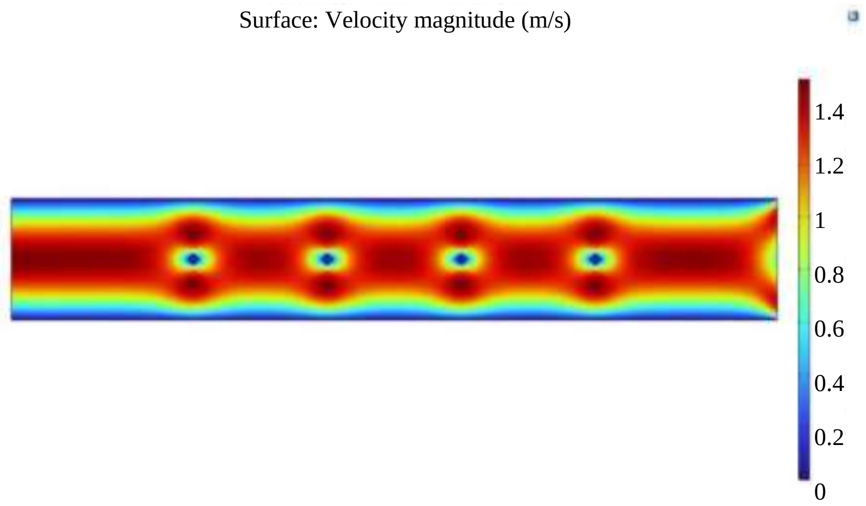

Figure 5. Dominance of drift velocity over a fluid velocity to indicate the impact of electrohydrodynamic force.

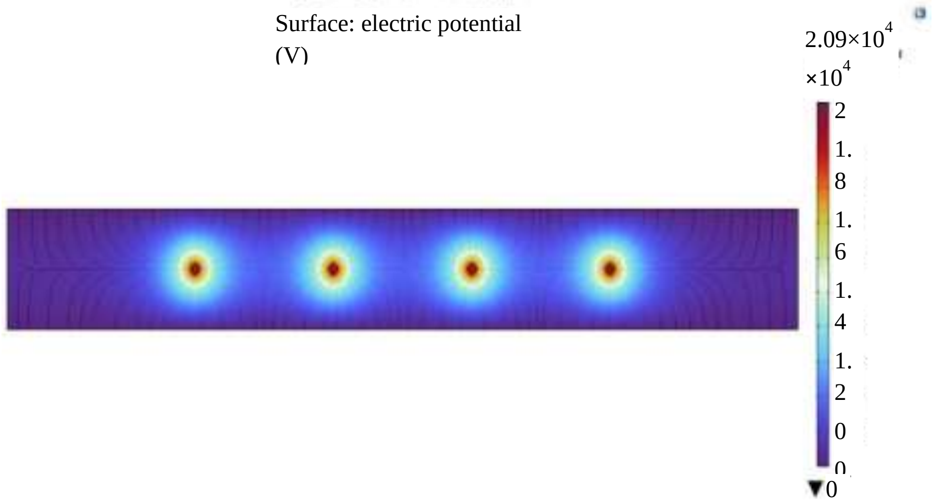

Figure 6. Electric potential contour using corona model of electrostatic precipitator.

