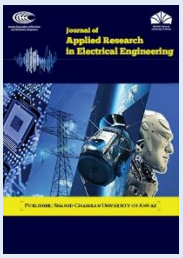
Shahid Chamran University of Ahvaz

Iranian Association of Electrical and Electronics Engineers

Journal of Applied Research in Electrical Engineering

E-ISSN: 2783-2864
P-ISSN: 2717-414X
Homepage: https://jaree.scu.ac.ir/



Research Article

Electrostatic Precipitators: Types, Principles, and Manufacturing a Modular-based Prototype

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Abstract: Electrostatic precipitators (ESPs) are widely used in industry due to their efficiency in particle filtration. In this paper, we first review the working principles and key performance parameters of ESPs as necessary background. Then, to address challenges such as implementation costs and high voltage requirements, we propose and experimentally evaluate novel modular ESP structures for industrial applications. Four modular prototypes with triangular, square, hexagonal, and circular cross-sectional geometries were designed and tested under identical laboratory conditions. Results indicate that the hexagonal-based structure is the most suitable candidate for industrial use, offering a practical and efficient option for industrial applications.

Keywords: Electrostatic precipitator, ESP, Modular structure, Tubular ESP.

Article history
Received 12 April 2025; Revised 19 December 2025; Accepted 25 February 2026; Published online 3 October 2026.
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How to cite this article
A. A. Haghighi, and M.Khodaei, " Electrostatic Precipitators: Types, Principles, and Manufacturing a Modular-based Prototype," *J. Appl. Res. Electr. Eng.*, vol. 4, no. 2, pp. 274-281, 2025.
DOI: https://doi.org/10.22055/jaree.2026.49382.1195

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1. Introduction

Electrostatic precipitators (ESPs) are essential devices in air pollution control, effectively removing particulate matter from industrial emissions. Utilizing high-voltage electrical forces, ESPs charge particles as they pass through a corona discharge, causing them to adhere to collection plates. This method can achieve removal efficiencies greater than 99%, significantly reducing harmful pollutants released into the atmosphere [1]. The operation of an ESP involves two sets of electrodes: negatively charged wires and positively charged plates, creating an electric field that attracts the charged particles. Once collected, these particles can be removed through mechanical means or washing. The efficiency and low energy consumption of ESPs make them a preferred choice for industries facing stringent environmental regulations [2]. As the air pollution is one of the most important human health risks that should be considered in modern cities [3], and as industries face growing pressure to minimize emissions, understanding the principles behind electrostatic precipitators is crucial for optimizing their performance and addressing contemporary air quality challenges. Their ability to operate at high temperatures and handle large gas volumes further highlights their importance in maintaining environmental standards.

1.1. Importance and different applications

ESPs are widely used in various industries, including cement manufacturing, fossil fuel-fired power plants, hazardous waste incineration, metal such as lead/zinc/copper smelting, municipal waste management, petroleum refining, pulp and paper production, and steel manufacturing.

By effectively removing fine particles from exhaust gases, ESPs play a crucial role in improving air quality and promoting sustainable industrial practices. In coal-fired power plants, ESPs are vital for capturing fly ash and other particulate matter from flue gases. This process significantly lowers emissions of harmful pollutants like sulfur oxides

and nitrogen oxides, which contribute to air pollution. Modern ESPs can achieve removal efficiencies greater than 99%, making them indispensable for meeting environmental standards [4]. Similarly, in the cement industry, ESPs collect kiln dust, helping manufacturers comply with emission limits while also recovering valuable materials for reuse [5]. The steel industry also benefits from ESP technology, as these systems control emissions from processes such as blast furnaces and sintering. By reducing the release of fine particulates, ESPs help protect both public health and the environment. Additionally, in waste incineration facilities, ESPs capture toxic substances and fine particles generated during combustion. Advanced designs enable these systems to handle high-temperature gases effectively while safeguarding downstream equipment from damage [6]. This capability is particularly important for waste-to-energy plants that aim to minimize their ecological footprint. Beyond their role in pollution control, ESPs enhance operational efficiency by preventing fouling and corrosion in industrial equipment such as boilers and heat exchangers. This leads to lower maintenance costs and extends the lifespan of machinery [7]. Furthermore, the ability of ESPs to recover valuable materials from captured particulates provides economic advantages for industries. These benefits highlight the importance of ESPs as a practical solution for balancing environmental responsibility with industrial productivity.

