Clean Energy and Smart Technology
Volume 03, Number 01, October 2024
DOI : https://doi.org/10.58641/

e-ISSN :2964-2647

DESIGN OF ELECTROSTATIC PRECIPITATOR (ESP) PROTOTYPE AS A SOLID PARTICLE CAPTURE DEVICE FOR WASTE INCINERATION CHIMNEY EXHAUST

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Submitted : 25 October 2024 | **Accepted** : 30 October 2024 | **Published** : 31 October 2024

Abstract: The waste discarded by the community every day comes from agricultural activities, markets, households, entertainment, and industry. One form of waste is domestic waste, which originates from household waste. The increase in domestic waste goes hand in hand with the development of physical infrastructure and the expansion of adequate facilities and infrastructure. As a result of this pollution, environmental balance is disrupted.
In this experiment, one method will be used to reduce or minimize environmental pollution, especially air pollution, by using an electrostatic precipitator as a tool to capture solid particles from exhaust gas in waste combustion smoke. It is expected to efficiently reduce the solid particle content in the exhaust gas from waste combustion. The electrostatic precipitator is an alternative for reducing environmental pollution, as it has high efficiency, reaching 98.4%, and can capture particles as small as 100 micrometers. The electrostatic precipitator works by capturing solid particles that pass through the particle charging area, which is at a high potential. The charging area provides high-speed electrons by ionizing molecules and particles in the exhaust gas from the smoke. The exhaust gas particles receive positive ions and become highly charged, allowing them to be attracted and captured by negatively charged electrodes (collecting plate). Through this process, the solid particle content in the exhaust gas from waste combustion can be eliminated. Therefore, this final project involves the development of an electrostatic precipitator prototype aimed at reducing environmental pollution, particularly air pollution.
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Keywords: *ESP, Waste management, Incineration, Air pollution, Enviromental*

1. INTRODUCTION

The increase in waste from various sources, including households, industries, and urban activities, has raised significant challenges in waste management. One commonly used method for reducing waste volume is incineration, especially in urban areas with limited land availability. However, this process presents new problems, primarily through emissions of exhaust gases containing solid particulate matter and other hazardous pollutants. These particulates, especially those of very small size, can remain airborne for extended periods and cause various health issues, including acute respiratory distress, cardiovascular diseases, and chronic lung conditions (WHO,

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2019). With growing public awareness and government policies aimed at tightening air quality standards, the need for effective air pollution control technologies is increasingly urgent.

The Electrostatic Precipitator (ESP) is one such technology that has proven effective in capturing fine particles released in exhaust gases across various industrial applications, such as power plants, cement factories, and kilns. ESP technology operates based on the electrostatic principle, where electrically charged particles are drawn toward collector electrodes, resulting in cleaner exhaust gases being released (Jaworek et al., 2021). This mechanism involves the application of a strong electric field to ionize the air and particles, causing oppositely charged particles to migrate to the respective electrodes. In this way, ESP can reduce particles to below the thresholds established by environmental regulations, making it a primary choice for controlling particulate emissions. Research by Zhu et al. (2020) has highlighted the effectiveness of ESP in capturing nano-sized particles, positioning it as superior to other methods, such as baghouse filters or cyclone separators, especially for industrial applications with high exhaust volumes.

While ESP has been widely adopted at large industrial scales, its application on a smaller scale, such as for waste incineration, still faces several challenges. In the context of waste incineration, the ESP design must be adapted to match the varied characteristics of exhaust emissions, which contain different particulate concentrations depending on the type of waste being burned (Chen et al., 2022). Another challenge is developing an ESP that not only effectively captures particulates but is also energy-efficient and affordable in terms of production and maintenance costs. For small-scale prototypes, several factors must be considered, including selecting electrode materials with high conductivity, thermal stability, and durability. This ESP prototype is intended to function as an initial step toward developing a solution that can be widely implemented, particularly in areas that require emission control but have limited financial resources.

