ASIIMETRIK
JURNAL ILMIAH REKAYASA DAN INOVASI
p-ISSN: 2655-1861, **e-ISSN:** 2716-2923
Volume **8** Number **2**, **2026**

Parametric Analysis of Disperse Phase Soot Transport and Mass Capture in an Ionized Diesel Exhaust Crossflow

Bangbang Kurniawan, Asep, Agung Sudrajat, Dhimas Satria, Dwinanto Sukamto, Sunardi, Syarif Abdullah, Mekro Permana Pinem*
Engineering, Faculty of Engineering, Universitas Sultan Ageng Tirtayasa, Banten, Indonesia

***Correspondence email**: mekro_pinem@untirta.ac.id*

Received: 28/05/2026 Revised: 30/05/2026 Accepted: 05/06/2026

Abstract: This study investigates the influence of applied voltage, electrode spacing, and operating duration on the collection rate of fine particulate matter ($PM_{2.5}$) in a diesel engine Electrostatic Precipitator (ESP). Using a laboratory-scale ESP integrated with a diesel exhaust system, experiments were conducted at three voltage levels (1.5, 4.5, and 6.7 kV), three electrode spacings (1.5, 2.0, and 2.5 cm), and three operating durations (3, 5, and 7 min). Precipitator performance was quantified using the gravimetric method. The peak particulate collection rate reached 1.10 mg/s under optimized operating parameters (6.7 kV applied voltage, 1.5 cm electrode spacing, and a 7 min operational duration. Statistical analysis via Analysis of Variance (ANOVA) indicates that operating time is the most dominant factor governing the recorded particulate collection rate. While increasing the applied voltage and minimizing electrode spacing demonstrated clear positive physical trends in collection performance by boosting local electric field intensity, their standalone individual effects were not statistically significant at a 95% confidence level. This behaviour reveals the kinetic nature of gravimetric mass accumulation, where sufficient residence time is required to differentiate field-driven transport variances from baseline analytical thresholds. These findings provide critical baseline insights for optimizing compact, low-pressure-drop electrohydrodynamic emission controls on small-scale diesel power systems.

Keywords: ESP; diesel; $PM_{2.5}$; gravimetric

SDGs Problem Solving

This study supports SDG Chapter #7 by optimizing the technology of the electrostatic precipitator to reduce the emissions of the diesel engine which results in cleaner combustion and more sustainable use of energy in the transport and industry sectors which thus supports affordable and clean energy.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

Jurnal Asiimetrik: Jurnal Ilmiah Rekayasa dan Inovasi - ASIIMETRIK is an open access and peer-reviewed journal published by Faculty of Engineering, Universitas Pancasila, Indonesia.

1. INTRODUCTION

The rapid expansion of global industrialization and urban transportation networks has drastically increased fossil fuel consumption, making tailpipe emissions a primary contributor to ambient air degradation. Modern environmental regulatory frameworks have continuously reduced the allowable thresholds for hazardous exhaust components, shifting their primary focus from macroscale gaseous pollutants to complex, microscopic solid-phase aerosols. Because these fine suspended particles serve as vehicles for toxic chemical compounds and remain airborne for extended periods, mitigating ambient aerosol loading has become a critical objective in the automotive and environmental engineering sectors globally.

At the core of this particulate crisis are compression-ignition platforms, which inherently generate vast quantities of carbonaceous matter due to the unique fluid mechanics of high-pressure fuel spray and diffusion combustion. Within a diesel combustion chamber, the highly transient, heterogeneous mixing of fuel and air creates localized fuel-rich zones under extreme thermal conditions, leading to rapid fuel pyrolysis and the nucleation of primary soot particles. As these hot carbon cores move through the cylinder and into the exhaust manifold, they undergo complex hydrodynamic interactions, including agglomeration, surface growth, and coagulation, transforming into complex, multi-branched soot networks. Managing these high-velocity, dispersed-phase soot streams poses a significant engineering challenge, as their variable aerodynamic diameters and high mass loading easily overwhelm conventional treatment systems.

Growing concerns about air quality and stricter emission regulations have spurred the development of advanced particulate emission control technologies. Combustion engines, the primary mode of transportation, emit significant amounts of particulate matter (PM), which contribute to air pollution and adversely affect human health and the environment (Agarwal and Krishnamoorthi, 2023). Fine particulate matter can penetrate deeply into the respiratory system and has been associated with respiratory and cardiovascular diseases as well as other adverse health effects (Long and Carlsten, 2022). Traditional tailpipe filtration systems, such as conventional air filters and glass wool configurations, have been demonstrated to reduce gaseous pollutants successfully CO, CO_2 and hydrocarbons from the transportation sector (Pinem *et al.*, 2025). However, these passive barrier systems often suffer from significant backpressure accumulation and rapid clogging when subjected to the high-volume, amorphous carbon soot characteristic of diesel combustion.

Among available emission control technologies, the Electrostatic Precipitator (ESP) is considered an effective method for reducing diesel particulate emissions because it uses electrostatic forces to capture charged particles from exhaust gases, with relatively low pressure drop and high collection efficiency. The interaction of electrical and geometric parameters governs ESP performance. Applied voltage determines the electric field strength and the corona discharge intensity, both of which are critical for particle charging. Simultaneously, electrode spacing influences the electric field distribution and particle migration velocity. In ESP systems, particulate matter is electrically charged through corona discharge and then attracted toward the collecting electrode by electrostatic forces. Recent experimental studies have demonstrated that ESP systems can achieve high particulate removal efficiency under diesel exhaust operating conditions, particularly by optimizing input voltage and particle residence time (Hansen, Sørensen and Hærvig, 2023).