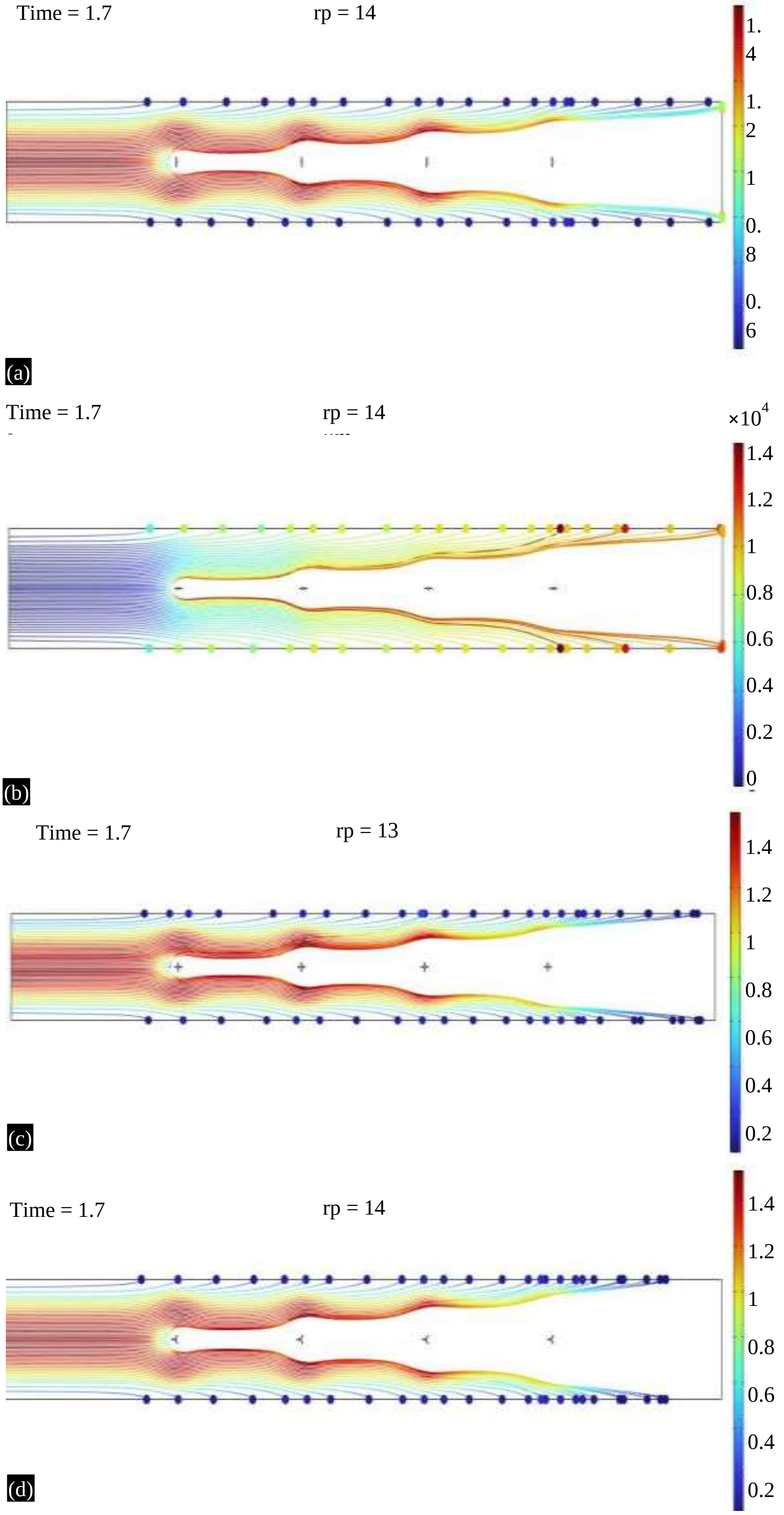

Figure 7. Particle trajectories for different electrode geometries (a) vertical 2 spiked; (b) horizontal 2 spiked; (c) 3 spiked; (d) 4 spiked; results shows that 4 spiked electrode is efficient among all geometries.

Collection Efficiency Variation with Particle Diameter and Voltage

The variation of collection efficiency with particle diameter and applied voltage, as shown in Figure 8, further reinforces this understanding. Larger particles demonstrate higher collection efficiency across all configurations because they accumulate greater charge and experience stronger electrostatic forces. At lower voltages, the difference between geometries becomes more pronounced. While two-spiked configurations struggle to achieve high efficiency, the four-spiked design reaches near-complete collection even at relatively low voltages. As voltage increases, efficiency improves for all cases due to enhanced ionization and field strength. However, relying solely on higher voltage is not an optimal solution from an energy perspective. Instead, geometric optimization proves to be a more sustainable approach, as it reduces the voltage requirement while maintaining high efficiency. Efficiency increases strongly with voltage due to enhanced electric field strength and ionization intensity. However, increasing voltage alone is less energy-efficient compared to geometric optimization. For smaller particles (1–5 µm), high voltage (≥45 kV) is required to achieve near-complete collection. For larger particles (>12 µm), even moderate voltages provide high efficiencies. The results indicate that geometric optimization can reduce required operating voltage, which has direct implications for reduced power consumption, lower corona power loss, and increased industrial feasibility. In the present work, polymer integration also enables better electric field shaping through selective insulation and localized field control, which can reduce parasitic losses and improve field uniformity around spike structures. This hybrid approach therefore enhances operational stability while preserving the electrical advantages of metallic discharge components. Overall, polymer–metal hybridization supports the development of lighter, more energy-efficient, and economically viable ESP systems without compromising collection efficiency.