The development of an ESP prototype for waste incineration chimneys aims to create a device capable of effectively capturing particulates before the exhaust gases are released into the atmosphere. This technology can help reduce particulate concentration in the air and preserve air quality in areas surrounding waste incineration sites. Thus, this effort represents a crucial step toward achieving air pollution reduction targets outlined in various regulations and international environmental commitments, including the Paris Agreement. The impact of implementing this technology will benefit not only the environment but also the surrounding community, as it will enhance public health safety. On a larger scale, this innovation could contribute to a global solution to worsening air pollution issues.

In addition to meeting the application needs for small to medium-scale pollution control, this study also aims to address various technical challenges commonly encountered in the design and implementation of ESP. One such challenge is ensuring that the energy used by the ESP remains minimal, given that energy costs often pose a major barrier to the application of this technology in smaller industries or settings that lack a stable energy resource. Therefore, energy-efficient and cost-effective design is a primary focus of this research. In a broader context, this research is expected to contribute to the advancement of ESP technology, particularly in innovative designs adaptable to exhaust gas conditions from waste incineration (Jiang et al., 2018).

This study will also contribute to the literature on emission and particulate control using ESP technology, as current literature primarily focuses on large-scale applications in the energy and chemical industries. The ESP prototype developed in this study is expected to provide practical references for designing and implementing ESP in medium and small-scale incineration facilities, which have not been widely researched. With a simpler design and accessible materials, this ESP is intended to become a feasible solution that can be adapted and implemented by various parties, including areas with waste incineration facilities but limited resources and technology for pollution control.

In the context of implementation in Indonesia, for instance, the development of small-scale ESP has promising potential, given the high rate of waste incineration in various cities and the limited pollution control technology available. This adaptive and affordable ESP technology could serve as a practical solution enabling safer and more sustainable waste management in urban environments. With its significant potential, ESP technology is expected to positively impact air quality and the quality of life for people living near incineration sites. Success in developing this ESP prototype could drive innovation in other pollution control technologies and serve as a reference for future research and implementation.

In conclusion, this research focuses on developing an ESP prototype suitable for waste incineration chimneys to effectively, economically, and energy-efficiently control particulate emissions. This prototype design is anticipated to become a technological alternative for industrial or urban areas that require practical solutions to air pollution problems resulting from waste incineration. Thus, this article is expected to contribute substantially

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to advancements in emission control technology and enrich the literature on ESP implementation for small to medium-scale applications.

2. MATERIALS AND METHOD

The research begins with a Needs Identification phase, where specific requirements are established based on the characteristics of particulate emissions from waste incineration processes. This information is critical for customizing the ESP to match the pollutants produced, especially in terms of the particle size and concentration levels expected.

Next, in the **Design Conceptualization** phase, initial blueprints are drawn up. This involves calculating optimal dimensions, airflow rates, and the best arrangement for collecting electrodes to ensure efficient capture of particles. This phase ensures that the ESP will be capable of handling the expected workload without loss of efficiency.

The third phase, **Material Selection and Power Supply Planning,** involves choosing materials for the electrode and collector plate that can endure the high temperatures and voltages associated with ESP operations. It also requires designing a power supply that can maintain a high-voltage field for charging particulates.

Following the design and material selection, the **Prototype Construction** phase brings the design to life, creating a functional ESP prototype ready for real-world testing.

The **Testing and Emission Analysis** phase involves using a diesel emission tester to gauge the ESP's effectiveness. This stage not only verifies that the ESP captures particulates as expected but also provides data on how well the ESP prototype performs across multiple tests.

Finally, in the **Result Analysis and Optimization** phase, data from the tests are analyzed to determine the ESP's effectiveness and to identify any areas for improvement. This cycle may repeat until the prototype meets the desired efficiency benchmarks.