Applied voltage is one of the most important operating parameters because it determines the strength of the electric field and the intensity of corona discharge generated within the ESP system. Higher applied voltage generally improves particle charging capability and enhances electrostatic attraction forces, thereby increasing particulate collection efficiency (Zhang *et al.*, 2022). In addition, electrode spacing significantly affects the electric field distribution between the discharge electrode and the collecting plate. Smaller electrode spacing increases electric field intensity and affects particle charging and migration characteristics; however, improper spacing and electrode configuration may lead to unstable discharge behavior and reduced ESP performance (Zhao *et al.*, 2023).

Operating time or particle residence time is another important parameter affecting ESP performance. Longer residence time allows particles to remain longer in the electric field region, increasing the probability of particle charging and deposition on the collector plate. Previous studies reported that particle residence time significantly affects particulate removal and overall collection efficiency in electrostatic precipitator systems (Hansen, Sørensen and Hærvig, 2023).

Several recent studies have investigated the influence of operational parameters on ESP performance. Zhang et al., reported that increasing the applied voltage improved particulate collection efficiency due to stronger ionization and enhanced electrostatic attraction (Zhang *et al.*, 2022). Meanwhile, recent studies have shown that ESP optimization depends on both electrode geometrical configuration and operating parameters that influence electric field characteristics and particle migration behavior (Badran and Mansour, 2022). However, most previous investigations have focused on industrial-scale ESP systems or numerical simulations. In contrast, experimental studies of laboratory-scale ESP systems integrated with diesel engine exhaust systems remain relatively limited.

Based on these conditions, this study investigates the effects of applied voltage, electrode spacing, and operating time on the particulate collection performance of a laboratory-scale Electrostatic Precipitator (ESP) integrated with a diesel engine exhaust system using the gravimetric method. The novelty of this study lies in the combined experimental evaluation of operational and geometric parameters that affect particulate collection rate under laboratory-scale diesel exhaust conditions, supported by ANOVA. The results of this study are expected to provide scientific information to optimize ESP operating conditions and improve diesel particulate emission control performance.

2. METHODOLOGY

2.1. Experimental Setup

The experimental system was anchored by a stationary, single-cylinder, four-stroke direct-injection diesel engine featuring a total displacement of 418 cc and a rated power output of 6.6 kW at an operational speed of 3600 RPM. The engine was operated under a constant partial load condition utilizing standard commercial diesel fuel to maintain a steady baseline particulate emission rate of 1.25 mg/s. The active collecting core of the wire-plate ESP consisted of an aluminium housing with an effective collection length of 250 mm and a cross-sectional channel height of 100 mm. A centralized tungsten discharge wire with a radius of 0.5 mm served as the corona source.

During the 27 experimental sequences, the exhaust gas volumetric flow rate entering the precipitator channel was held constant at 0.003 m^3/s (10.8 m^3/h), yielding a convective bulk fluid velocity of approximately 0.12 m/s through the minimum electrode gap. The mean thermodynamic temperature of the exhaust stream inside the precipitation zone was monitored continuously and maintained at 100 °C ± 5°C, while the relative humidity was verified at 12 % ± 2 % to eliminate unpredictable dielectric breakdowns. Particulate mass quantification was executed via gravimetric analysis using a high-precision digital analytical balance exhibiting a measurement uncertainty threshold of ± 0.001 g.

Precipitator (ESP) driven by a regulated high-voltage direct current (HVDC) power supply. The block diagram maps out the sequential fluid and electrical steps, from exhaust generation to gravimetric mass analysis described in Figure 1.

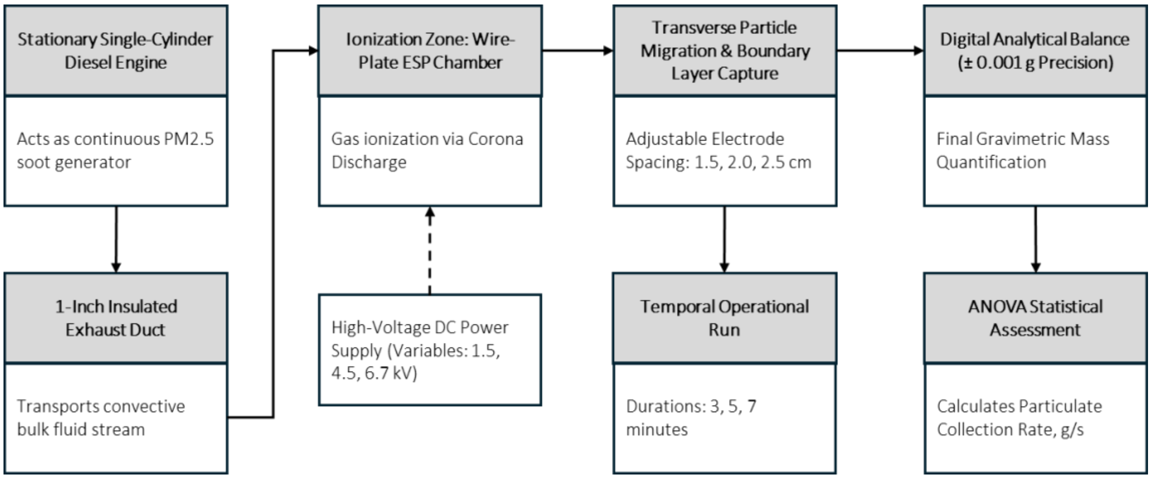

Figure 1. Operational flow loop block diagram highlighting the sequential fluid transport, electrohydrodynamic variables, and analytical boundaries of the laboratory-scale ESP experimental setup

