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Numerical Simulation and Structural Optimization of Electrostatic Precipitators for Particle Purification in Space Capsules

Lingzi Meng¹, Hao Wang¹✉, Nan Su¹, Mengdie He¹, Fan Mo², Cheng Liu³

To address the demand for performance optimization of electrostatic precipitators (ESPs) for space applications, this study numerically solves and analyzes the electric field characteristics and microparticle flow behaviors of ESP structures by coupling the discrete phase model (DPM) with the user-defined scalar (UDS) transport equation. Taking the structural optimization of electrodes and dust collection plates as the core entry point, four types of ESP structures were established for comparative research, namely the conventional Flat-type, W-type, W1-type (wave plate-auxiliary electrode composite type) and Single-type (horizontal single-electrode type). The research focuses on investigating the synergistic effect of the pre-installed filter screen, the flow field distribution inside the ESP structure, the characteristics of electric field and charge density, as well as the correlation between particle motion trajectories and dust collection efficiency. The results show that after adopting strategies including expanding the area of dust collection plates, optimizing electric field distribution and extending the corona discharge region, the dust collection efficiency of particles with sizes ranging from 0.2 to 1.0 μm in the W1-type and Single-type structures both exceeds 92%. Compared with the Flat-type structure, the dust collection efficiency of the W1-type and Single-type structures for 0.5 μm particles is increased to over 90%, representing an improvement of approximately 40% relative to the conventional structure. In addition, the pre-installed filter screen enables the synergistic purification of mechanical interception and electrostatic collection, further enhancing the dust removal efficiency, which verifies the feasibility of the multi-stage purification mode. This study provides a theoretical basis for the design and optimization of electrostatic precipitators in the aerospace field.

Keywords Electrostatic precipitator; Structural optimization; Collection efficiency; Pre-filter

1. Introduction

With the continuous advancement of space resource exploration and development, the significance of ensuring the safety of crewed space missions and the reliable operation of spacecraft has become increasingly prominent. Spacecraft cabin particulate dust removal technology has thus emerged as a core component of the space station's environmental control and life support systems [1]. Complex particulates that remain suspended for extended periods in microgravity environments present multidimensional and high-risk potential hazards [2]. First, studies have demonstrated that fine particles with a diameter of less than 10 μm can penetrate the barriers of the human respiratory system, leading to severe respiratory diseases, cancer, and other health issues [3]. Second, certain conductive metal debris with sharp edges are highly likely to cause short circuits in precision instruments and electronic equipment,

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block heat dissipation systems, or contaminate optical systems. In extreme cases, such debris may even trigger catastrophic on-orbit failures. However, cabin particulates derive from diverse sources and exhibit significant variations in physical and chemical properties, with complex and variable spatiotemporal distribution and evolution patterns. Moreover, these particulates lose their natural sedimentation capability under microgravity conditions, remaining suspended in the cabin air for long durations, which substantially increases the difficulty of accurate assessment and effective control of cabin air quality [4]. In conclusion, for the unique environment of spacecraft cabins, the development of efficient, reliable, and autonomously operable particulate dust removal and control technologies has become one of the key core technologies to ensure the smooth implementation of crewed space missions, support the long-term on-orbit operation of space stations, and enable future deep-space exploration.

The electrostatic dust removal technology is regarded as a highly promising technology for treating particulate matter in spacecraft cabins due to its high efficiency, low energy consumption, and long service life [5, 6]. This technology first charges the dust particles through a high-voltage electric field, then uses the electric field force to direct the charged dust to be adsorbed onto the dust collection plate, ultimately achieving gas-solid separation and realizing the separation of gas and solid [7, 8]. Compared with traditional mechanical dust removal technologies, the electrostatic dust removal technology operates based on the mechanism of Coulomb force and is independent of gravity, and has been proven to maintain a dust removal efficiency of over 98% in microgravity conditions [9]. To further enhance the ability of electrostatic dust removal for tiny particles, especially to strengthen the capture efficiency of submicron particles, optimizing the complex electrode structure and studying the synergistic effect between the dust collection plate and the high-voltage electrode have become the main methods to improve the dust removal efficiency [10]. For example, changing the traditional flat dust collection plate to a corrugated plate structure [11] not only enables it to adapt to uneven electric field distribution to capture more particles, but also forms a relatively stable airflow within the channel, promoting particle deposition. Additionally, using needle-shaped, star-shaped, or thorn-shaped discharge electrodes with pointed structures can generate a strong local electric field concentration effect, significantly enhancing the corona discharge intensity and expanding the ionization area range, thereby ensuring the efficient charging of submicron particles that are difficult to capture [12].

The electrostatic dust removal process involves complex physical behaviors such as electric field, flow field, and particle charging-migration-deposition [13]. In recent years, related research has mainly focused on revealing the process mechanism, optimizing structural design, etc., based on the improvement of dust removal efficiency. In terms of mechanism exploration, Kim et al. [14] successfully analyzed the electric field distribution, spatial charge density, and ion convection laws using characteristic line method, finite difference method, and lattice Boltzmann method, and verified the effectiveness of the coupling method in the analysis of complex physical processes. Dastoori

et al. [15] clarified the significant influence of the presence of particulate matter and its particle size on the uniformity of the airflow through simulation. Aiswarya et al. [16] designed a micro single-stage wire mesh square section based on computational fluid dynamics (CFD), demonstrating a capture efficiency of up to 99.99% for various pollution sources, with advantages of low energy consumption and low by-product emissions. Zhang et al. [17] revealed that the influence of diffusion charging on dust removal efficiency increases as the particle diameter decreases and the applied voltage decreases, and is crucial for capturing sub-micron particles; Song et al. [18] found that particles within the concentration range of $3\text{--}20\text{ mg/m}^3$ do not affect the capture efficiency, and particles exhibit periodic fluctuations within the channel; Gao et al. [19] established a two-stage electrostatic dust removal numerical model, clearly showing that the dust removal length is proportional to the square of the dust collection plate spacing and inversely proportional to the discharge voltage, and large particle diameters are mainly charged by spatial charge, with the dust removal length being proportional to the particle diameter and inversely proportional to the inlet air velocity.