Table 1 Initial Size and Calculation Results of the ESP Prototype

Part	Dimension	Unit
Inlet cross-sectional area	2.826	cm²
Smoke velocity	0.2	m/s
Smoke flow rate	0.5652	L/s
Distance between electrodes	8	mm
Electrode points in 1 column	187	pcs
Electrode diameter and length	2	mm
Electrode arrays in 1 column	1	unit
Electrode arrangement units	5	unit
Collecting plate area per column	26	cm²
Total Collecting plate area	260	cm²
Collecting plate layers	6	pcs
Collection area height	130	mm
Collection area width	200	mm
Collection area length	161	mm
Total collection area	158.26	cm²

The prototype design planning to determine the dimensions of the Electrostatic Precipitator (ESP) for capturing dust particles in exhaust smoke to reduce air pollution from waste incineration must take into account the exhaust flow rate produced by the combustion process. This exhaust flow rate can then be used to determine the appropriate dimensions for the ESP prototype design. Based on this flow rate, the entry velocity should be minimized to align with the flow according to Stokes' law.

The design of the ESP prototype focuses on two main considerations: technical and ergonomic. For technical requirements, the materials for the discharge electrode and collecting plate must withstand high voltage

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and temperatures up to 400°C to maintain effectiveness and stability in extreme conditions. High-temperature insulators are also essential to prevent short circuits, and the airflow system is optimized to manage gas flow and capture particles based on the emission characteristics of waste combustion. Ergonomically, the prototype is tailored to handle the daily waste output of an average household, enabling efficient operation in a single cycle. This user-focused approach not only supports practical daily use but also contributes to reducing air pollution effectively.

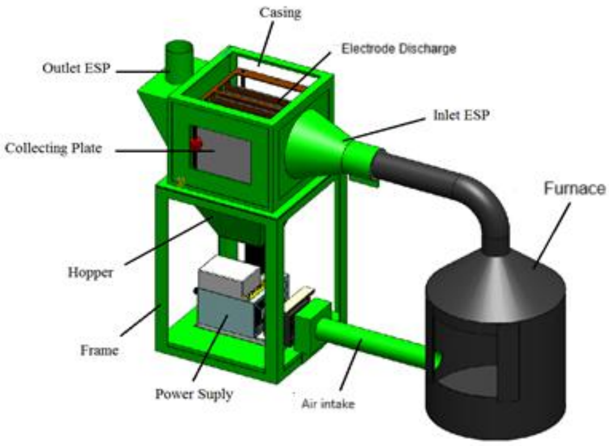


Figure 1. Design Electrostatic Precipitator

3. RESULT

A. Prototype Design Calculations

The ESP prototype is designed as a single-stage type, where the capture of solid exhaust particles and electrical charging occurs in one area between the positive and negative electrodes. In the particle capture area, there is a particle collector plate (collector plate) and a wire that creates a corona discharge to electrically charge the particles (discharge electrode). The inlet cross-sectional area for gas entry into the filter chamber can be calculated mathematically as follows:

$$A = \pi r^2$$

A = 3,14x 30^2 (30 = radius *inlet ESP*).

= 2.826 mm^2 = 2,826 m^2,

The normal gas velocity is limited to a range of V = 0 – 2.0 m/s, so a value of V = 0.2 m/s is chosen as the gas entry velocity in the ESP. Therefore, the maximum exhaust flow rate in the filter chamber can be calculated mathematically as follows.

(A = Q/v)

2,826 = *Q*/0,2 (*Q* = Maximum Exhaust Flow Rate).

Q = 2,826x0,2

= 0,5652 m^3/s

The spacing between the positive and negative electrodes is planned to be l=10l = 10l=10 mm. For the discharge electrode, designed as a rigid plate, each column contains 187 electrode points with each point having a diameter of 2 mm and a wire length p=5p = 5p=5 mm, with 8 mm spacing between each point. The cross-sectional area of a single collector plate (ApA_pAp) is calculated as Length (P) 200 mm x Width (L) 130 mm = 26,000 mm². With 10 columns (CCC) in the capture area (filter), the total collector plate cross-sectional area (AtA_tAt) can be calculated as follows.

$$A_t = A_p \, x \, C$$

A_t = 26.000 x 10
= 260.000 mm^2 = 260 m^2

To calculate the total particle collection area, it is necessary to know the planned shape. Since the collection area is rectangular, the following equation can be used:

