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Experimental Study of a Cylindrical Electrostatic Precipitator with Real-Time Monitoring Applied to Simulated Smoke

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Abstract: This paper presents an experimental study of a cylindrical electrostatic precipitator (ESP) equipped with a real-time monitoring system for flue gas treatment. To simulate particulate emissions under controlled conditions, a white smoke generator was used to produce a visible aerosol representing combustion-derived particles. The ESP operates by generating a radial electric field between a central high-voltage electrode and a grounded cylindrical shell, causing the ionized particles to migrate and deposit on the collector surface. Integrated sensors continuously monitor voltage, current, aerosol density, and gas temperature, enabling adaptive control, fault detection, and performance analysis. The cylindrical geometry offers advantages such as compactness, uniform flow distribution, and reduced particle re-entrainment. Experimental results confirm the system's effectiveness in capturing fine particles and demonstrate the value of combining traditional electrostatic filtration with smart monitoring technologies. This setup provides a useful platform for educational purposes, pre-industrial validation, and the development of energy-efficient, automated emission control systems.

Keywords: Electrostatic precipitator (esp), Flue gas treatment, Particulate removal, Air pollution reduction

Introduction

Electrostatic Precipitator (ESP) systems are well-established and widely used technologies in the field of air purification and treatment (Mizono, 2000). These systems operate on the principle of ionizing airborne particles and then collecting them on charged electrodes, allowing for effective removal of particulate pollutants from various airflows, from large industrial facilities to household appliances. ESPs are widely used in air purification. However, existing techniques and common approaches for evaluating their performance face several challenges and limitations (Aouimeur, 2018):

Offline or Post-Operational Evaluation Methods

Many existing systems rely on offline or post-operational methods for performance evaluation, such as collecting and analyzing treated air samples using separate particle measuring devices. These methods do not provide immediate, real-time assessment of the precipitator's performance during operation, making it difficult to identify operational issues or dynamically optimize performance in response to changing conditions.

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

Monitoring Basic Electrical Parameters (Voltage and Current)

The voltage and current applied to the electrostatic precipitator are monitored as an indicator of its status (Bottner, 2003). Despite their importance for ensuring safe operation, these monitoring methods alone do not provide direct or quantitative information about the actual particle removal efficiency or the level of air purity achieved, but rather only indicate the electrical circuit's condition (Aouimeur, 2018).

Use of Simple Charge Sensors for Downstream Evaluation

Some charge-based sensors are added downstream of the precipitator to attempt to estimate the amount of residual particles or ions (Popa, 2014). These sensors suffer significantly from ionic interference caused by the generation of free ions by the main precipitator (especially at high voltages). This makes it extremely difficult to distinguish between ions and actual particles (Larab, 2024), leading to inaccurate readings regarding true purification effectiveness.

Periodic Maintenance and Visual Inspection for Dust Accumulation

Some systems rely on intermittent visual inspection and scheduled maintenance to remove accumulated dust from collection electrodes (Mizono, 2000). This method is not continuous and cannot predict potential hazards like electrical arcing (flashover) caused by excessive dust buildup in real-time. It also results in significant downtime for cleaning, reducing the system's overall efficiency.

One of the most significant challenges facing current Electrostatic Precipitator (ESP) systems is the absence of an integrated and accurate real-time performance evaluation system (Aouimeur, 2018). This makes it difficult to reliably determine particle removal efficiency, especially given the problem of ionic interference affecting charge-based sensors (Dascalescu, 2025). Additionally, operational challenges resulting from dust accumulation on electrodes increase the risk of electrical discharge (flashover) (Wang, 2016) and necessitate frequent maintenance, thereby limiting the system's overall efficiency and adaptability to diverse operating conditions.

Objective of the Paper

The objective of the paper is to develop an integrated and improved electrostatic precipitator system that incorporates accurate and reliable mechanisms for real-time performance evaluation (Aouimeur, 2018). It aims to overcome the problem of ionic interference to ensure precise particle measurements and to facilitate accurate particle accumulation monitoring to enhance operational continuity and efficiency, while reducing maintenance requirements. This new technique aims to ensure optimal air purification efficiency under various and changing operating conditions.