In terms of the design and optimization of electrostatic structures, Shen et al. [20] designed various new types of dust collection plate structures such as flat plates, C-shaped, triangular, and W-shaped ones. After combining them with the discharge electrodes, they systematically explored the electrodynamic (EHD) flow characteristics and particle transport laws within the electrostatic dust collector, and further revealed the mechanism of the effects of different dust collection electrode shapes on the EHD flow pattern and electrical properties. Zhu et al. [21] compared and evaluated the dust collection processes of ESP under the two dust collection plate structures of corrugated plates and parallel plates. The results confirmed that structural optimization could effectively weaken the adverse effects of the EHD channel flow on the dust removal efficiency. Abdel-salam et al. [22] used numerical simulation methods to analyze the electric field distribution, initial discharge voltage, and discharge current characteristics in the tip region of the needle-shaped lines under two configurations of parallel plates and grid plates. They found that the combination of grid plates and needle-shaped lines could significantly reduce the initial discharge voltage. Brocilo et al. [23] further explored the matching effects of I-type, C-type, U-type, etc. dust collection plates with different discharge electrodes, clarified the regulatory laws of electrode geometric structures on ion density, electric field distribution, and particle dust collection efficiency, and the results showed that compared with traditional circular discharge electrodes, the peak-shaped discharge electrodes had a significant advantage in dust collection efficiency for fine particles. Neimarlija et al. [24] constructed an advanced fully coupled numerical simulation method, relying on which they quantitatively analyzed the electric field and flow field characteristics of the C-shaped special-shaped dust collection plate electrostatic dust collector, providing theoretical support for the optimization design of electrode structures.

Currently, electrostatic dust removal technology has been extensively studied and applied in laboratory and production workshop settings. However, there are few reports on the electrostatic collection of ultrafine particles (0.1 - 1 μm) in microgravity environments [25]. Particularly, there is a lack of systematic exploration of the mechanism and evolution law of improving the collection efficiency by optimizing the electrostatic dust removal structure. Therefore, this paper proposes a new electrostatic dust removal scheme integrating a filter screen structure, and constructs a coupling model of filter screen and porous medium: on the one hand, the porous medium model is used to accurately represent the pressure drop characteristics of fluid flowing through the filter screen; on the other hand, the filtering function of the discrete phase model (DPM) is used to achieve pre-capture of large particle dust, effectively enhancing the adaptability of the dust removal system to particles of various sizes. At the same time, this paper further improves the numerical characterization methods of the discharge and mass transfer processes, using user-defined functions (UDF) to accurately solve the high-speed ion jet caused by the electron avalanche effect, and combining custom scalars (UDS) to quantitatively characterize key parameters such as electric field strength, charge density, and Coulomb force; by correcting the current density model with a power law function, ensuring that the numerical simulation results are highly consistent with the classical experimental conditions. Finally, by optimizing the configuration of the collection plate and the electrode arrangement, the improved design of the electrostatic dust removal structure is completed, providing theoretical basis and technical support for the structural design and performance optimization of electrostatic dust removal devices in microgravity scenarios such as space stations.

2. Numerical method

In the numerical simulation of the electrostatic dust removal process under microgravity conditions, the particle-laden gas flow driven by the electric field force exhibits turbulent characteristics, and its flow behavior is highly complex [26]. To address this challenge, the present study systematically investigates the coupling mechanisms among multiple physical processes, including gas-phase turbulence, porous-media filtration, corona discharge, and particle charging. A multi-physics coupled model is consequently established within the Euler–Lagrange framework, which consistently integrates the electric field, flow field, and particle dynamic field.

2.1. Gas flow model

Owing to the airflow disturbance induced by the ion wind effect, the majority of the flow within the electrostatic active region exhibits turbulent characteristics. Accordingly, the incompressible Reynolds-averaged Navier – Stokes (RANS) turbulence model is employed in this study to numerically simulate the flow-field distribution inside the dust removal structure, thereby satisfying the fundamental conservation requirements of the mass and momentum equations.

$$\nabla \cdot (\rho \overline{u_g}) = 0 \quad (1)$$

$$\rho \left[\frac{\partial \overline{u}_g}{\partial t} + \overline{u}_g \cdot \nabla \overline{u}_g \right] = -\nabla \overline{p} + \mu \nabla^2 \overline{u}_g + \rho_{ion} \overline{E} \quad (2)$$

where, $\overline{u}_g$ the gas velocity, ρ the gas density, μ the gas dynamic viscosity, P the absolute pressure, ρ_{ion} the space charge density, $\rho_{ion} \overline{E}$ indicates the ion wind effect of the electric field on the flow field [27].

2.2. Porous medium model

To accurately characterize the flow resistance behavior within the filter-screen region, a porous medium model is constructed in this paper by introducing appropriate source terms into the momentum equation, thereby equivalently representing the resistive effect of the porous structure on the fluid. The source term is formulated based on the Darcy – Forchheimer law, which concurrently accounts for both viscous resistance and inertial resistance [28]. The governing expression is given as follows:

$$S_i = -\left(\frac{\mu}{\alpha} v_i + C_2 \frac{1}{2} \rho |v| v_i\right) \quad (3)$$

where, α represents the permeability, C_2 represents the inertial resistance coefficient, ρ represents the density of the fluid.

2.3. Electric field model

In the context of fluid dynamics, gas ionization occurs in the vicinity of the high-voltage electrode surface, generating ions that are subsequently driven by the electric field force and migrate directionally toward the dust collection plate [25]. The electrodynamic behavior of charged particles within both the corona discharge zone and the dust collection zone is governed jointly by the electric field Poisson equation and the current continuity equation. Specifically, the Poisson equation establishes the quantitative relationship between the electric potential distribution and the spatial charge density, and is expressed as follows:

$$\nabla^2 \varphi = -\frac{\rho_{ion}}{\varepsilon_0} \quad (4)$$

where, φ represents electric potential, ε_0 is the vacuum dielectric constant, $8.854 \times 10^{-12} F/m$; ρ_{ion} is the ion charge density. The continuity equation of current characterizes the flow and accumulation of charges:

$$\nabla \cdot J = 0 \quad (5)$$

$$J = \rho_{ion} (k_{ion} \overline{E} + \overline{u}_g) - D_e \nabla \rho_{ion} \quad (6)$$

$$\overline{E} = -\nabla V \quad (7)$$

where, E represents the electric field intensity, J represents the ion current density, k_{ion} represents the ion mobility, $\overline{u_g}$ represents the gas velocity and D_e represents the ion diffusion coefficient.

Calculate the charge distribution and electric field intensity in the space using user-defined scalar quantities, and convert equations (4) to (7) into transport equations:

$$\nabla(F_i\Phi - \Gamma_\Phi \nabla\Phi) = S_\Phi \quad (8)$$

where, Φ represents the target scalar (electric potential or ion charge density), F_i represents the flow rate, Γ_Φ represents the diffusion coefficient, and S_Φ represents the source term.