Therefore, the role and significance of ESPs in a wide range of applications, such as power generation, heavy manufacturing, and waste management, make them crucial for managing emissions and enhancing air quality. Their high efficiency, adaptability in different settings, and ability to recover valuable resources make them essential tools for addressing current environmental challenges. As industries face growing demands to reduce their environmental footprint, the development and widespread use of ESP technology will be vital for supporting environmentally responsible operations [4-7].

1.2. Advantages, limits and challenges

ESPs are highly efficient in removing particulate matter from industrial emissions, often achieving removal rates exceeding 99%. Their ability to handle large gas volumes with low pressure drops makes them energy-efficient. However, ESPs face limitations, particularly in capturing ultrafine particles smaller than 0.1 micrometers, and their performance can be influenced by gas properties such as humidity and temperature. Scaling up ESPs for larger industrial processes introduces unique challenges. A key issue is maintaining a uniform electric field distribution across larger geometries. As system size increases to handle higher gas flow rates, uneven fields can reduce particle charging and collection efficiency, which can make it harder to meet emission standards [8]. Another challenge is optimizing electrode geometry, including spacing and configuration, to ensure effective particle capture while minimizing pressure drop. Altered flow dynamics in larger ESPs may further reduce fine particle capture efficiency [9]. While research has optimized ESP geometries, many studies have overlooked scalability. For instance, Chang and Bai in [9] examined how wire-to-wire spacing and plate-to-plate distance affect collection efficiency but did not assess performance at larger scales. Similarly, [8] modeled dust layer effects on ESP performance without addressing scaling implications. These gaps highlight the need for scalable designs that maintain efficiency under varying conditions. Additionally, the development of electrostatic precipitators (ESPs) has mainly focused on optimizing individual parts rather than creating systems that can easily adapt to different industrial needs. However, building a modular ESP prototype is important because it allows for efficient scaling without losing performance. This approach makes maintenance easier and reduces costs compared to traditional designs.

This paper first establishes a foundational overview of ESP structures, working principles, and key performance parameters. The core of this study, however, presents original applied research with direct industrial value. Its primary contributions are: 1) the introduction of a new modular design approach, which utilizes small, low-voltage units to simplify manufacturing, maintenance, and repair; 2) the systematic experimental comparison of geometric performance through the fabrication and testing of modular prototypes with triangular, square, circular, and hexagonal cross-sections; and 3) the identification of the hexagonal shape as the most efficient configuration, providing a practical guideline for optimized ESP design and efficient material use. The compact arrangement of these modular units within this architecture enhances adaptability and implementation speed, contributing to more effective particulate removal and air quality management.

This paper is organized as follows: Section 2 covers the types of ESP structures and filter components; Section 3 examines how different parameters impact performance and strategies for improving efficiency; finally, Section 4 presents the design, experimental setup, and comparison results among triangular, rectangular, and circular ESP prototypes based on their performance.

2. FILTER TYPES, COMPONENTS, AND MODELLING

ESPs can be classified into two main types based on their structures: plate-wire and tubular ESPs. Both types are widely utilized in industrial applications and are briefly introduced below.

2.1. Plate-wire ESPs

Wire-plate electrostatic precipitators (ESPs) are a widely adopted technology for controlling particulate emissions in various industrial applications. As shown in Fig. 1, in this design, high-voltage wires are suspended between parallel plates, establishing a strong electric field that ionizes the gas flowing through. As exhaust gases traverse this electric field, particles become charged and are attracted to the collection plates.