Method

This method provides a detailed description for implementing the integrated electrostatic precipitation device for real-time performance evaluation, which aims to overcome known challenges in measuring the efficiency of electrostatic precipitators, particularly ionic interference and the effect of dust accumulation on overall performance. This methodology is implemented through the systematic assembly of precise functional units, each playing a crucial role in achieving the ultimate goal of air purification and reliable performance evaluation, as shown in the accompanying illustrative figures depicting the overall system design.

The system construction begins by preparing the particulate-laden airflow source. This is done using a Smoke Generator, a box-shaped device precisely positioned at the inlet of the airflow path, where it introduces a controlled and constant quantity of fine particles into the air stream. This serves to simulate real pollution conditions and acts as a standard source for evaluating the system's performance during testing and verification phases. The experimental setup is designed to evaluate the electrostatic filtration system and the innovative Particle Electrostatic Sensor (PES), with a focus on analyzing particle charge behavior and filtration efficiency under varying airflow and voltage conditions. Below is a detailed description of each component used in the test bench.

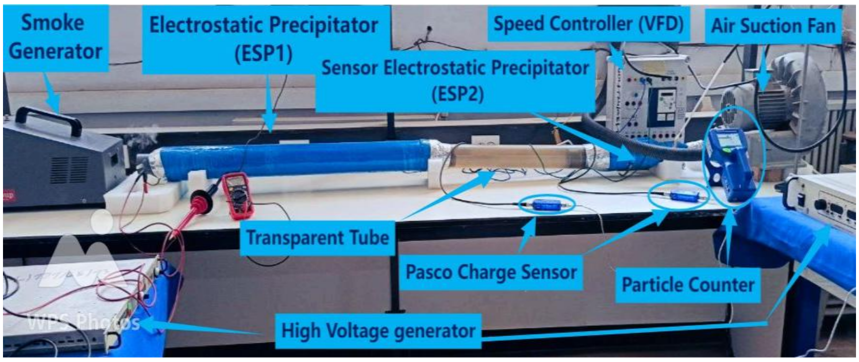

Figure 1. Experimental setup

This section outlines the methodology adopted to evaluate the hybrid electrostatic filtration system and the Particle Electrostatic Sensor (PES). The procedure was conducted in a controlled environment and aimed at analyzing charge behavior, filtration efficiency, and the dynamic response of the sensor under various airflow conditions. Preparation Phase :

Calibration of the Pasco Charge Sensor using Capstone software.
Verification of electrical insulation in ESP1 and PES to prevent leakage.
Installation of the smoke generator and airflow adjustment using the VFD.
Initial test run to ensure signal stability and synchronization between the sensor and the acquisition system.


Figure 2. Photograph of the smoke generator used

Test Protocol :
Each test was performed under a defined airflow condition with a specific voltage applied to ESP1 and PES:
Activate the smoke generator to introduce charged particles.
Set the high voltage of ESP1 (e.g., 12–20 kV) for particle ionization.
Apply a separate voltage to PES via its dedicated high voltage supply.
Allow particles to pass through ESP1, and then into the PES measurement zone.
Record:
- Charge variation over time via the Pasco sensor.
- Particle count before and after ESP using Aerotrak™.

To ensure continuous and controlled movement of the airflow through all system components, an Air Suction Fan is used. This is a centrifugal fan with a volute casing, installed at the end of the air path to draw air through the system. The rotational speed of this fan is precisely controlled using a Variable Frequency Drive (VFD), a box-shaped device. This unit allows for adjusting the fan speed, thereby controlling the airflow rate and volume processed at each stage, enabling performance testing of the precipitators under various airflow conditions and determining the optimal operating point.