Table 1. Parameters of the transport equation

Equation	Φ	F_i	Γ_Φ	S_Φ
Electric potential	φ	0	ε_0	ρ_{ion}
Charge density	ρ_{ion}	$\rho(k_{ion}\overline{E} + \overline{u_g})$	ρD_e	0

The parameters governing the scalar transport equations for electric potential and charge density are summarized in Table 1. These equations are solved iteratively in conjunction with Equation (7). Specifically, the charge density is determined by solving the Poisson equation for electric potential (Equation (4)), while the electric field intensity distribution is obtained from the electric field equation (Equation (7)). The convergence and physical consistency of the solution are subsequently verified by checking whether the current continuity equation (Equation (6)) and the numerical error criterion (Equation (11)) are satisfied.

$$\rho_w^n = (1 - \omega)\rho_w^{n-1} + \omega\rho_w^{n-1} \left(E_w^{n-1} / E_{peek} \right)^\gamma \quad (9)$$

$$E_{peek} = 3.1 \times 10^6 m\delta \left(1 + 0.03 / \sqrt{\delta r} \right) \quad (10)$$

$$\left| (E_w^n - E_{peek}) / E_{peek} \right| < 1 \times 10^{-5} \quad (11)$$

where, ρ_w and E_w represent the average values of the space charge density and electric field intensity on the surface of the high-voltage electrode respectively, n is the number of iterations, E_{peek} is the electric field intensity in the peek semi-empirical formula, δ is the relative density of the gas, which is 1 when is 0.1 Mpa .

2.4. Particle charging

The charge quantity of particle corona discharge mainly depends on the size of the particle. The combined charging model proposed by Lawless [29] can be used to calculate the corona charge quantity of ultrafine particulate

matter:

$$\frac{dq_p}{dt} = \begin{cases} \frac{q_s}{\tau} \left(1 - \frac{q}{q_s}\right) + \frac{2\pi\alpha\rho k_{ion} k_B d_p}{e}, & q < q_s \\ \frac{\alpha}{4\tau} (q - q_s) \exp\left(\frac{e(q_s - q)}{2\pi\epsilon_0 k_{ion} k_B T d_p}\right), & q > q_s \end{cases} \quad (12)$$

$$\alpha = \begin{cases} 1, & e_{norm} < 0.525 \\ \frac{1}{(e_{norm} + 0.457)^{0.575}}, & e_{norm} \geq 0.525 \end{cases} \quad (13)$$

$$q_s = 3 \frac{\epsilon_r}{\epsilon_r + 2} \pi \epsilon_0 d_p^2 E \quad (14)$$

$$e_{norm} = e d_p E / (2 k_B T) \quad (15)$$

$$\tau = \frac{4\epsilon_0}{\rho_{ion} k_{ion}} \quad (16)$$

where q_s is the saturation charge, ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the particles, τ is the time constant of particle charging (the time taken to reach half of the saturation charge), k_B is the Boltzmann constant.

3. Model parameters and boundary conditions

As shown in Figure 1, the micro-particle electrostatic dust removal structure mainly consists of the air intake pipe, the filter screen, and the electrostatic dust collection area. Among them, the core configuration of the electrostatic dust collection area is two grounded dust collection plates and multiple groups of equally spaced high-voltage electrodes, and the high-voltage electrodes are symmetrically arranged in the middle area of the dust collection plates. Given that the geometric configuration of the dust collection plates and the arrangement of the electrodes are the key factors determining the dust collection efficiency, this paper designs four differentiated electrostatic dust collection area structures: Flat-type, W-type, W1-type, and Single-type. The specific size parameters of each structure are shown in Table 2. Figure 1 (a) is the traditional flat structure of Flat-type, where the dust collection plate is a parallel straight plate, and the high-voltage electrodes are evenly distributed at the center axis of the two dust collection plates; Figure 1 (b) shows the W-type structure based on Flat-type, which optimizes the dust collection plate into a zigzag configuration. This not only effectively increases the dust collection area, but also its wavy structure can induce the formation of vortex effects in the flow field, prolonging the residence time of micro-particles in the dust collection area, and theoretically significantly improving the capture efficiency of micro-particles; Figure 1 (c) shows the W1-type structure, which adds auxiliary electrode plates on the basis of W-type, further strengthening the regional electric field intensity and enhancing the driving effect on charged particles; Figure 1 (d)

shows the Single-type structure, which optimizes the traditional vertically discrete high-voltage electrodes into a horizontal arrangement to achieve the design goal of expanding the corona discharge area.

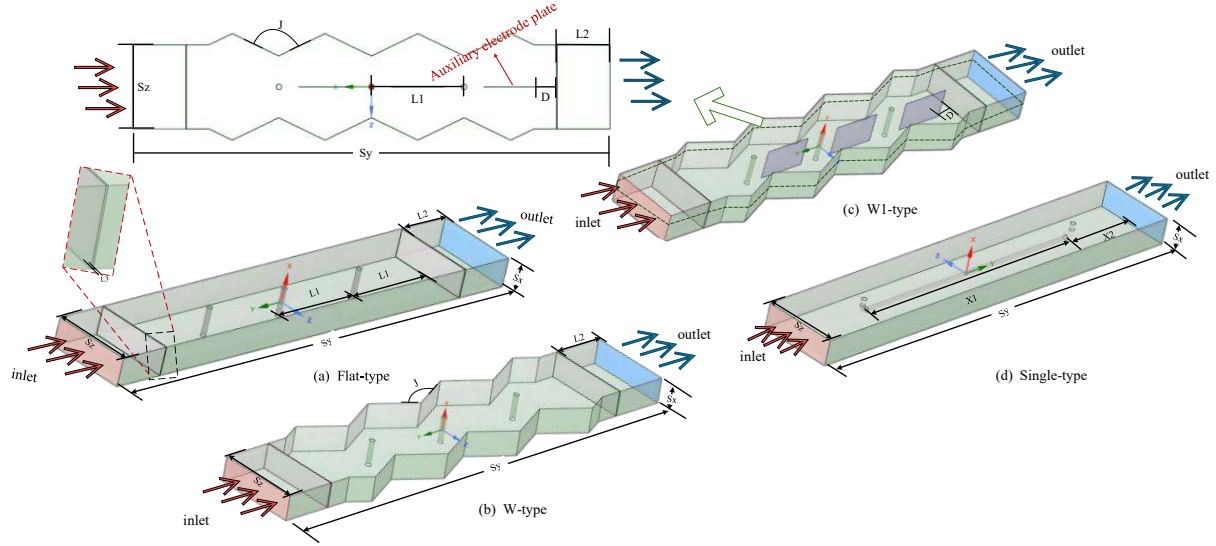


Figure 1. Schematic of the four precipitator designs

Table 2. Geometric Dimensions of the Electrostatic Precipitation Section (mm)

S_x	S_y	S_z	L_1	L_2	L_3	x_1	x_2	D	J
5.25	90	15	17.4	10	0.1	17.6	54	3.7	130°

The boundary condition parameters for the numerical simulation of this article are shown in Table 3. Among them, the potential of the high-voltage electrode is set to the system working voltage; the ion wind field induced by the high-voltage corona discharge presents a typical double-spiral distribution characteristic within the electric field space. The potentials of the dust collection plate, gas inlet and outlet, as well as the space charge density, are all set to 0. The filter screen adopts a mesh filtering structure [30], and its porosity value is set to 0.346; the viscous resistance coefficient and inertial resistance coefficient can be quantitatively calculated based on the flow rate-pressure drop correlation curve shown in Figure 2, combined with fluid dynamic viscosity, porous medium thickness and medium density, etc. parameters.