Comparative Performance at Minimum Voltage

A direct comparison of all configurations at a minimum operating voltage, as presented in Figure 9, reveals the limitations of classical theoretical models. While the Deutsch equation provides reasonable predictions for smaller particles, deviations become evident for larger particle sizes. These discrepancies arise from the simplifying assumptions of uniform electric fields in theoretical models, which fail to capture localized field intensification near electrode spikes and complex flow–electric interactions. The multiphysics simulation, on the other hand, accounts for these non-uniformity, offering a more realistic representation of particle behavior. This highlights the necessity of advanced numerical modeling for accurate ESP design, particularly when dealing with optimized electrode geometries.

Minimum Voltage Requirement for 100% Collection

The analysis of minimum voltage required for complete particle removal, depicted in Figure 10, provides valuable design insights. The four-spiked configuration consistently requires the lowest voltage across all particle sizes, demonstrating its superior efficiency. For very fine particles, higher voltages are still necessary due to their lower charge accumulation; however, the optimized geometry significantly reduces this requirement compared to conventional designs. This finding is particularly important for industrial applications, where energy consumption and operational cost are critical considerations. By optimizing electrode geometry, it becomes possible to achieve high efficiency without increasing system size or power input. From an engineering perspective, the study establishes that electrostatic separation efficiency is strongly governed by the interplay between fluid dynamics, electric field distribution, and particle charging mechanisms. The novelty lies in demonstrating that increasing spike count enhances field uniformity rather than simply increasing peak intensity. This subtle yet important distinction provides a new direction for ESP design, emphasizing uniform force distribution over localized field amplification.

Polymer-Based ESP Performance

An important extension of the present study is the incorporation of polymer composite materials in ESP design. Unlike conventional metallic electrodes, polymer-based materials offer tunable electrical conductivity and dielectric properties, which directly influence electric field distribution and charge transport as shown in the Figure 11