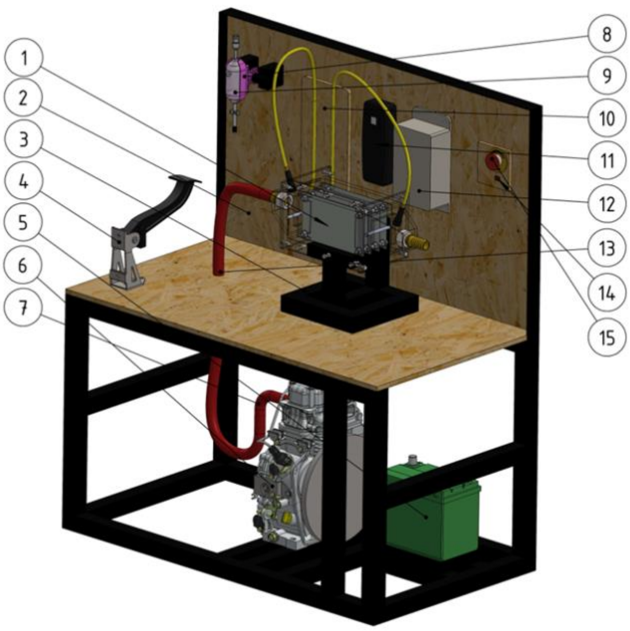

Figure 2. Laboratory scale diesel Engine Electrostatic Precipitator (ESP) system

The operational layout and spatial distribution of the complete diagnostic system components are schematically illustrated in Figure 2., where: (1) Box; (2) Table; (3) Plate Collector; (4) Accelerator Pedal; (5) Accu 12 Volt; (6) Engine Diesel; (7) Exhaust; (8) Fuel Tank Support; (9) Fuel Tank; (10) U-Tube Manometer; (11) High-Voltage Meter; (12) Power Supply HVDC; (13) Hose 1 Inch; (14) Switch on Off; (15) Emergency Switch.

Hydrodynamically, the exhaust stream serves as the continuous carrier fluid phase, transporting a high concentration of multi-branched, amorphous carbonaceous soot particles downstream through a 1-inch connecting hose into the precipitation zone. The core separation mechanism of the ESP relies on localized gas ionization governed by electrohydrodynamic (EHD) principles. As the high-temperature exhaust gas traverses the intense localized electric field, a sustainable corona discharge is initiated around the centralized discharge wire electrodes (Holubčík *et al.*, 2022; Hansen, Sørensen and Hærvig, 2023). This ionization field generates a high-density stream of unipolar gas ions that collide with the incoming disperse-phase soot, imparting a baseline electrical charge (q) onto the individual particulates via field and diffusion charging mechanics. Driven by the dominant transverse electrostatic force, the newly charged particles migrate radially outward, deviating from their horizontal convective fluid streamlines, and move toward the grounded parallel collector plates, where they are captured within the viscous boundary layer. This active open-duct separation configuration enables the system to maintain exceptional fine-particulate removal efficiencies under dynamic tailpipe conditions while avoiding the high backpressure penalties, fluidic stalling, and sudden aerodynamic clogging typically associated with conventional porous barrier filters.

The independent variables in this study were applied voltage, electrode spacing, and operating time. The dependent variable was the particulate collection rate obtained using the gravimetric method. The selection of brief, discrete operational durations align with established bench-scale diesel testing protocols, in which progressive soot loading over moderate timeframes strongly modulates electrical collection performance (Gao *et al.*, 2017).

2.2. ESP Specifications

The ESP used in this study was a plate-type electrostatic precipitator equipped with a discharge electrode and a collector plate positioned inside the exhaust gas channel. A DC high-voltage power supply was used to generate the electric field required for particle charging and collection processes.

The diesel engine exhaust gas was directed through the ESP chamber, allowing particulate matter to interact with the electrostatic field before exiting the system. The collector plate was periodically removed and weighed to determine the amount of collected particulate matter using the gravimetric method.

The analytical balance used in this study had a precision of ±0.001 g to ensure accurate measurements of particulate mass. According to Kim et al., accurate measurement of particulate mass is important for evaluating ESP performance under different operating conditions (Kim *et al.*, 2022).

2.3. Experimental Design and Research Variables

To systematically isolate and evaluate the electrohydrodynamic and temporal mechanisms governing fine particulate capture, this study implemented a full factorial (3^3) full factorial matrix was executed with three independent, randomized replications (n = 3) for each of the 27 operational combinations. This approach resulted in a total of 81 distinct experimental runs. The integration of true replication allowed for the accurate determination of the experimental residual error variance, yielding 54 degrees of freedom for the error term, which validates the high statistical power and significance of the calculated F-elements and p-values. This statistical approach enables rigorous evaluation not only of the standalone primary effects of individual parameters but also of their higher-order multivariate interaction profiles—a methodological framework vital for capturing non-linear particle transport phenomena in compact exhaust loops.