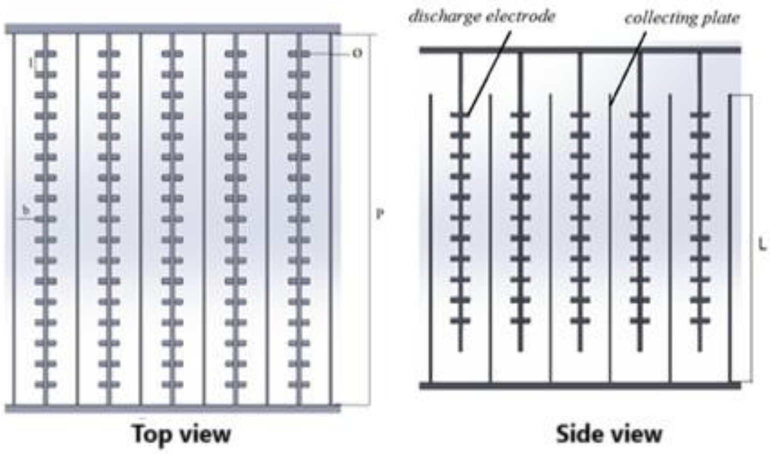
A_L =2(PxL+Pxt+Lxt),

with dimensions P=? L=200 mm L = 200 and t=130 mm.
The length P can be calculated as the number of collector plates multiplied by the thickness of each collector plate plus the number of spaces between plates multiplied by the spacing between plates:

P = 6 x 1 + 5 x 31
= 161 *mm*

A_L = 2(PxL+Pxt+Lxt)
= 2 (161x200 + 161x130 + 200x130)
= 2 (32200 + 20930 + 26000)
= 2 x 79130
= 158260 mm^2
= 158,26 m^2

The cross-section of the ESP prototype filter is shown in Figure 2, and the dimensions along with the initial calculation results are presented in Table 1. The particle collection area cross-section in the ESP prototype is designed to maximize the capture of particulate matter from exhaust gases. This section includes the arrangement of collecting plates and electrodes, which are spaced to create an effective electrostatic field for particle attraction. The cross-section layout is optimized to handle the volume and flow rate of the exhaust, ensuring efficient collection and removal of particles from the gas stream before it exits the ESP.



Gambar 2. Particle Collection Area Cross-Section

In the voltage planning for generating electrode corona, a power supply with a minimum output of 10 kV DC high voltage is used (Tobing, B.L., 2002). Therefore, in the ESP prototype design, a power supply is used with an AC input capacity of 220 volts, a maximum power of 100 watts, and a DC output of 10 kV – 40 kV, with a frequency of 50/60 Hz.

B. Testing of the Electrostatic Precipitator (ESP)

1. *ESP Prototype Testing*

Clean Energy and Smart Technology
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The ESP prototype testing involves several steps to evaluate its particle collection performance and operational stability. Here’s an outline of the testing process:

a. Electrical Setup Preparation:
First, the electrical system is prepared by connecting the AC power source to the DC high voltage output in the power supply. This setup is crucial for stabilizing the power and ensuring safety by preventing short circuits or electrical leakage within the ESP prototype components.

b. Combustion Sample Preparation:
To simulate real-world conditions, samples of waste materials—such as small wood pieces, plastic, and paper—are prepared for combustion. These materials are representative of typical waste combustion emissions, allowing for realistic testing of the ESP's efficiency in capturing particles.

c. Visual Assessment of Particle Reduction:
A visual observation is conducted by comparing the exhaust gas opacity when the ESP is turned on and off. This simple test provides an initial indication of the ESP's effectiveness in reducing visible particulate emissions.

d. Emission Opacity Measurement:
Using a diesel emission tester, the opacity of the exhaust is quantitatively measured both before and after treatment by the ESP. This device assesses the concentration of particles, with reduced opacity indicating the ESP's success in trapping particulates. Multiple tests are conducted to confirm consistent performance.

This comprehensive testing approach validates the ESP prototype’s ability to effectively capture and reduce particulate matter from combustion emissions, contributing to cleaner air output.