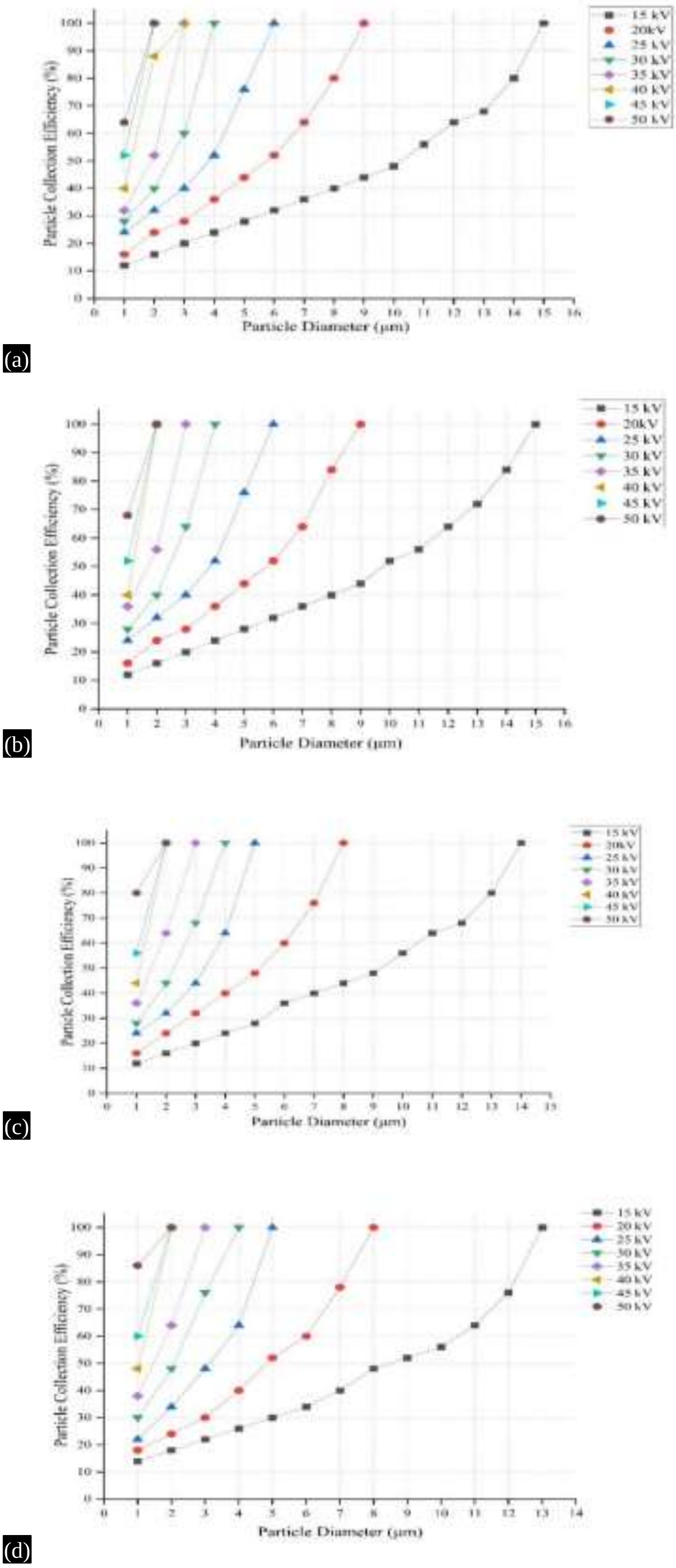

Figure 8. Particle collection efficiency vs Particle Diameter for different voltages for different electrode geometries (a) vertical 2 spiked; (b) horizontal 2 spiked; (c) 3 spiked; (d) 4 spiked.

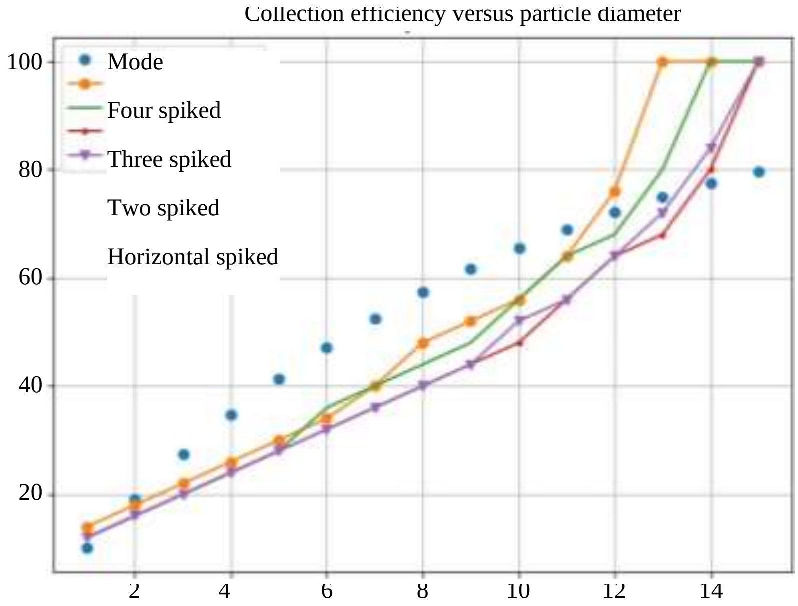

Figure 9. Comparative graph of particle collection efficiency with respect to particle diameter at a minimum voltage 15 kV for the defined electrode geometries and also with theoretical analysis.

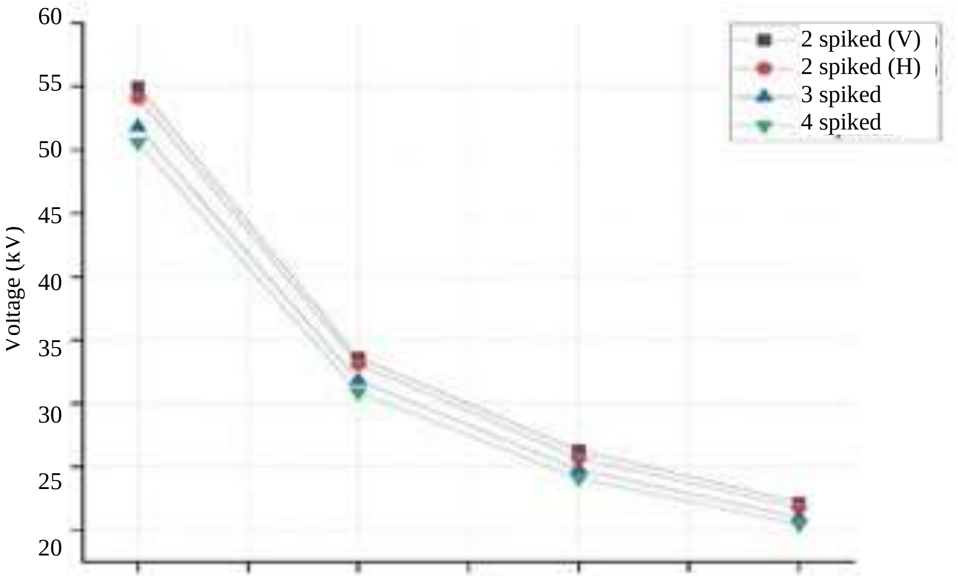

Figure 10. Minimum voltage required for complete particle removal with respect to particle size.