The polluted airflow first passes through the primary purification unit: the Electrostatic Precipitator 1 (ESP1). This precipitator is cylindrical in shape and characterized by its substantial dimensions, with a length of approximately 1 meter (100 cm) and a diameter of approximately 100 mm. The internal ionization electrodes of ESP1 are connected to a High Voltage Generator, a box-shaped device that provides the necessary electrical voltage (tens of kilovolts) to generate a Corona Discharge. This discharge ionizes air molecules and electrically charges the particles suspended in the air. These charged particles are then attracted by the Coulomb Force towards the collecting electrodes, where they adhere, resulting in the removal of a significant portion of pollutants from the air stream. After undergoing primary purification in ESP1, the air stream, now partially purified, moves into the Transparent Tube. This tube is cylindrical and completely transparent, with a length of approximately 75 cm and a diameter of approximately 75 mm. This tube serves as both a visual and functional link between the main precipitator and the sensing unit. Its transparency allows for visual observation of the airflow, and more importantly, it provides a calculated transition distance to ensure homogeneous and stable distribution of residual particles and ions before they enter the subsequent sensing unit, thereby contributing to increased measurement accuracy.

Directly following the transparent tube is the most innovative part of this technique: the Sensor Electrostatic Precipitator (PES). This cylindrical-shaped precipitator features carefully designed dimensions, with a length of approximately 40 cm and a diameter of approximately 90 mm. PES functions as an advanced sensing unit. Its role is not limited to secondary precipitation of residual particles but primarily focuses on conditioning and preparing particles and ions for precise measurement. This is achieved through its interaction with the Pasco Charge Sensor. This small, compact sensor, cylindrical or oval in shape, is strategically installed either after ESP1 or inside/after ESP2 (PES).

The Pasco sensor measures the total electrical charge remaining in the air. By analyzing the charge pattern collected by this sensor, the system can reliably evaluate filtration effectiveness and determine the presence and impact of free ions, thereby overcoming the problem of ionic interference that plagues traditional sensors. This integration between PES and the Pasco sensor eliminates the need for external particle counters in daily operation, as the innovation itself takes over the role of evaluating air quality and purification efficiency. For initial testing and calibration of the system, and to justify the rationality of the results, a Particle Counter (Aerotrak™) can be used. This portable device, with a clear digital display, is positioned at the system's outlet and performs accurate counting and classification of residual particles in the purified air by size (e.g., 0.3, 0.5, 1.0, 3.0, 5.0, 10.0 micrometers). This tool is crucial during system development phases to verify the accuracy of PES and Pasco sensor data and compare it with real-world measurements.

Smart Monitoring and Preventive Maintenance Mechanism: The system designed in this manner is not limited to purification; it also provides an intelligent mechanism for continuous monitoring of ESP1's performance. By analyzing data collected by PES and the charge sensor, the system can detect any decrease in efficiency or abnormal changes in charge levels that may indicate dust accumulation on ESP1's internal electrodes or the potential for an electrical Flashover.

This proactive monitoring enables immediate responses, such as activating self-cleaning mechanisms (if present) or sending alerts for scheduling preventive maintenance, thereby ensuring optimal continuous operation of the system and significantly reducing unplanned breakdowns and operational costs. In this detailed manner, an invention is implemented that offers a comprehensive and intelligent air purification solution, characterized by its ability for accurate real-time evaluation and adaptation to changing conditions, while enhancing reliability and operational efficiency unprecedentedly.

Results and Discussion

This experiment was conducted under standard and controlled operating conditions to evaluate the performance of the electrostatic precipitation system. The voltage applied to the main electrostatic precipitator (ESP1) was set at -17 kV, while the voltage for the Particle Electrostatic Sensor was set at -7 kV. To ensure a stable airflow, the fan was operated at 6 Hz, resulting in an air outflow velocity of approximately 7.45 m/s. Based on the principle of flow continuity (V1*D1 = V2*D2), the air velocity inside the main precipitator (ESP1) was calculated to be approximately 2.24 m/s. A stable smoke generator was used as the pollution source. The total test duration was approximately 240 seconds. For data collection, both Pasco charge sensors and an Aerotrak™ particle counter were utilized.