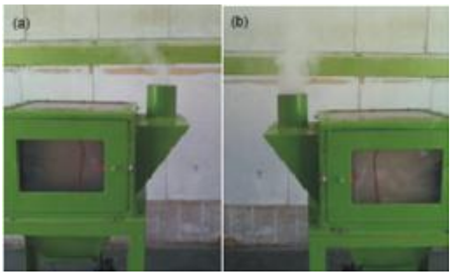

Figure 3. Visual Results of ESP Prototype Testing (a) Switch on, (b) Switch off

This figure 3 illustrates the visual results of the ESP prototype testing, highlighting the difference in particle concentration in the exhaust gas as observed through the ESP outlet. The comparison is made between instances when the power supply is turned on and off, showing the effectiveness of the ESP in reducing visible particulate emissions.

2. Emission Level Testing

Emission testing was conducted using a diesel vehicle emission tester with a 1-Mode system. This testing measures the opacity (smoke density) of particulate emissions in the exhaust gases from the ESP prototype. The opacity values obtained from the emission tester provide an estimate of particle reduction achieved by the ESP prototype, serving as a basis for calculating the efficiency of particle reduction in exhaust gases from waste combustion.

Samples were taken eight times to gather opacity values. In the first test, the ESP prototype’s power supply switch was set to “off” to record the maximum particle concentration in the exhaust. In subsequent tests (from the second to the eighth), the switch was set to “on” to capture the particle reduction impact of the ESP prototype. This comparison allows for calculating the reduction in particle concentration in the exhaust.

The values obtained from this 1-Mode emission testing system are illustrated in the graph shown in Figure 4 and summarized in Table 2 below.

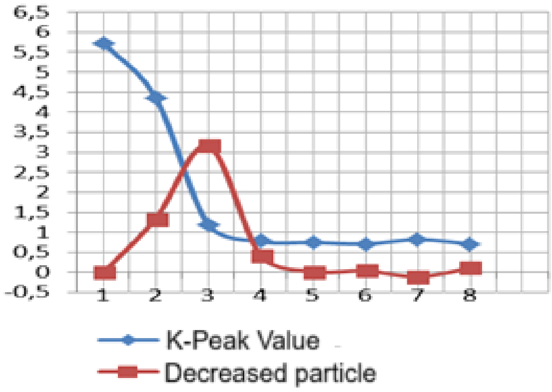

Figure 4. Emission Test Results Graph of the ESP Prototype's Impact

The graph illustrates the effect of the ESP prototype on reducing particulate emissions. It shows two key variables:

1. K - Peak Value (Blue Line):
   Represents the opacity or density of the exhaust gas. Initially, the value is high, indicating a higher concentration of particles when the ESP is off. As the ESP is activated, the opacity value decreases, showing that the ESP effectively reduces the density of particulate matter in the exhaust gas.
2. Particle Reduction (Red Line):
   Indicates the decrease in particulate matter as a result of the ESP prototype being activated. The particle reduction peaks when the ESP is most effective and then stabilizes as the system reaches a steady state.

C. Discussion

The design of the ESP prototype includes a specific electrode arrangement, with the collecting plate having a thickness of approximately 1 mm and the discharge electrode designed with a rigid plate, also 1 mm thick. The electrode has a diameter of 2 mm and a length of 10 mm across two columns. The spacing between the collecting plate and the end of the discharge electrode wire is set at 10 mm. This design utilizes a minimum DC voltage of 10 kV, which is sufficient to generate the corona discharge necessary for the ESP prototype's operation. The corona discharge is responsible for charging the exhaust gas particles with ions (ionization process), a phenomenon where high-voltage DC electricity creates a uniform glow on the surface of the electrodes （Arismunandhar, 1968）. The use of corona discharge has been widely recognized for its efficiency in particle charging, crucial for electrostatic particle collection（Jaworek et al., 2021).

The prototype uses SM 25-type insulators and a shaft as support and separator between the positive and negative electrodes. However, the choice of these materials was suboptimal due to the unstable variation in impulse voltage generated by the power supply, which caused electrical arcing (sparking) between the discharge electrode and the collecting plate. This limitation has been observed in other studies where proper material selection and insulation play a key role in preventing arcing and improving ESP efficiency（Zhu et al., 2020）.