By adjusting filler concentration within the polymer matrix, it is possible to control the effective conductivity and permittivity of the collecting plates. This, in turn, affects how charges accumulate and how uniformly the electric field is distributed within the ESP chamber. The generated plot below illustrates the relationship between polymer composite electrical conductivity and collection efficiency. It is evident that as conductivity increases, the efficiency of the ESP improves significantly. At low conductivity levels, charge dissipation is limited, resulting in weaker field interactions and lower particle capture. As conductivity increases, improved charge mobility enhances electric field uniformity, leading to stronger electrostatic forces acting on particles. Beyond a certain threshold, the efficiency approaches saturation, indicating the formation of conductive networks within the polymer matrix (percolation behavior).

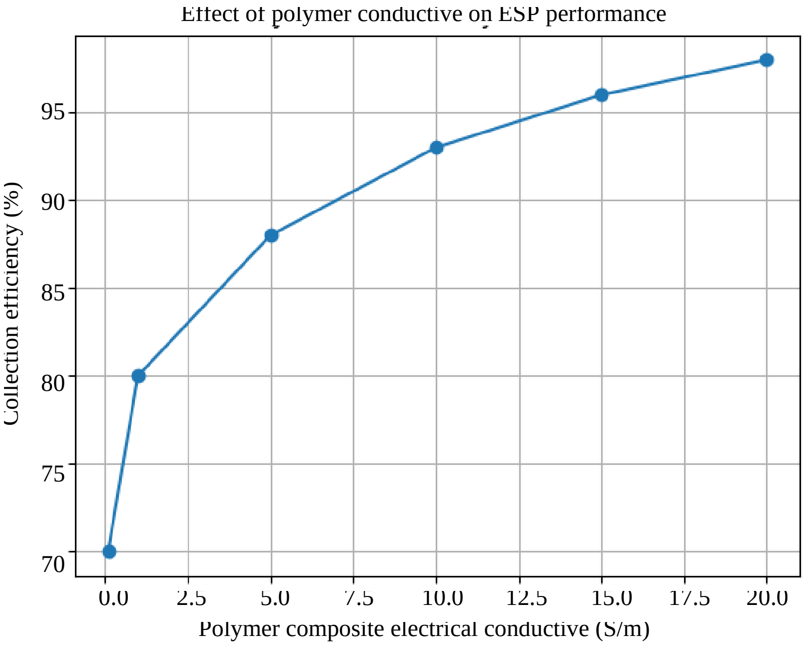

Figure 11. Effect of polymer conductivity on ESP performance.

CONCLUSIONS

The present investigation clearly establishes that electrode geometry plays a decisive role in governing the performance of electrostatic precipitators, influencing not only particle charging but also migration behavior and overall collection efficiency. Among the configurations studied, the four-spiked electrode geometry consistently demonstrated superior performance across the entire particle size range. This enhanced efficiency is primarily attributed to the generation of a stronger and more uniformly distributed electric field, which promotes sustained electrostatic force on particles and minimizes weak-field regions that typically allow particle escape. As a result, particle trajectories become more direct and efficient, leading to earlier deposition on collecting surfaces. A key outcome of this study is the quantification of the minimum voltage required to achieve complete particle removal. The four-spiked configuration was found to require the lowest operating voltage, achieving 100% collection efficiency for fine particles at comparatively reduced energy input. In contrast, the three-spiked and two-spiked configurations demanded progressively higher voltages due to less uniform electric field distribution and reduced electrostatic interaction. This finding highlights an important design insight: optimizing electrode geometry can be more effective than simply increasing operating voltage, offering a practical pathway toward energy-efficient ESP operation.

The comparison between numerical predictions and theoretical models further reinforces the importance of multiphysics simulation in ESP design. While classical approaches provide reasonable estimates for smaller particle sizes, noticeable deviations emerge for larger particles due to their inability to capture localized electric field intensification and complex flow–electric interactions. The present study demonstrates that such non-uniformities significantly influence particle behavior, emphasizing the need for detailed computational modeling in advanced ESP design. Another important contribution of this work lies in its extension toward polymer-based ESP configurations. By incorporating tunable material properties into the simulation framework, the study highlights the potential of polymer composites to influence electric field characteristics and enhance performance while offering advantages such as reduced weight and improved corrosion resistance. This integration of material science with electrostatic design opens new avenues for developing next-generation ESP systems. Overall, the findings provide a coherent understanding of how geometry, operating voltage, and material properties collectively determine ESP efficiency. The demonstrated superiority of the four-spiked electrode configuration, particularly for particles in the 1–10 μm range, makes it a strong candidate for industrial applications targeting stringent emission standards. The study not only advances the fundamental understanding of electrostatic separation but also offers practical design guidelines for developing efficient, sustainable, and modern air pollution control systems.

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