This configuration allows for multiple flow lanes to operate in parallel, making wire-plate ESPs particularly effective for handling substantial gas volumes. The structure of wire-plate ESPs typically consists of high-voltage wires suspended between parallel plates, creating an electric field that ionizes the gas as it flows through. The wires can be configured in various forms, including traditional long wires, spiral wires, or rigid electrodes such as hollow pipes,

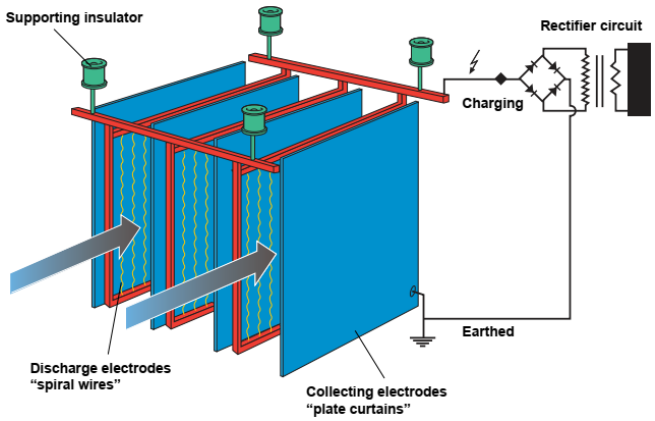


Fig. 1: Wire-plate ESP [10].

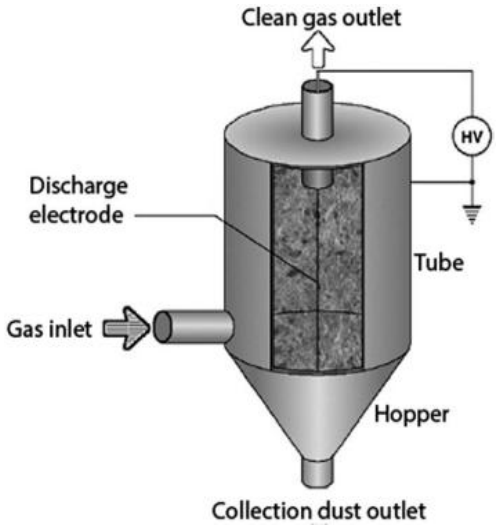


Fig. 2: Structure of a tabular ESP [11].

depending on the application requirements. The wires are fixed in position using a metal frame to ensure stability. The system operates with a transformer and rectifier, maintaining a negative polarity for the wires. This negative corona discharge supports higher voltages before sparking occurs, enhancing the ionization process and particle charging efficiency.

The spacing between plates typically ranges from 19 to 38 cm, optimizing the flow path for gas and enhancing particle collection efficiency.

Maintenance is essential for the effective operation of wire-plate ESPs. Collected particles must be dislodged from the plates without reintroducing them into the gas stream, typically achieved through mechanical rapping systems. Additionally, factors such as gas temperature and pollutant loading influence performance and must be managed.

2.2. Tubular ESPs

Tubular electrostatic precipitators (ESPs) are designed with cylindrical collection chambers to efficiently remove particulate matter from gas streams. As shown in Fig. 2, in this system, gas flows through the tubes where particles are charged by a DC negative corona discharge produced from the discharge electrode and collected on the grounded walls of the tubes under the influence of their own space charge.

This configuration is particularly effective for fine particle removal in biomass combustion applications, where emissions often include sticky or wet particulates [12]. The tubular design provides a compact structure, making it suitable for installations with space constraints. Additionally, tubular ESPs feature automatic cleaning systems to maintain high collection efficiency while minimizing maintenance. Operational parameters such as gas temperature, flow rate, and applied voltage significantly influence performance. For instance, gas temperatures between 250–270°C and applied voltages of 16–18 kV have been found to optimize efficiency [12]. These systems are widely used in industry facilities due to their effectiveness in reducing particulate matter emissions while maintaining low operational costs.

Although most ESPs are classified as wire-plate or tubular designs, they can also be categorized as wet or dry. Wet ESPs handle moist or sticky particles using water sprays for cleaning, while dry ESPs collect dry particulates like ash without water [10].