The experimental matrix was constructed across three discrete levels for each of the three key operational parameters: applied HVDC voltage (1.5 kV, 4.5 kV, and 6.7 kV), inter-electrode geometric spacing (1.5 cm, 2.0 cm, and 2.5 cm), and operating duration (3 minutes, 5 minutes, and 7 minutes). This configuration yielded 27 unique experimental combinations, ensuring a robust, comprehensive assessment of the ESP's performance envelope under highly variable boundary conditions. The structured categorization of these parameters into independent, dependent, and tightly regulated controlled variables is detailed below:

- Independent variables
  The active operational inputs manipulated across the factorial matrix were the applied electrical potential gradient (governing corona intensity and field-charging kinetics), the physical electrode spacing (modulating the localized electric field distribution and the transverse migration distance), and the total exposure run time (dictating the cumulative mass integration and residence timescales).
- Dependent Variable
  The primary quantitative system response was defined as the particulate mass collection rate.
- Control variables
  To maintain experimental consistency, several process boundary conditions were held constant throughout the entire 27-run sequence. These baseline constants included a uniform diesel engine operating speed and torque load profile, a standardized fuel composition, a fixed horizontal exhaust gas crossflow direction, and a rigid, unvaried plate-type ESP structural housing configuration.

The use of factorial experimental design in this study enables systematic evaluation of interaction effects between variables, a common approach in recent ESP studies for determining optimal operating conditions and improving system performance characteristics (Badran and Mansour, 2022).

The independent variables in this study were applied voltage, electrode spacing, and operating time. The dependent variable was the particulate collection rate obtained using the gravimetric method.

Controlled variables included diesel engine operating condition, fuel type, exhaust gas flow direction, and ESP configuration to maintain experimental consistency throughout the study.

2.4. Data Collection

The experimental procedure began with cleaning and weighing the collector plate using a digital analytical balance to determine the initial mass. The diesel engine was then operated to produce exhaust gas containing particulate emissions.

During the experiment, the applied voltage and electrode spacing were adjusted according to the predetermined experimental variables. Exhaust gas flowed through the ESP chamber, allowing particulate matter to be charged and migrate toward the collector plate.

After the specified operating time was reached, the collector plate was removed and weighed again to determine the mass of collected particulate matter. The gravimetric method was selected because it provides direct measurement of particulate accumulation on the collector plate and is widely used in particulate emission studies (Vicente *et al.*, 2022).

2.5. Data Analysis

The experimental data were analyzed quantitatively and statistically to evaluate the influence of operating parameters on the performance of the Electrostatic Precipitator (ESP). Quantitative analysis was conducted by comparing particulate collection rates under different operating conditions.

Statistical analysis was performed using Analysis of Variance (ANOVA) to determine the significance of the main factors, namely applied voltage, electrode spacing, and operating time, as well as their interaction effects on particulate collection performance.

In addition, a factorial regression model was used to evaluate the relationship between the operating variables and the particulate collection rate. The regression equation used in this study is expressed as:

$$y = \beta_0 + \beta_a a + \beta_b b + \beta_c c + \beta_{ab} ab + \beta_{ac} ac + \beta_{bc} bc + \beta_{abc} abc + \varepsilon \quad (1)$$

Where y particulate collection rate (response variable); β_0 is the intercept or constant term; $\beta_a, \beta_b, \beta_c$ is the regression coefficient for the main effects; $\beta_{ab}, \beta_{ac}, \beta_{bc}$ is the regression coefficient for two-factor interaction effects; β_{abc} is the regression coefficient for the three-factor interaction effect, a is applied voltage, b is operating time; c is electrode spacing, ε is experimental error.

The regression model was used to identify the dominant operating parameters and interaction effects influencing particulate collection performance. The suitability of the regression model was evaluated based on statistical significance and the coefficient of determination. (R^2). Statistical calculations, regression analysis, and ANOVA were performed using Microsoft Excel.

3. RESULTS AND DISCUSSION

3.1. Experimental Results

The ESP successfully captured diesel particulates under all tested conditions. The highest collection rate, 1.10 mg/s, was achieved at the highest voltage (6.7 kV), the narrowest spacing (1.5 cm), and the longest duration (7 minute). To evaluate the operational performance of the wire-plate ESP more objectively across distinct boundaries, the empirical mass capture rates were converted into fractional collection efficiencies relative to the engine's baseline mass emission output (1.25 mg/s).

$$\eta = \left(\frac{collection\ rate\ in\ {}^{mg}/_{s}}{1.25\ {}^{mg}/_{s}}\right)\ x\ 100\% \tag{2}$$

The comprehensive experimental datasets that highlight the interplay among operating duration, voltage variations, and geometric spacing are organized in Table 1, Table 2 and Table 3.