Table 3. Boundary conditions for the simulation

Boundary	gas	Particle	Discharge wires	Discharge wires
inlet	v_0	v_0	$\frac{\partial \varphi}{\partial n} = 0$	$\frac{\partial \rho_{ion}}{\partial n} = 0$

outlet	p_0	Escape	$\frac{\partial \varphi}{\partial n} = 0$	$\frac{\partial \rho_{ion}}{\partial n} = 0$
Collecting plates	No slip	Trap	$\varphi = 0$	peek's law as show(8b)
Discharge wires	v_i (UDF)	Rebound	$\varphi = \varphi_w$	$\frac{\partial \rho_{ion}}{\partial n} = 0$

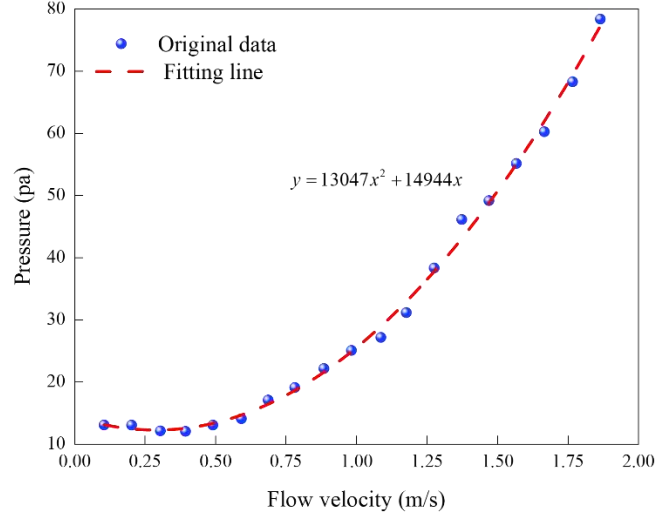


Figure 2. Relationship between flow velocity and pressure drop^[30]

4. Results and discussion

4.1. Model validation

To verify the reliability and accuracy of the established simulation model, this paper constructed a geometric model that was exactly the same as the Kallio experiment, and applied the same key parameters such as gas flow rate, high-voltage electrode voltage, and particle size. The simulation results were compared and verified with the experimental data [31]. The geometric configuration of the electrostatic dust collection area in the Kallio experiment is shown in Figure 3. By correcting the model coefficients, the current density - electric field strength function relationship obtained from the simulation was made to match the experimental law shown in Figure 4; within the experimental voltage range of 15 kV - 17 kV, the maximum deviation between the simulation results and the experimental data was less than 7%, and the two showed good consistency. On this basis, this paper further used the experimental data of Penney and Matick, etc., to verify the calculation results of the potential distribution of the corrected model; the simulation and experimental comparison curves of the potential distribution along the x-axis under different y values are shown in Figure 5 [32], and the deviation between the two is small. Figure 6 shows the simulation and experimental comparison results of the dust removal efficiency of particles of different diameters, and this result indicates that under the same operating conditions, the simulation dust removal efficiency of different particle diameters has good consistency with the measured values from the Kallio experiment.

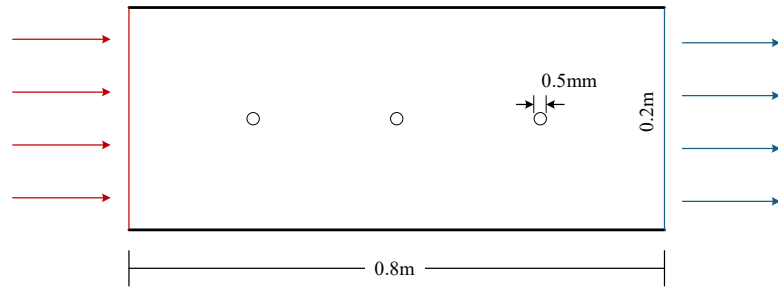


Figure 3. Schematic of the ESP used in experimental study by Kallio

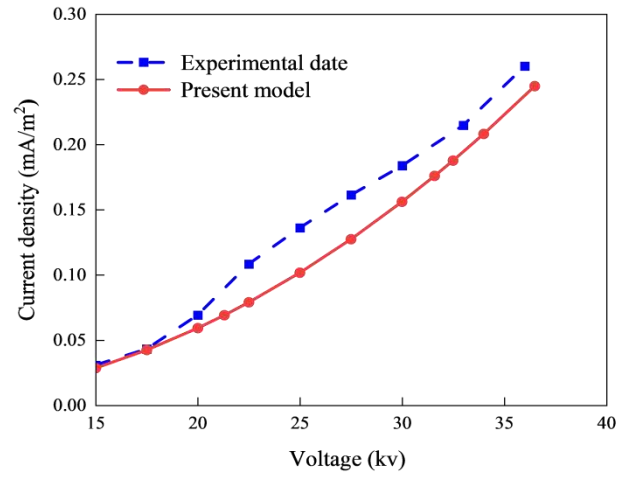


Figure 4. Simulated and experimental current density versus applied voltage

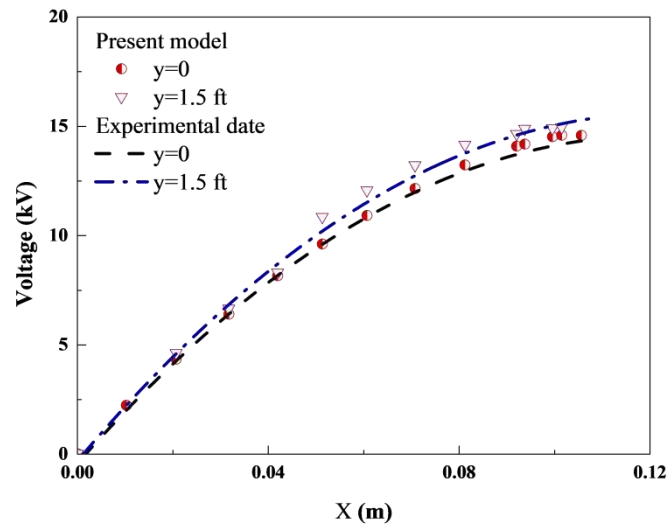


Figure 5. A Comparative study of potential distribution in a wire-plate ESP: numerical simulation versus experiment