2.3. Filter components

Electrostatic precipitators (ESPs) consist of several critical components, including electrodes, cleaning mechanisms, hoppers, gas distribution systems, and power systems. Electrodes are essential for creating the electric field necessary for particle charging. Discharge electrodes, typically thin wires or rods, generate a corona discharge to ionize particles, while collection electrodes, such as flat plates or tubular surfaces, capture the charged particles. The characteristics of such discharges and the associated electromagnetic phenomena are also of critical importance in the condition monitoring of other high-voltage equipment, such as gas-insulated switchgears [13]. Materials like stainless steel and aluminum are commonly used for their conductivity and durability [14]. The cleaning mechanisms for collection plates or tubes are vital for maintaining efficiency. In dry ESPs, rapping systems use mechanical hammers or vibrators to remove accumulated particulates into hoppers for collection. Wet ESPs, on the other hand, employ water-washing systems to clean sticky or moist particles from collection surfaces. Proper hopper design prevents re-entrainment of removed particles into the gas stream [15]. Additional components include gas distribution systems, which ensure uniform gas flow through perforated plates or baffles at the inlet, maximizing collection efficiency. The power system, typically a high-voltage direct current (DC) supply delivering 30–100 kV, significantly influences particle charging and collection efficiency [16]. Advanced designs optimize these systems to enhance performance in challenging applications, such as removing fine aerosols and airborne particles in highly dynamic environments [17].

2.4. Working principles and mathematical modelling

The working principle in ESPs, whether in wire-plate or tubular configurations, is fundamentally the same. Basically, we have a high voltage applied to centered wire electrodes, which creates a strong electric field to ionize particles. These particles are then moved toward the opposite electrode due to electrostatic attraction. In an ESP, discharge electrodes (often wires) are negatively charged by a high-

voltage DC source. As gas passes through the system, solid particles gain an electrostatic charge from these discharge electrodes and drift toward positively charged collecting plates under the influence of the electric field. Once they reach these plates, they form a cake-like mass of particles that is periodically removed -either by rapping mechanisms for dry systems or washing for wet systems- allowing continuous operation and effective pollution control. For more information about the working principles of ESP, the reader is referred to [18].

one of the most critical equations for ESPs is the collection efficiency formula. This is often expressed using the Deutsch-Anderson equation [14], which calculates collection efficiency (η) as follows:

$$\eta = 1 - e^{-\frac{w_e A}{Q}} \tag{1}$$

where w_e is the particle migration velocity, A is the effective collecting plate area, and Q is the gas flow rate through the precipitator. The particle migration velocity can be influenced by factors such as electric field strength and particle size. For instance, it can be approximated using [19]:

$$w_e = \frac{qE}{3\pi\mu d_p} \tag{2}$$

where E is the electrical field strength (V/m), /mu is the viscosity (Pas), d_p is the diameter of particle (m), and q is the particle charge where for its saturation state is given as

$$q = \pi\varepsilon_0 \frac{3\varepsilon_s}{\varepsilon_s + 2} d_p^2 E \tag{3}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ (F/m) is the permittivity of vacuum and ε_s is the specific permittivity. Using (2) and (3) yields

$$w_e = \frac{\varepsilon_0 \varepsilon_s}{\mu(\varepsilon_s + 2)} d_p E^2 \tag{4}$$

The electric field strength is directly proportional to the applied voltage to the ESP. Considering (4) and (1), clarify the reason why high voltages are applied to ESPs: they enhance electric field strength, boosting particle migration velocity and ultimately improving filter efficiency.

3. Efficiency Related Parameters

The efficiency of electrostatic precipitators (ESPs) is influenced by several key parameters that affect particle collection and overall performance. Understanding these factors is crucial for optimizing the design and operation of ESPs.

3.1. Particle Characteristics

The characteristics of particles, including size, shape, charge, and composition, play a significant role in determining the efficiency of ESPs. Smaller particles, particularly nanoparticles (defined as particles smaller than 100 nm), present unique challenges due to their lower inertia and increased susceptibility to Brownian motion, which can hinder effective capture [18]. Additionally, the electrical properties of particles—such as conductivity and surface charge—are critical in influencing how effectively they can be charged and collected by the electrodes [20].

3.2. Wet and Temperature Effects

Moisture content and temperature variations can substantially impact the performance of ESPs. Wet ESPs are specifically designed to handle high humidity levels, effectively removing sticky or moist particles. However, excessive moisture can lead to problems such as electrical arcing or reduced collection efficiency. Temperature also affects gas viscosity and particle behavior; higher temperatures may enhance particle mobility but can increase gas volume flow rates, potentially reducing residence time within the ESP [18; 21].