Table 1. Experimental results of particulate collection rate at electrode spacing of 1.5 cm

No	Operating Time (min)	Voltage (kV)	Collected Particulate Mass (mg)	Collection Rate (mg/s)	Efficiency (%)
1.	3	1.5	0	0.00	-
2.	3	4.5	0	0.00	-
3.	3	6.7	20	0.11	8.89
4.	5	1.5	30	0.10	8.00
5.	5	4.5	40	0.13	10.67
6.	5	6.7	50	0.17	13.33
7.	7	1.5	360	0.86	68.57
8.	7	4.5	390	0.93	74.29
9.	7	6.7	460	1.10	87.62

Table 2. Experimental results of particulate collection rate at electrode spacing of 2.0 cm

No	Operating Time (min)	Voltage (kV)	Collected Particulate Mass (mg)	Collection Rate (mg/s)	Efficiency (%)
1.	3	1.5	10	0.06	4.44
2.	3	4.5	10	0.06	4.44
3.	3	6.7	20	0.11	8.89
4.	5	1.5	80	0.27	21.33
5.	5	4.5	100	0.33	26.67
6.	5	6.7	120	0.40	32.00
7.	7	1.5	160	0.38	30.48
8.	7	4.5	180	0.43	34.29
9.	7	6.7	200	0.48	38.10

Table 3. Experimental results of particulate collection rate at electrode spacing of 2.5 cm

No	Operating Time (min)	Voltage (kV)	Collected Particulate Mass (mg)	Collection Rate (mg/s)	Efficiency (%)
1.	3	1.5	10	0.06	4.44
2.	3	4.5	10	0.06	4.44
3.	3	6.7	30	0.17	13.33
4.	5	1.5	60	0.20	16.00
5.	5	4.5	80	0.27	21.33
6.	5	6.7	110	0.37	29.33
7.	7	1.5	200	0.48	38.10
8.	7	4.5	230	0.55	43.81
9.	7	6.7	260	0.62	49.52

The experimental results for electrode spacing of 1.5 cm are presented in Table 1. The experimental results for electrode spacing of 2.0 cm are presented in Table 2. The experimental results for electrode spacing of 2.5 cm are presented in Table 3.

From a fluid-mechanics perspective, particle transport and deposition within an ESP channel are governed by the balance between hydrodynamic drag forces exerted by the exhaust-gas crossflow and the transverse electrostatic forces that drive particles toward the collection plates (Richardson and Theodore, 2025). To evaluate this behavior beyond raw empirical data, the experimental fractional collection efficiency can be fundamentally modeled using the classic Deutsch-Anderson equation:

$$\eta = 1 - \exp\left(-\frac{A}{Q}w\right) \tag{3}$$

Where A represents the effective surface area of the collecting electrode plates, Q is the volumetric flow rate of the diesel exhaust gas stream $(m^3 s^{-1})$, and w is the theoretical particle migration velocity $(m\, s^{-1})$. Under standard creeping flow conditions, the migration velocity of a fine particulate subjected to a uniform electric field is defined by Stokes' Drag Law incorporating the Cunningham correction factor:

$$w = \frac{q\, E\, C_c}{3\pi\mu d_p} \tag{4}$$

Here, q does the particle acquire the electrical charge, E is the local electric field strength, C_c is the Cunningham slip correction factor, μ is the dynamic viscosity of the exhaust fluid, and d_p is the particle aerodynamic diameter.

3.2. Effect of Applied Voltage on Particulate Collection Rate

As illustrated by the experimental trends, a higher applied voltage and a downscaled electrode spacing consistently correspond to elevated mass collection metrics. This physical behavior matches the theoretical framework where the average electric field strength within the ESP collection zone is a function of the geometric gap:

$$E \approx \frac{V}{d} \tag{5}$$

Increasing the high-voltage DC supply from 1.5 kV to 6.7 kV heightens the potential gradient, thereby intensifying the corona discharge and subsequent gas ionization rates. A dense corona environment accelerates the field-charging kinetics of incoming sub-micron diesel soot, leading to a substantial surge in individual particle charge. On the other hand, narrowing the electrode spacing from 2.5 cm to 1.5 cm reduces the distance a charged particle must traverse to reach the collector plate's boundary layer, thereby maximizing the electric field intensity. According to Stokes' formulation, the simultaneous maximization of q and E exponentially increases the terminal migration velocity, rapidly moving particles out of the primary bulk fluid streamlines and onto the solid boundaries.

However, despite the visible upward trajectories captured in Figure 3 and Figure 4, individual ANOVA diagnostics reveal that the isolated effects of voltage (p=0.218) and electrode spacing (p=0.218) are not statistically significant at the standard 95% confidence level. The results reveal that inside a dynamic bench-scale exhaust stream, the fluidic residence time dictates whether these field forces have sufficient opportunity to drive particles to completion before they escape the precipitator stage.