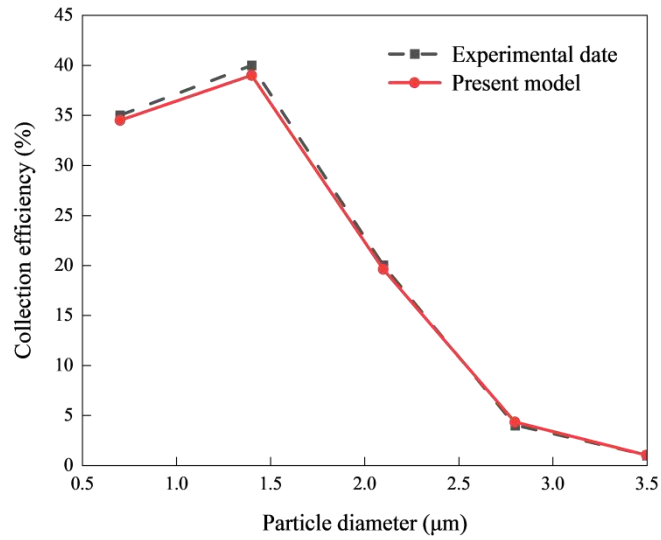


Figure 6. Simulated and experimental collection efficiency versus particle diameter

4.2. Effects of Filter Screen

In the engineering design of electrostatic precipitation systems, the pre-filter screen has become a mainstream pretreatment scheme for dust removal. Relying on physical interception, it can trap large-size particulate matters in advance, thereby effectively reducing the dust treatment load of the subsequent electrostatic precipitation unit. Figure 7 compares the dust removal performance of mixed dust airflow with and without the filter screen. The test condition was set at an air flow velocity of 1.5 m/s, and the mixed dust airflow consisted of equal proportions of particles with four particle sizes: 0.7 μm, 1 μm, 2 μm, and 4 μm. Figure 7(a) presents the working condition without a filter screen: particles larger than 2 μm directly enter the electrostatic precipitation channel and are fully captured on the surface of the collecting plate under the electric field, whereas a small amount of fine particles of 1 μm and 0.7 μm cannot be collected effectively. Figure 7(b) shows the case equipped with a pre-filter screen. After pretreatment, all particles larger than 2 μm are efficiently intercepted, and the treatment efficiency of the subsequent electrostatic precipitation unit is remarkably improved. The simulation results reveal that installing a pre-filter screen increases the overall particle collection efficiency of the system by approximately 10%, while greatly alleviating the operating load of the electrostatic precipitation channel.

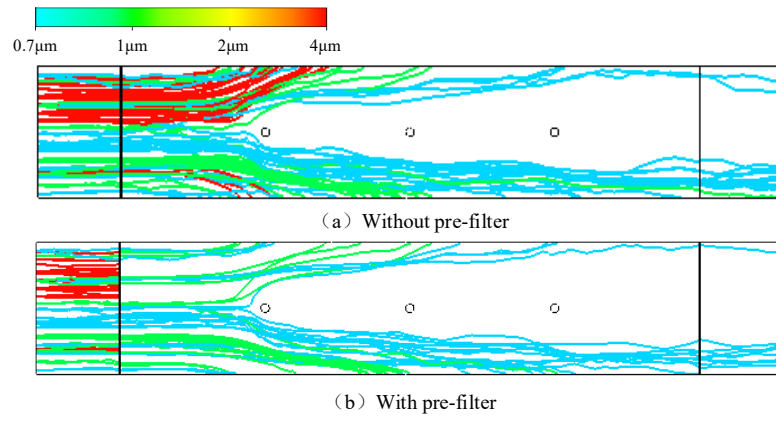


Figure 7. Effect of pre-filter installation on the collection efficiency of particulate-laden flow

Figure 8 compares the pressure distribution characteristics at 3 mm from the central line of the dust removal channel ($z=3\text{mm}$) with and without the pre-filter screen. In the case without the pre-filter screen, the relative air pressure decreases gently from 4.5 Pa at the inlet to 0 Pa at the outlet, showing a uniformly decaying trend highly consistent with the typical characteristics of frictional resistance. Meanwhile, the total pressure drop of the system is extremely low and exerts no obvious adverse effect on airflow driving. After installing the pre-filter screen, the inlet air pressure surges to 76.967 kPa. A sharp pressure drop occurs as the airflow passes through the filter screen region. Once entering the electrostatic precipitation zone, the pressure decline becomes mild again and stabilizes at approximately 39 kPa. When the airflow flows through the filter structure a second time, a second steep pressure drop takes place, reducing the pressure to 4.672 kPa, followed by a gradual smooth decay toward the outlet pressure. The above results demonstrate that although the pre-filter screen can markedly improve the dust removal performance of the system, it greatly increases the fluid flow resistance. Consequently, airflow driving requires power equipment with higher rated power, which conflicts with the power-saving requirements of microgravity environments such as space cabins.

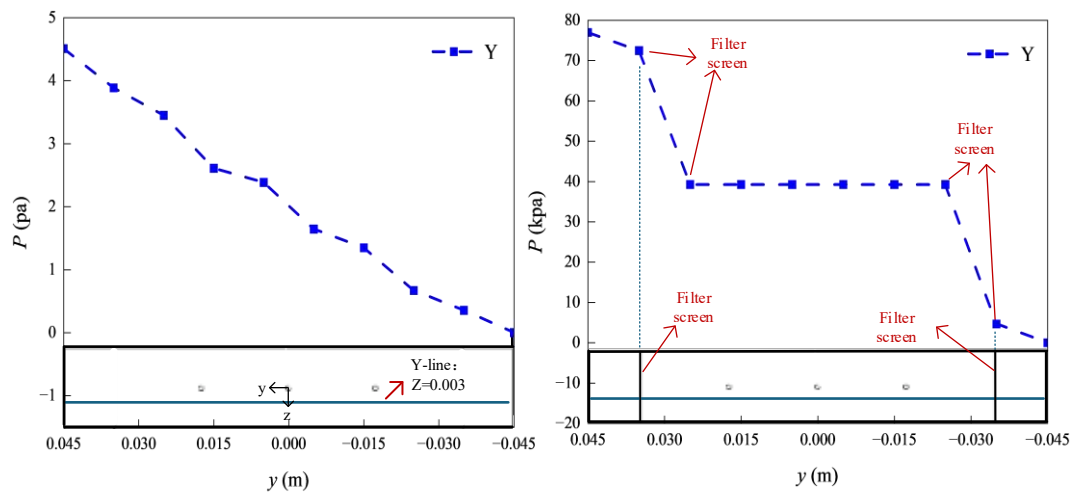


Figure 8. Pressure distribution at 3 mm from the centerline: effect of the pre-filter (Left: without pre-filter; Right: with pre-filter)