3.3. Gas Injection Techniques

Gas injection methods can significantly improve ESP performance by enhancing gas flow distribution and increasing particle charging efficiency. Techniques such as flue gas recirculation or air assist create turbulence in the gas stream, facilitating better mixing of particles with the electric field. This turbulence ensures that particles remain in the active charging zone longer, thereby increasing the likelihood of effective collection [22]. Also, electrospray, a process, i.e., the generation of charged droplets or particles from a liquid by applying a high voltage, can enhance particle collection efficiency by 21-36% [18]. In Fig. 3, the gas injection technique is seen in a wire plate ESP.

Injecting gases such as sulfur trioxide (SO_3) into ESPs can also enhance the efficiency by improving the collection of particulate matter due to reducing the particle resistivity. SO_3 promotes the formation of sulfuric acid mist, which condenses on fly ash particles, increasing their size and charge. This process facilitates better agglomeration and enhances particle migration toward the collection plates, ultimately improving removal rates. Studies have shown that maintaining SO_3 concentrations around 34.3 mg/m³ can boost ESP efficiency to 99.5% or higher [23]. Thus, SO_3 injection is an effective strategy for optimizing ESP performance, particularly in systems dealing with high-resistivity dust.

3.4. Geometry of Filters

Innovative geometrical designs in ESPs have been shown to significantly enhance their collection efficiency. Key design elements such as electrode shape/spacing, plate configuration, and overall dimensions influence gas flow patterns and particle collection effectiveness [16].

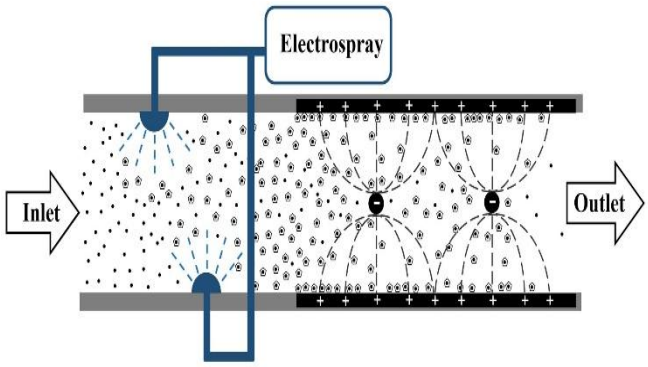


Fig. 3: Electrospray in a wire plate ESP to enhance particle collection.

For example, increasing the surface area of collection electrodes or fine-tuning the spacing between electrodes can lead to improved particle capture rates [18]. Additionally, sawtooth electrodes, designed in [24] for tubular ESPs, optimize electric field distribution and particle charging, achieving a 15% improvement in collection efficiency compared to standard geometries. Similarly, spike-plate electrodes for wire-plate ESPs create effective electric fields, improving the collection of submicron particles by enhancing particle agglomeration and migration toward collection plates [25] (see Fig. 4). Also using multiple discharge electrode can be used to enhance the efficiency [26] Another approach involves truncated conical precipitators, which improve gas flow distribution and reduce re-entrainment of particles, leading to higher collection efficiencies [27]. Additionally, metal foam filters combined with electrostatic assistance offer low-pressure drop and efficient removal of fine particles by increasing the effective surface area for particle capture [28]. Using multi-stage ESPs or combining ESPs with other filters can also be effective approaches to improve filter efficiency (see [28]).

4. MANUFACTURE MODULAR ESP PROTOTYPE

The modular structure refers to the arrangement of multiple ESPs placed side by side to form a network, which is used to fill an output, such as a cylindrical gas container, for particle removal from the gas. This concept is illustrated in Fig. 5; the cross-sectional geometry of the filters within the ESPs can be triangular, square, hexagonal, or circular. This modular setup offers flexibility and scalability in both the design and operation of the system, while eliminating the need for a single large filter and the dependence on very high voltages. It also brings added benefits, such as simpler maintenance and more straightforward manufacturing processes.

To evaluate performance, we compare different cross-sectional geometries. Four filters/ESPs were built with triangular, square, hexagonal, and circular shapes, as shown in Fig. 6. Their dimensions are listed in Table 1. To ensure fairness, each filter has the same cathode rod, filter height 10 cm, and a cross-sectional area of 25 cm^2. The collecting surface area for each is also in Table 1. All filters were operated at a fixed voltage of 10 kV (see Fig. 6). This voltage was chosen as it represents the maximum stable output of the power supply, thereby allowing a performance comparison of all geometries under the highest feasible driving force in our experimental setup. The test for the filter involves passing the same volume of smoke with the same density through different filter shapes within a specified time frame considered to be 2 minutes.