Table 1. Sequence of events and time intervals of the ESP/PES performance test

Time (s)	Event
0–87	Particle Electrostatic Sensor ON – clean air baseline
87–167	Smoke ON – polluted airflow enters system
167–200	ESP1 (main filter) ON – filtration phase
200–230	Smoke OFF – clean air returns
>230	System OFF – full shutdown (ESP1 + Particle Electrostatic Sensor)

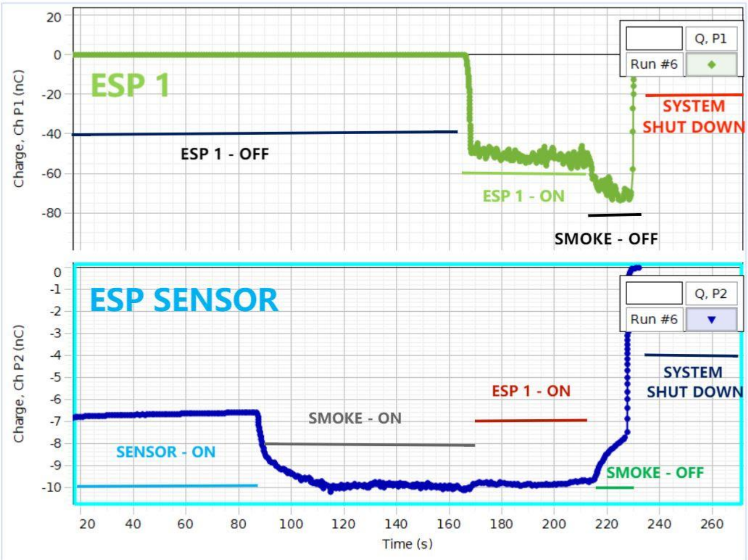

Figure 3. Dynamic response of the main electrostatic precipitator (ESP 1) and the particle electrostatic sensor (PES) during the smoke injection and filtration cycle

Table 2. Experimental phases and corresponding electrostatic charge status (ESP1 and PES)

Phase	Time Range (s)	Event	ESP1 (P1)	Particle Electrostatic Sensor	Comments
1	0–87	Clean air, Particle Electrostatic Sensor ON	0 nC	Stable at –7 nC	Clean baseline established
2	87–167	Smoke ON	0 nC	Gradual drop to ~–10 nC	Sensor charges as particles arrive
3	167–200	ESP1 ON	Drop to ~–55 nC	Slight recovery (~–9 nC)	Filtration starts; sensor stabilizes slightly
4	200–230	Smoke OFF	Continues to ~–72 nC	PES returns to –7 nC	Clean air helps system reset
5	>230	Power OFF	Discharges to 0	Instant discharge to 0	Full system shutdown

Interpretation

- Particle Electrostatic Sensor gradually charged up to around –10 nC during the smoke injection phase.
- Once ESP1 was activated, the particle concentration near the sensor dropped slightly, allowing the Particle Electrostatic Sensor to begin stabilizing.
- When the smoke generator was turned off, the Particle Electrostatic Sensor gradually returned to its clean-air baseline of –7 nC.
- However, the sensor did not exhibit a perfectly ideal discharge profile during operation.
- This behavior should not be interpreted as a sensor malfunction, but rather as a result of measurement limitations under real-world dynamic conditions particularly due to high particle load density, transient ion flow, and limited sensor resolution (Aouimeur, 2018).

Such limitations are common in compact electrostatic test environments and are expected when testing highly responsive systems like ESPs.

Physical Analysis of Charge Behavior

This section provides an in-depth physical analysis of the electrical charge behavior observed by the Pasco charge sensor within the "Particle Electrostatic Sensor" during the experimental phases, linking empirical observations to fundamental principles of electrostatic precipitation and particle charging phenomena.