4.3. Effects on Flow Field Distribution

Figure 9 presents the flow field distribution patterns of four electrostatic dust removal structures under different air intake speeds. As can be seen from the figure, the Flat-type structure has a simple and regular geometric configuration, resulting in a uniformly stable overall flow field. However, the movement behavior of charged particles within this structure is mainly dominated by fluid inertia forces, and the directional driving effect of the electric field on the particles is relatively weak, which leads to a relatively low electrostatic collection efficiency. In contrast, the W-type structure's zigzag-shaped dust collection plates will significantly disturb the airflow movement, and the uniformity of the flow velocity and streamline distribution in the flow field significantly decreases. The concave-convex configuration of the dust collection plates is the core factor in regulating the flow field characteristics: the inward-contracting peak and valley areas reduce the cross-sectional area of the channel, and the flow velocity at this position significantly increases; the outward-projecting wave peak areas increase the cross-sectional area of the flow channel, and connect with the contracting area to form an expansion-type flow channel structure. When the high-speed airflow passes through the contracting section and enters the expansion section, it is pulled by the fluid viscosity, and the high-speed mainstream will drive the low-speed fluid in the wave peak area to move synchronously, thereby forming a significant vortex effect. For charged particles, the existence of the vortex significantly prolongs their residence time in the wave peak area of the dust collection plate, significantly increasing the probability of particle contact with the dust collection plate, thus the dust removal efficiency of the W-type structure is superior to that of the Flat-type structure.

As the intake flow velocity increases, the flow field disturbance caused by the boundary layer separation in the electrode backwind area intensifies, and the pressure gradient within the area significantly increases. Under this condition, the pressure difference resistance of charged particles flowing through this area in the resultant force significantly increases, while the trend of particle directional migration towards the dust collection plate dominated by Coulomb force is significantly weakened. To address this issue, this study proposes the W1-type structure with additional auxiliary plates and the Single-type structure with single-line horizontal arrangement. These improved structures not only effectively suppress the adverse effects of flow field disturbance in the electrode backwind area on particle movement, but also expand the effective range of the corona discharge area, ensuring that Coulomb force always occupies a dominant position in the particle force system, and ultimately achieving a significant improvement in electrostatic dust removal efficiency.

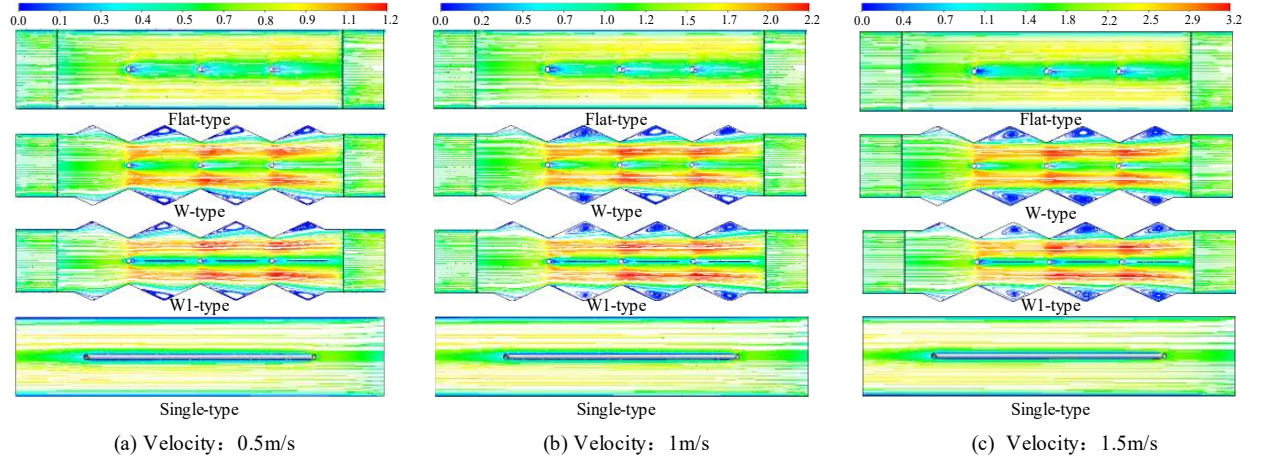


Figure 9. Flow field distribution under different inlet velocities for four ESP configurations (voltage: 10 kV)

4.4. Effects on Electric Field and Current Density

Electric field intensity is the core physical quantity that directly characterizes the strength of the Coulomb force's effect on micro-particles. Figure 10 shows the distribution cloud of electric field intensity under the condition of an airflow speed of 0.5 m/s and an electrode potential of 10 kV. From the figure, it can be seen that the electrode, as the potential source term, has a relatively high potential in the surrounding area, and the potential value decreases gradually with the increase of the distance from the electrode. The potential distribution of the Flat-type structure shows an elliptical characteristic, and the area between the electrodes forms a distinct low potential zone. When the particle flow passes through this low potential zone, the Coulomb force acting on it significantly weakens, and the dominant proportion of fluid inertia force increases accordingly, thereby having an adverse effect on the overall dust removal efficiency. The potential and electric field intensity distribution pattern of the W-type structure is similar to that of the Flat-type structure, and there is also a low potential area between the electrodes; however, thanks to the concave-convex configuration of the electrodes in the flow cross-section direction, when charged particles flow through the channel contraction area, they will be driven by a stronger Coulomb force.

In response to the inherent defect of the above structure, which has low potential areas, the potential distribution along the flow direction of the W1-type structure is more uniform compared to the W-type structure. The range of the low potential area is significantly compressed, and the electric field intensity can cover the entire dust collection area, allowing the Coulomb force acting on the particles to have a longer duration and a more sufficient effect. As a result, the dust removal efficiency of this structure is superior to that of the W-type structure. For the Single-type structure, which optimizes the traditional vertical electrodes into a single-line horizontal arrangement, the potential along the flow direction shows a long elliptical distribution, and there are no obvious low potential areas along the air flow path. The electric field intensity of this structure can cover the entire dust collection area, and its cross-sectional distribution characteristics are similar to those of the W1-type model, with the advantage of uniform

distribution. On this basis, the range and duration of the action of the corona discharge region on the particles are further improved, which is more conducive to the directional migration of charged particles towards the dust collection plate, and ultimately achieves the optimization and improvement of the dust removal effect.