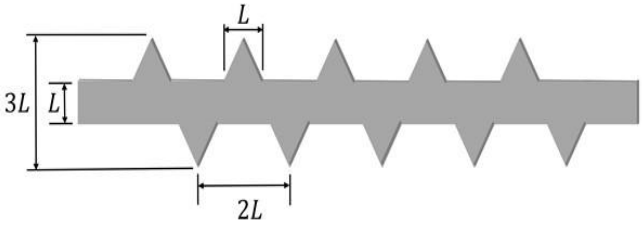


Fig. 4: Spike plate electrode for wire plate ESPs. A typical size of *L* is 1cm.

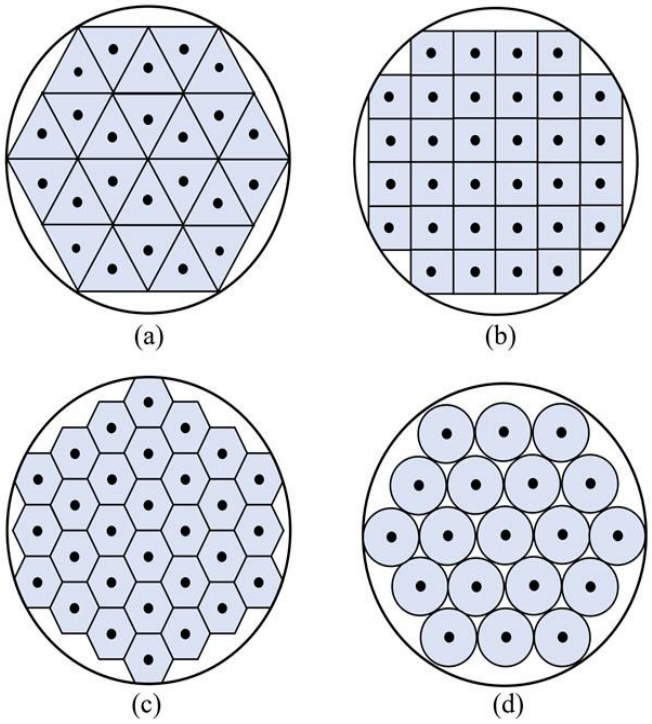


Fig. 5: Modular structure; (a) triangular, (b) square, (c) hexagonal, and (d) circular configurations. Discharge electrodes are shown by bold points.



Fig. 6: The manufactured prototypes of triangular, square, hexagonal, and circular shapes. The utilized high voltage power supply can produce a DC voltage between 1kV to 10kV.

Table 1: Dimensions of the different manufactured ESPs

Shape	Side length (cm)	Radius (cm)	Collecting surface area (cm^2)
Triangular (equilateral)	7.5	-	226
Square	5	-	198
Hexagonal	3.1	-	185
circular	-	2.8	176

The difference in the filter's weight before and after the test indicates its performance, i.e., the amount of smoke particles captured by the filter. The test aerosol is smoke from combusted paper towels, representing fine organic particulate matter. The identical aerosol generation ensures a constant background for a fair geometric comparison, though the precise Particle Size Distribution (PSD) cannot be measured due to equipment limitations. This is noted as a study constraint but does not affect the validity of the performance ranking between the four geometries.

Fig. 7 illustrates the performance of the four filter shapes. The experiments have been repeated 3 times, and the average± std. dev. values are reported. The yellow error bounds on the bars represent the twice of standard deviation, indicating the level of measurement variability. The performance ranking is hexagonal > circular > square > triangular. This is because the hexagon's shape creates a more uniform electric field than the square or triangle, based on the electromagnetic principle that sharper corners disrupt and weaken the electric field. Furthermore, as Table 1 shows, the hexagon also has a larger collecting surface area than the circular filter, which leads to its higher collection mass. In Fig. 8, the mass of particles collected by each filter is normalized by the area of its collecting surface, indicating that the filter with a hexagonal cross-section remains a suitable candidate for use. This suggests the hexagonal surface is used more efficiently. This higher efficiency is attributed to its electric field, which is more uniform than in angular shapes and has points of higher local strength than the circle, making more of its area electrostatically active. In Fig. 9, the mass of collected particles in 2 minutes for the hexagonal filter shape is shown for different applied voltages to the cathode rod. As predicted, increasing the voltage improves the performance.