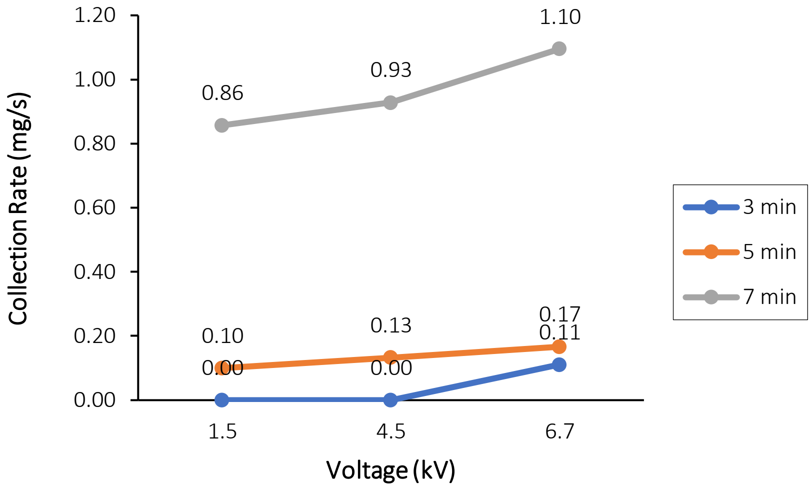

Figure 3. Effect of applied voltage on particulate collection rate at electrode spacing of 1.5 cm

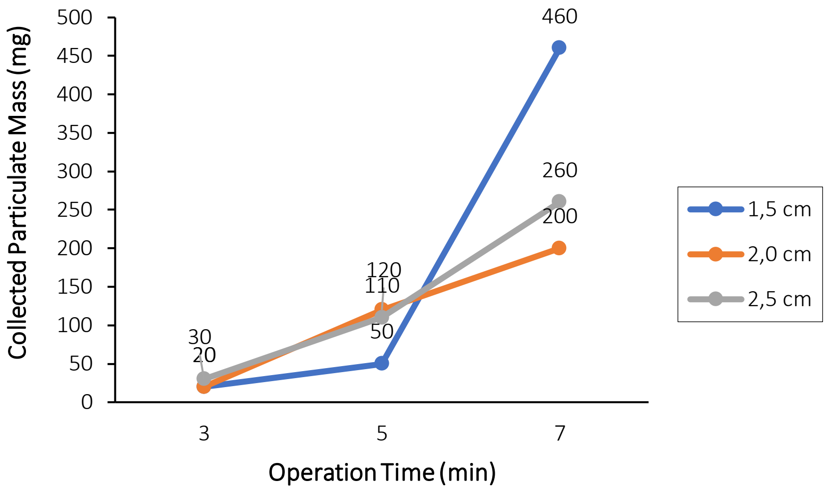

Figure 4. Effect of electrode spacing on particulate collection rate at voltage 6.7 kV

3.3. Hydrodynamic Dominance of Operating Time and Kinetic Mass Integration

Statistical computations via ANOVA identify Operating Time as the overwhelmingly dominant variable affecting the system's response performance, yielding a highly critical p-value of 1.08×10^{-7} (detail see Table 4). The ANOVA results indicate that operating time was the most influential parameter affecting particulate collection performance. In contrast, voltage and electrode spacing did not individually significantly affect the particulate collection rate within the investigated operating range.

The interaction between electrode spacing and operating time was statistically significant, indicating that the influence of operating time depended on the electrode configuration used in the experiment. The regression model produced a coefficient of determination (R^2) of 0.8025, indicating that approximately 80.25% of the variation in particulate collection rate could be explained by the operating variables included in the model.

Table 4. ANOVA results for particulate collection rate

Parameter	p-value	Statistical Interpretation
Operating Time	1.08×10^{-7}	Significant
Voltage	0.218	Not Significant
Electrode Spacing	0.218	Not Significant
Electrode Spacing × Operating Time	0.027	Significant

This extreme statistical significance is fundamentally linked to the gravimetric measurement methodology utilized in this research. Because the dependent response variable relies on a digital analytical balance registering the total dry cumulative mass (Δm) settled over a discrete timeframe, the recorded mass is an integrated function of fluid exposure duration:

$$\Delta m = \int_0^t \dot{m}_{in}\, \eta\, dt \tag{6}$$

Where $\dot{m}_{in}$ is the mass flow rate of incoming raw diesel particulates exiting the engine manifold. At short operating durations (3 min), the absolute mass of soot swept into the ESP chamber is highly localized, generating minute deposits (less than 30 mg) that border the physical detection and stability boundaries of the gravimetric apparatus. This dampens the visible variations caused by changes in electrical parameters over brief intervals. On the other hand, extending the duration to 7 min yields a massive, steady-state volume of particulate-laden exhaust fluid crossing the corona field. This extended duration allows for clear differentiation of the electrical and geometric boundary conditions. These results are consistent with Hansen et al., who identified residence time as one of the dominant parameters affecting ESP particulate collection efficiency (Hansen, Sørensen and Hærvig, 2023).

3.4. Engineering Implications and Turbulent Flow Realities

The high performance of the ESP system under combined optimal parameters demonstrates the practical feasibility of electrostatic emission controls for micro-scale diesel power units and regional transportation systems. Traditional porous barrier filters often experience severe exhaust backpressure buildup as amorphous soot rapidly cakes the microscopic substrate pores, introducing aerodynamic restrictions that lead to fluidic stalling and a substantial reduction in engine thermal efficiency (Vicente *et al.*, 2022). However, the non-linear fluctuations observed in our experimental data—such as the overlapping mass curves between the 2.0 cm and 2.5 cm configurations at intermediate times —point to complex fluid-particle interactions.