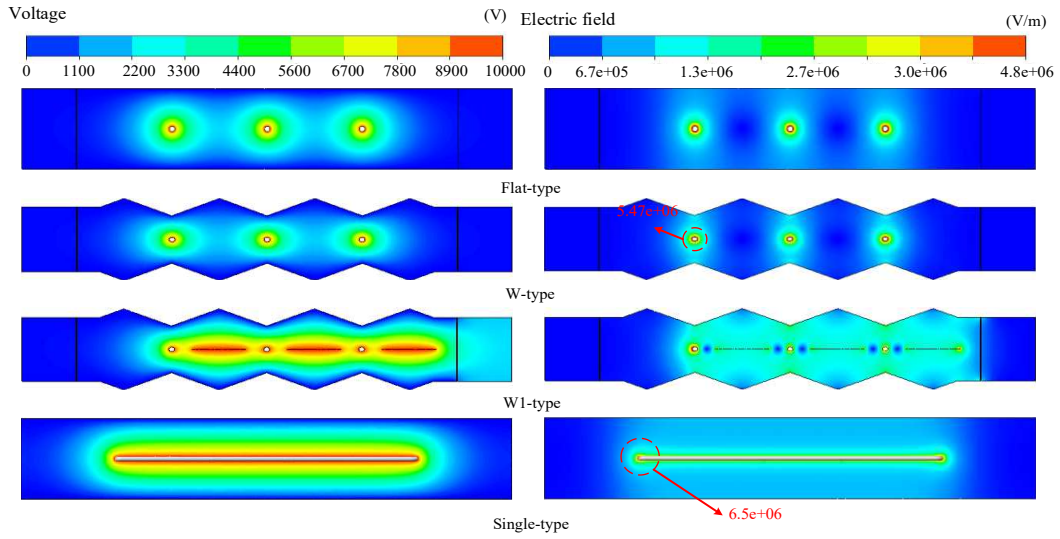


Figure 10. Electric field distribution

In the analysis of electrostatic dust removal performance, the current density distribution near the dust collection plate is the core indicator for evaluating the efficiency of charge transport and particle collection. Figure 11 shows the Y-line current density curve and the cross-sectional current density distribution cloud map under the working conditions of an airflow speed of 0.5 m/s and an electric potential of 10 kV. The distribution characteristics of current density are significantly different from the distribution of electric potential. For the Flat-type dust removal structure, the current density distribution patterns around the three electrode lines are different: the current density around the central electrode is distributed in an elliptical shape, while the current density distribution patterns of the two side electrodes are also approximately elliptical, but their long axes are perpendicular to the dust collection plate. Since ultrafine particles mainly obtain charges through the diffusion charging method, a larger range of high current density distribution areas are more conducive to promoting the charging process of particles.

From the Y-line current density curve, it can be further seen that the current density distribution of the Flat-type electrostatic dust removal structure and the W-type electrostatic dust removal structure both show symmetrical characteristics along the central electrode line, and the current density peaks all appear near the electrodes. The particles in this area can obtain more charges and are driven by the Coulomb force to migrate towards the dust collection plate. W1-type effectively optimizes the current density distribution state by adding auxiliary electrode plates. Under the influence of the auxiliary electrode plates, the current density values near the second and third electrodes are higher than that of the first electrode, and the current density peak can reach 0.613 mA/m². Single-type presents the most uniform and overall higher current distribution characteristics, and the current density peak

appears near the single electrode. In summary, W1-type enables particles to be uniformly charged in the channel, and its electric field strength can cover the entire dust collection area. The dominant role of the Coulomb force on the particles is more significant, thereby accelerating the migration rate towards the dust collection plate, and ultimately achieving better dust removal effect.

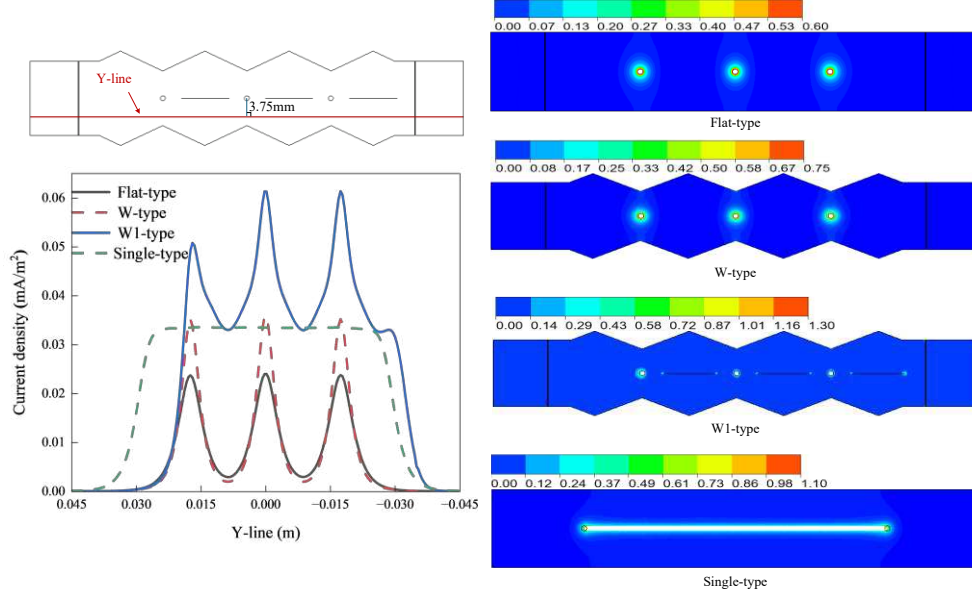


Figure 11. Distribution of current density in the vicinity of the collector plate

4.5 Particle Motion Trajectory and Dust Removal Efficiency

Selecting micro-particles with diameters of 0.2 μm , 0.35 μm , 0.5 μm , 0.7 μm and 1 μm , a comparative analysis was conducted on the dust removal efficiency under two electrode potential conditions of 10 kV and 5 kV. Figure 12 shows the distribution of the trajectories of different particle sizes under the conditions of 10 kV electrode potential and 0.5 m/s inlet velocity. From the figure, it can be seen that in the Flat-type structure, when the particle flow passes through the first electrode area, it is significantly deflected towards the dust collection plate under the dominance of the Coulomb force; however, as the particles migrate along the flow direction, they are affected by the dual influence of the low potential area between the electrodes and the backwind area of the electrode, and the deflection effect gradually weakens, and the deflection distance towards the dust collection plate significantly decreases. The movement trajectory pattern of the particles in the W-type structure is similar to that of the Flat-type structure. Additionally, the combined effect of the contraction-expansion effect of the channel cross-section in the flow direction and the vortex effect at the peak is superimposed, resulting in a slight improvement in the dust removal efficiency compared to the Flat-type structure. Figure 13 presents the comparison results of dust removal efficiency under the low potential (5 kV) and high flow rate (1 m/s) conditions. The data shows that the W-type structure improves the dust removal efficiency of particles with diameters of 0.2 μm to 0.5 μm by approximately 10%, and for larger particle diameters, the improvement can reach up to 20%.