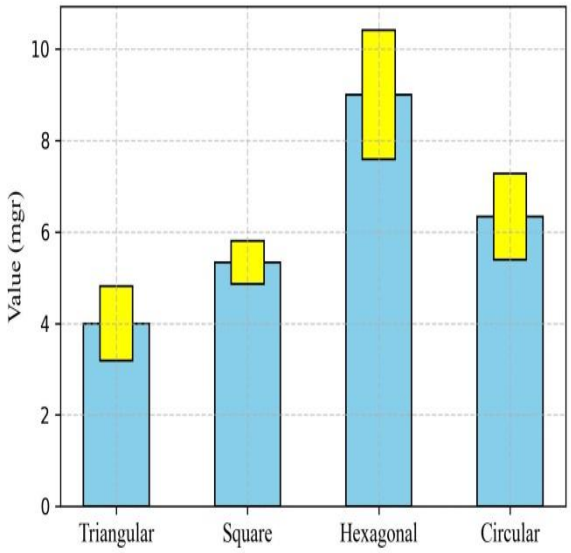


Fig. 7: The mass of collected particles in 2 minutes for different filter shapes. The height of each bar represents the mean of the experimental trials; the yellow error bars indicate the standard deviation.

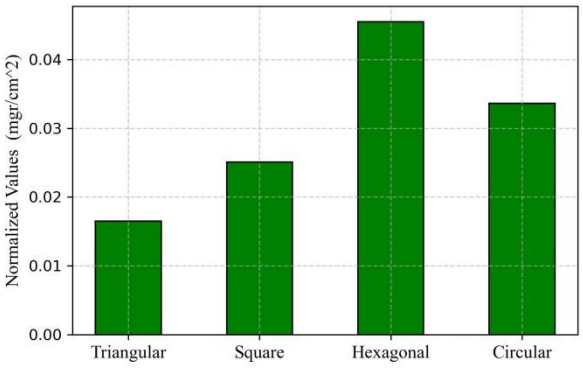


Fig. 8: Collected particles in 2 minutes normalized by the collecting surface area for different filter shapes.

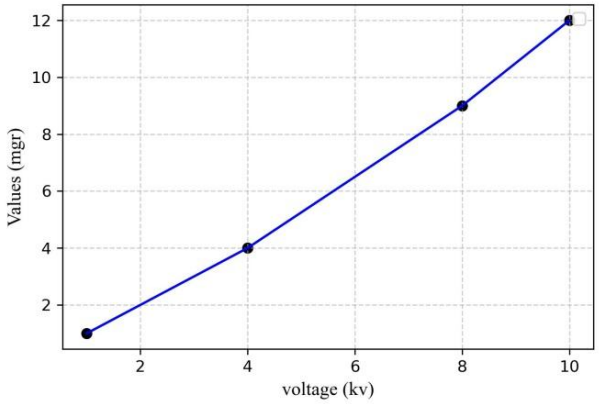


Fig. 9: The mass of collected particles in 2 minutes versus different voltages at the cathode rod for the hexagonal filter shape.

5. CONCLUSION

ESPs, recognized for their effectiveness in particulate matter capture across various applications, operate on distinct mechanisms and offer unique advantages, though they face limitations such as high costs and scalability challenges. This paper analyzed the working principles of various ESP types and identified key parameters influencing their efficiency. To address these challenges, we focused on modular-based structures, which provide flexibility, cost-effectiveness, and scalability. Four prototypes with triangular, square, hexagonal, and circular cross-sections were designed and tested under controlled conditions, demonstrating their potential to be implemented as modular structures. The results highlight the hexagonal-based design as a strong candidate, offering reliable performance and practicality for industrial applications.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ali Asghar Haghighi: Conceptualization, Validation, Visualization, Roles/Writing - original draft. **Mohammad Khodaei**: Investigation, Methodology, Supervision, Writing - review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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