The exhaust gas velocity profile is inherently non-uniform, yielding distinct velocity shear layers near the walls. High-velocity turbulent eddies within the channel crossflow can actively break up loosely bound soot agglomerates or initiate localized particle re-entrainment, where captured low-resistivity carbonaceous dust is aerodynamically sheared off the collection plate by the passing gas and swept back into the core fluid stream (Ning *et al.*, 2024). This competitive interaction underscores why maximizing ESP fractional collection efficiency requires a simultaneous, balanced optimization of both the local electrical potential and the hydrodynamic velocity profiles.

In a physical laboratory setup, the exhaust gas velocity profile is not perfectly uniform. High-velocity turbulent eddies can break up agglomerated soot particles or cause re-entrainment, where captured dust is sheared off the collection plate by the gas flow and swept back into the core fluid stream. This interaction underscores why maximizing ESP efficiency requires balancing electrical potential and fluid velocity profiles simultaneously.

3.5. Practical Implications of ESP Optimization

Optimizing the operating parameters of Electrostatic Precipitators (ESP) is crucial for controlling diesel emissions in both transportation and industrial sectors. Experimental results showed that extending the operating time and adjusting the electrode spacing enhanced particulate collection performance. These findings suggest that ESP systems have significant potential to reduce diesel particulate emissions in small-scale combustion systems.

The application of laboratory-scale ESP systems may also contribute to the development of sustainable emission control technologies. Improved particulate removal efficiency can reduce air pollution levels and minimize the environmental impact of diesel combustion processes. Furthermore, optimizing ESP operating conditions may support the development of energy-efficient pollution-control systems for future industrial applications. Recent studies have highlighted that PM2.5 exposure may cause a broad spectrum of adverse health effects, including respiratory disorders, cardiovascular diseases, endothelial dysfunction, and chronic systemic inflammation, largely mediated by oxidative stress pathways and inflammatory signaling triggered after fine particles penetrate deep into the pulmonary system and circulate throughout the body (Krittanawong *et al.*, 2023; Mahiyuddin *et al.*, 2023).

Despite these advantages, further optimization is still required to improve collection efficiency under varying exhaust gas conditions. Parameters such as exhaust gas velocity, particle size distribution, gas temperature, humidity, and electric field uniformity should be investigated in future studies to obtain a more comprehensive understanding of ESP performance characteristics. Badami et al., explained that operating conditions, electric field distribution, and system geometry configuration strongly influence ESP collection efficiency (Badami *et al.*, 2023).

3.6. Research Limitations

This study was conducted using a laboratory-scale ESP system under controlled operating conditions. Therefore, the experimental results may differ from those in industrial-scale applications due to differences in exhaust-gas flow characteristics, chamber dimensions, and operating environments.

In addition, particulate measurements were limited to gravimetric analysis without particle-size classification (e.g., PM2.5 and PM10). The study also focused only on variations in voltage, electrode spacing, and operating time. In contrast, other important parameters such as gas velocity, exhaust temperature, humidity, and electrode geometry were not investigated.

Another limitation of this study is the absence of numerical simulations, such as Computational Fluid Dynamics (CFD), which could provide a deeper understanding of the electric field distribution and particle flow behaviour inside the ESP chamber. Integrating experimental gravimetric data with comprehensive Multiphysics models specifically, tracking the spatial interactions between ionized electric-field profiles and fluid streamlines is vital for perfecting collector geometries (Ferron *et al.*, 2008). According to Badami et al., optimizing ESP systems requires a comprehensive evaluation of electric field characteristics and particle migration behaviour to improve particulate collection efficiency (Badami *et al.*, 2023). Therefore, future studies are recommended to combine experimental investigation with numerical simulation approaches to improve ESP system optimization and performance prediction.

4. CONCLUSION

This study systematically investigated the multi-phase transport and electrostatic deposition kinetics of fine particulate matter (PM2.5) within a compact, laboratory-scale plate-type Electrostatic Precipitator (ESP) integrated with an active diesel engine exhaust loop. Experimental evaluations utilizing the gravimetric method confirm that the ESP configuration maintains robust particulate capture capabilities across all designated electrical, geometric, and temporal operating boundaries. The maximum performance threshold yielded a peak particulate collection rate of 1.10 mg/s, achieved under a highly intensified localized electric field with a maximum applied voltage of 6.7 kV and a compressed inter-electrode spacing of 1.5 cm, over an extended operating duration of 7 min. In general, increasing the potential gradient and extending the tracking duration significantly enhanced total mass capture by accelerating particle-field charging and increasing the electrostatic migration velocity. Contrarily, expanding the electrode spatial gap diminished the average field strength, thereby shifting the particle trajectories closer to the core fluid convective stream.

Statistical diagnostics via Analysis of Variance (ANOVA) conclusively demonstrated that Operating Time is the overwhelmingly dominant parameter governing the gravimetric collection performance ($p < 0.05$). This statistical behavior emphasizes the kinetic nature of mass aggregation in dynamic exhaust channels, where sufficient temporal residence time is mandatory to elevate captured soot volumes beyond baseline analytical balance detection thresholds and stabilize the fluid boundary layer against turbulent re-entrainment. In addition, the presence of a statistically significant two-factor interaction between electrode spacing and operating time ($p= 0.027$) confirms that geometric variations directly modulate particle deposition rates over time.