For the electrode material, stainless steel was selected for the collecting plate due to its high resistance to corrosion. This is crucial as oxidation reactions occur in the system, which could otherwise lead to corrosion and affect the ESP's performance. The discharge electrode (rigid plate) used two materials: ST37 iron for the plate and copper wire. While iron is prone to corrosion, copper was chosen for its excellent conductivity. However, there were issues with the use of soft solder joints and the ST37 plate, which were not ideal for high-temperature operation. Despite these limitations, these materials were deemed sufficient for short-term experimental use（Tobing, 2002). The use of different electrode materials, such as copper, has been shown to enhance electrical conductivity, contributing to improved particle charging efficiency（Jaworek et al., 2021）.

The design of the waste combustion chamber in the ESP prototype features a conical cylinder connected to a pipe, aimed at optimizing the exhaust gas flow. An air inlet is also added to supply oxygen for the combustion process. ST37 iron was chosen for the combustion chamber due to its availability and ease of manufacturing, as well as its cost-effectiveness. However, ST37 is not an ideal material for this purpose as it is prone to corrosion and poses a heat hazard, making it unsafe for nearby personnel. Nevertheless, it was considered adequate for experimental use (Zhu et al., 2020). Future designs may benefit from exploring more heat-resistant materials to enhance safety and performance during long-term operation.

In visual tests of the ESP prototype, the reduction in particulate concentration in the exhaust gas was apparent when the power supply switch was turned on. The emission testing was conducted using a 1-Mode system, with samples taken eight times. The first sample, taken with the power supply switch off, showed 100% particulate concentration from waste combustion. For the second to eighth samples, a gradual reduction in particulate concentration was observed, with reductions of 24.08%, 55.15%, 7.33%, 0.35%, 0.07%, -1.92%, and 1.92%, respectively. The total efficiency in reducing particulate concentration with the ESP prototype was calculated to be 86.99%. This high efficiency aligns with other research on the potential of ESPs in removing fine particles from exhaust gases, confirming the feasibility of such systems for reducing air pollution (Chen et al., 2022).

The results of this ESP prototype design provide a foundation for further development of a device capable of reducing particulate concentrations in exhaust gases from waste incineration. In terms of particle physics, the ESP can reduce combustion particles by applying an electrostatic field. The prototype is designed to handle particles up to 100 microns in size, while the exhaust gas particles range between 0.01 to 0.1 microns. Therefore, the ESP prototype is capable of capturing particles from waste combustion exhaust gases effectively (Jaworek et al., 2021). As such, the application of ESPs for smaller particle sizes presents an opportunity to address more fine-grained pollutants, a common challenge in air pollution control (Zhu et al., 2020).

4. CONCLUSION

The design and testing of the ESP (Electrostatic Precipitator) prototype demonstrate its significant potential in reducing particulate emissions from waste incineration exhaust. The prototype, utilizing a combination of rigid discharge electrodes and stainless steel collecting plates, effectively captures particles through corona discharge. With an efficiency rate of 86.99% in reducing particle concentration, the ESP prototype shows promise for applications in air pollution control, particularly in small-scale waste combustion systems.

Several key aspects contribute to the prototype's success, including the choice of materials for the collecting plates and electrodes, as well as the proper voltage generation to create the necessary ionization for particle capture. However, issues such as material corrosion (ST37 iron) and electrical instability due to arcing highlight areas for future improvement, especially when considering long-term use. In terms of particle size, the prototype is designed to handle particles up to 100 microns, while it effectively captures exhaust particles as small as 0.01 to 0.1 microns. This confirms the ESP's capability in addressing fine particulate matter, which is a major contributor to air pollution.

Moving forward, refinements in material selection, electrode arrangement, and airflow management could further improve the performance and efficiency of the ESP prototype. The findings of this research provide a solid foundation for the development of more robust and reliable systems to mitigate air pollution in waste incineration processes.

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Clean Energy and Smart Technology
Volume 03, Number 01, October 2024
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