In response to the inherent defect of the traditional structure, which is the flow field disturbance in the low potential area and the backwind area of the electrode, the improved W1-type and Single-type structures exhibit more excellent capture performance. Among them, the majority of particles of different diameters in the W1-type structure show a directional migration towards the dust collection plate, while only a few particles move along the original flow direction; the optimization effect of the Single-type structure is more significant. Under the same working conditions, particles of all particle sizes can stably deviate towards the dust collection plate area. Under the 5 kV low potential condition, for the 0.5 μm particle diameter that is difficult to capture, the dust removal efficiency of both the W1-type and Single-type structures can reach above 85%, demonstrating outstanding low potential adaptability.

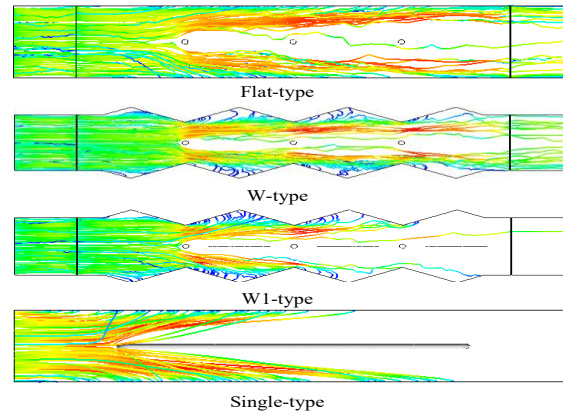


Figure 12. Particle trajectory velocity under a flow velocity of 0.5 m/s

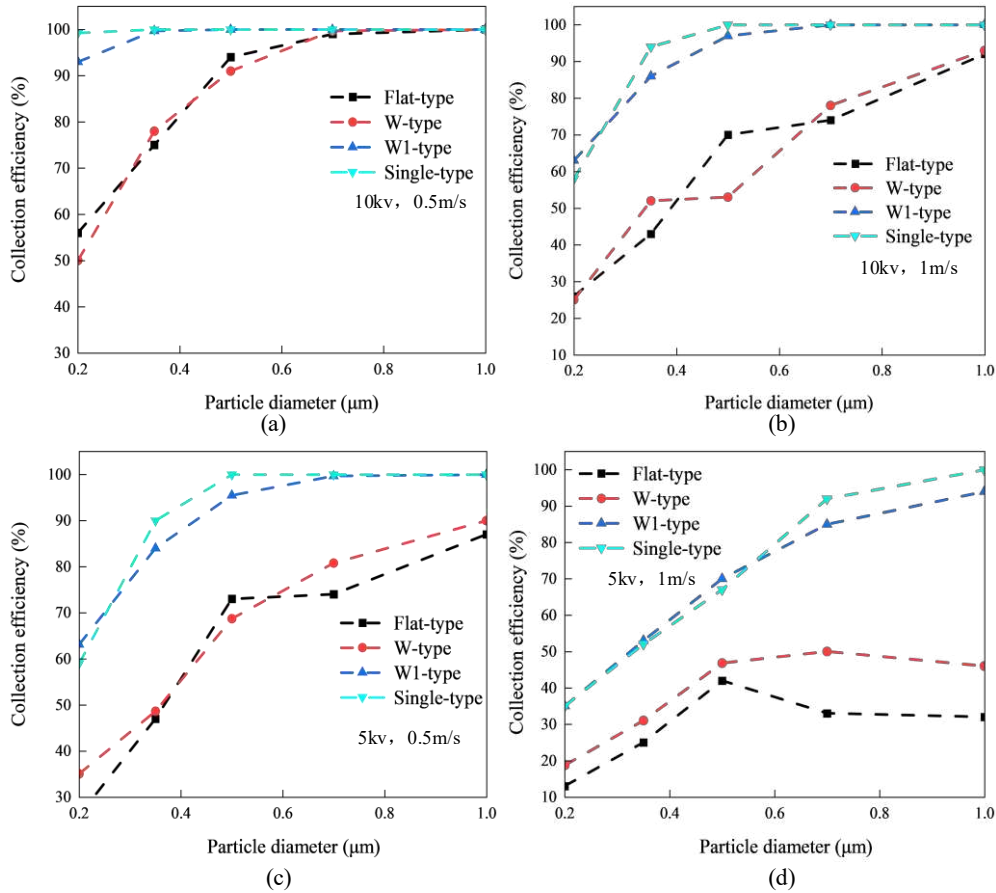


Figure 13. Collection efficiency of four ESP structures as a function of particle diameter

5. Conclusions

This paper presents the design and systematic analysis of four typical electrostatic precipitator configurations, with an in-depth investigation into the coupled interactions among the airflow field, high-voltage electric field, and particle capture dynamics throughout the dust removal process. The findings demonstrate that structural optimization of the electrostatic precipitator can substantially enhance dust collection performance, particularly in improving the capture efficiency of ultrafine particulate matter. The principal contributions and conclusions of this study are summarized as follows:

(1) The installation of a pre-filter screen effectively enhances the overall dust removal efficiency by approximately 10%, primarily through the interception of coarse particulate matter. However, this improvement is accompanied by a notable increase in flow resistance, which raises the system pressure drop by 76.9625 kPa and consequently leads to higher operational energy consumption. In contrast, in the absence of such a screen, particulate matter across the entire size spectrum directly enters the electrostatic precipitation zone. This not only reduces the collection efficiency but also adversely affects the long-term service life of the equipment.

(2) Four structural configurations were constructed and examined in this study: the traditional flat-plate type, the W-type, the W1-type (employing a corrugated plate as the auxiliary electrode), and the single-electrode type. For each configuration, the distribution of the internal flow field, the characteristics of the electric field and charge density, as well as the correlation between particle trajectory and dust removal efficiency, were systematically analyzed. Through structural optimization, the flow field within the collection zone was effectively regulated to suppress the adverse effects of flow disturbances in the wake region of the electrode on particle motion. Meanwhile, the effective range of the corona discharge region was extended, ensuring that the Coulomb force consistently dominated the force balance acting on the particles. Consequently, the electrostatic precipitation performance was significantly improved.

(3) The dust collection efficiency of each precipitator configuration was evaluated for particles with diameters of 0.2 μm , 0.35 μm , 0.5 μm , 0.7 μm , and 1 μm . For both the Single-type and W1-type structures, the removal efficiency exhibited a trend of initial increase followed by a plateau as particle diameter increased. Notably, for particles in the size range of 0.2 μm to 0.5 μm , both the W1-type and Single-type configurations achieved collection efficiencies exceeding 90%, representing an improvement of approximately 40 percentage points over the conventional flat-plate structure.

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