This work establishes that the simultaneous multi-variable optimization of electrohydrodynamic (EHD) operational conditions is vital for engineering low-pressure-drop emission controls on decentralized diesel power systems. To expand upon the baseline boundaries identified in this work, further research is highly recommended to explore broader operating ranges alongside active hydrodynamic parameters, including exhaust gas volumetric flow velocity profiles, shifting thermal fields, and complex discharge wire geometries. These future inquiries should ideally pair empirical testing with high-fidelity Computational Fluid Dynamics (CFD) and discrete phase modeling to capture real-time turbulent soot transport behavior.

REFERENCES

Agarwal, A.K. and Krishnamoorthi, M. (2023) 'Review of Morphological and Chemical Characteristics of Particulates from Compression Ignition Engines', *International Journal of Engine Research*, 24(7), pp. 2807–2865. Available at: https://doi.org/10.1177/14680874221114532.

Badami, M.M. *et al.* (2023) 'Design, Optimization, and Evaluation of a Wet Electrostatic Precipitator (ESP) for Aerosol Collection', *Atmospheric Environment*, 308, p. 119858. Available at: https://doi.org/10.1016/j.atmosenv.2023.119858.

Badran, M. and Mansour, A.M. (2022) 'Evaluating Performance Indices of Electrostatic Precipitators', *Energies*, 15(18), p. 6647. Available at: https://doi.org/10.3390/en15186647.

Ferron, A.S. de *et al.* (2008) 'Removal of Diesel Soot Particules Using an Esp Supplied by a Hybrid Voltage', *The European Physical Journal Applied Physics*, 43(1), pp. 103–109. Available at: https://doi.org/10.1051/epjap:2008125.

Gao, J. *et al.* (2017) 'Oxidation Behaviours of Particulate Matter Emitted by a Diesel Engine Equipped With a NTP Device', *Applied Thermal Engineering*, 119, pp. 593–602. Available at: https://doi.org/10.1016/j.applthermaleng.2017.03.101.

Hansen, N.H., Sørensen, H. and Hærvig, J. (2023) 'Experimental Study of a Full-Scale Hexagonal Wet Electrostatic Precipitator for Collection of Black Carbon and Particulate Matter Generated by a Marine Diesel Engine', *Journal of the Air & Waste Management Association*, 73(2), pp. 146–156. Available at: https://doi.org/10.1080/10962247.2022.2121325.

Holubčík, M. *et al.* (2022) 'Decreasing Solid Aerosols from Small Heat Sources Using the Optimized Electrostatic Precipitator', *Atmosphere*, 13(9), p. 1438. Available at: https://doi.org/10.3390/atmos13091438.

Kim, Y.-S. *et al.* (2022) 'Improvement of an In-Duct Two-Stage Electrostatic Precipitator via Diffusion Charging', *Toxics*, 10(11), p. 686. Available at: https://doi.org/10.3390/toxics10110686.

Krittanawong, C. *et al.* (2023) 'PM2.5 and Cardiovascular Diseases: State-of-the-Art review', *International Journal of Cardiology Cardiovascular Risk and Prevention*, 19, p. 200217. Available at: https://doi.org/10.1016/j.ijcrp.2023.200217.

Long, E. and Carlsten, C. (2022) 'Controlled Human Exposure to Diesel Exhaust: Results Illuminate Health Effects of Traffic-Related Air Pollution and Inform Future Directions', *Particle and Fibre Toxicology*, 19(1), pp. 1–35. Available at: https://doi.org/10.1186/s12989-022-00450-5.

Mahiyuddin, W.R.W. *et al.* (2023) 'Cardiovascular and Respiratory Health Effects of Fine Particulate Matters (PM2.5): A Review on Time Series Studies', *Atmosphere*, 14(5), p. 856. Available at: https://doi.org/10.3390/atmos14050856.

Ning, L. *et al.* (2024) 'Effect of High-Voltage Electrostatic Precipitator Dust Collection Plate Structure on Collection Efficiency', *ACS Omega*, 9(35), pp. 37396–37407. Available at: https://doi.org/10.1021/acsomega.4c06500.

Pinem, M.P. *et al.* (2025) 'Filter System Designed to Reduce the Emission of Gasoline Motorcycle Pollutants', *Machine: Jurnal Teknik Mesin*, 11(2), pp. 169–173. Available at: https://doi.org/10.33019/rwkk7894.

Richardson, J. and Theodore, L. (2025) 'Electrostatic Precipitators', *Optimizing Air Pollution Control Equipment Performance*. John Wiley & Sons, Ltd, pp. 147–173. Available at: https://doi.org/10.1002/9781394288687.ch15.

Vicente, E.D. *et al.* (2022) 'Efficiency of Emission Reduction Technologies for Residential Biomass Combustion Appliances: Electrostatic Precipitator and Catalyst', *Energies*, 15(11), p. 4066. Available at: https://doi.org/10.3390/en15114066.

Zhang, B. *et al.* (2022) 'Plasma-Enhanced Electrostatic Precipitation of Diesel Exhaust Particulates Using Nanosecond High Voltage Pulse Discharge for Mobile Source Emission Control', *Science of The Total Environment*, 851, p. 158181. Available at: https://doi.org/10.1016/j.scitotenv.2022.158181.

Zhao, H. *et al.* (2023) 'Research on the Shielding Effect of The Electrode Frames in the Electrostatic Precipitator', *Journal of the Air & Waste Management Association*, 73(6), pp. 462–470. Available at: https://doi.org/10.1080/10962247.2023.2200402.