- Baseline Phase (0-87 s): During this phase, prior to smoke introduction and with clean air flowing, the charge sensor readings were consistently low and stable, approaching zero. This indicates an almost complete absence of charged particles or free ions in the ambient air or those generated by the Particle Electrostatic Sensor itself (at -7 kV). This establishes a critical charge baseline for subsequent evaluation of changes due to pollution or filtration.
- Pollution Phase (87-167 s): Upon smoke introduction, increase in charge sensor readings was observed. This rapid rise reflects a dense influx of charged (from the smoke generator or partially charged within the system's corona discharge) and uncharged particles, along with an increasing quantity of free ions generated within the discharge system. The arrival of these particles and ions at the Particle Electrostatic Sensor directly translates to an increase in the total observed charge, confirming the sensor's effectiveness in detecting air pollution.
- ESP1 Filtration Phase (167-200 s): Immediately after activating the main electrostatic precipitator (ESP1) at -17 kV, a sharp decrease in charge readings occurred. This drop directly reflects the electrostatic precipitation process, where ESP1 electrodes effectively charge, attract, and collect airborne particles. A lower charge reading after ESP1 indicates higher efficiency in pollutant removal. This phase is vital in demonstrating ESP1's air purification capability.
- Recovery Phase (200-230 s): Following the cessation of the smoke source, the charge sensor readings gradually returned to levels near the baseline. This suggests that the remaining air within the system was efficiently cleared of residual charged particles and free ions. This behavior also highlights the Particle Electrostatic Sensor's ability to respond to changes in pollutant concentration and revert to a reference state, establishing it as a reliable tool for continuous monitoring.

Connection to Saturation and Innovation Validation: In the context of experiments where traditional particle counters (e.g., Aerotrak™) exhibited saturation at high concentrations or specific operating conditions (like the low-frequency and high-voltage conditions that were excluded), the analysis of charge behavior gains paramount importance. The "Particle Electrostatic Sensor's" ability to measure total charge rather than "particle count" makes it less susceptible to saturation in extreme conditions, providing a more reliable measure of performance and validating the core innovation of this system for evaluating electrostatic precipitator performance.

Conclusion

This study successfully designed, developed, and experimentally validated a compact cylindrical electrostatic precipitation system, integrating an innovative Particle Electrostatic Sensor (PES) for real-time monitoring of simulated smoke. The system is characterized by its cylindrical geometry, offering uniform flow distribution and reduced particle re-entrainment. Experimental results confirm the system's effectiveness in capturing fine particles and, more importantly, demonstrate the value of PES integration. The analysis of charge behavior successfully detected the arrival of pollutants, the start of the filtration process by ESP1 , and the gradual return to the clean air reference state. This approach circumvented one of the major challenges of traditional sensors: the inability to reliably distinguish between ions and particles due to ionic interference. By measuring the total charge rather than the simple particle count, the PES system proves less susceptible to saturation under high particle loads, thus offering a more reliable performance evaluation and validating the core innovation of this system for evaluating electrostatic precipitator performance. In conclusion, this project is not limited to purification; it presents a smart, compact, and cost-effective filtration solution. This accessible, embedded solution has the potential to significantly improve particulate waste management performance in resource-constrained environments, paving the way for future innovation and broad industrial applications.

Recommendations

To consolidate the results and extend the impact of this research, the following avenues are recommended:

1. PES Sensor Optimization and Measurement Limit Reduction:

- Conduct further research on improving the resolution of the Particle Electrostatic Sensor (PES) to minimize the impact of measurement limitations under real-world dynamic conditions, especially high particle load density and transient ion flow.

- Develop a signal processing algorithm to actively filter out the stable ionic component of the corona discharge, thereby allowing for better isolation of the signal specifically related to particle charge only.

2. Validation in Industrial Conditions and Durability Tests:
   - Scale up the system to an industrial pilot and test it with real combustion flue gases (not simulated) over an extended period to evaluate the long-term efficiency and durability of the electrodes.
   - Quantify the correlation between PES data and actual filtration performance (measured by the Aerotrak™) for different types of pollutants, covering a variety of chemical and physical characteristics.

3. Development of an Adaptive Control System (Smart Control):
   - Design and implement a real-time feedback control loop based on PES data. This loop should dynamically adjust the ESP1 supply voltage to maintain optimal collection efficiency while proactively preventing electrical discharges (flashovers) caused by excessive dust accumulation.

4. Analysis of Erosion and Predictive Maintenance:
   - Conduct studies to correlate the charge variation measured by the PES with the mass of dust accumulated on the ESP1 electrodes. This is crucial for precisely determining predictive maintenance intervals and reducing the need for periodic visual inspections.

5. Energy Analysis:
   - Precisely evaluate the energy consumption of the complete system (fan, ESP1, and PES) and compare it to existing high-energy filtration or incineration technologies, in order to quantitatively justify the system's "cost-effective" advantage.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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