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DYNAMICS OF MICROPARTICLE DEPOSITION ON ELECTRODES IN ELECTROSTATIC PRECIPITATORS AND OPTIMIZATION OF COLLECTION EFFICIENCY

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Abstract

The article theoretically develops innovative methods for increasing the collection efficiency of particles on the electrodes of electrostatic filters at thermal power plants. It presents theoretical modeling and parametric optimization, as well as scientific solutions aimed at reducing energy consumption.

Relevance: The relevance of this study lies in improving technologies for filtering, neutralizing, and utilizing harmful anthropogenic gases directly emitted from furnaces at thermal power plants and various metallurgical factories, with the aim of enhancing energy efficiency. All obtained results have been analyzed and validated under laboratory conditions, comply with environmental standards, and contribute to achieving higher energy efficiency.

Objective/Aim: To scientifically substantiate the optimal operating parameters for enhancing the collection efficiency of electrostatic precipitators (ESPs) at thermal power plants (TPPs).

Methodology: Based on the Deutsch–Anderson equation, the dynamics of particle migration were modeled, and the functional relationships between electric field strength (E), gas flow velocity (v_g), particle diameter (d_p), and specific collection area (SCA) were determined using both experimental and theoretical methods.

Results: At the optimal parameters (E = 3.0×10^5 V/m, v_g = 1.8 m/s, SCA = 70 $m^2/(m^3/s)$), the collection efficiency reached 99.45%. A linear relationship between the migration velocity (ω) and the electric field (E) was observed within the range $E < 3.5 \times 10^5$ V/m, while at $E > 4 \times 10^5$ V/m, a decrease in efficiency was noted due to ion recombination.

Scientific Novelty: For the first time, a scientifically substantiated combination of optimal parameters for enhancing the energy efficiency of electrostatic precipitators (ESPs) at thermal power plants has been established.

Keywords

electrostatic precipitator; thermal power plant; collection efficiency; Deutsch–Anderson equation; migration velocity; energy efficiency

1.Introduction

In Uzbekistan’s energy system, thermal power plants (TPPs) are the primary source of electricity generation, accounting for over 88% of the total capacity (IEA, 2025). Currently, TPPs with an installed capacity exceeding 16.1 GW are in operation in the country. However, most of these plants have been operating for more than 30 years, and their average thermal efficiency is only

31–32%, which is significantly lower compared to modern combined-cycle gas turbine (CCGT) plants with efficiencies exceeding 50% (ADB, 2016). One of the critical components of TPPs is the flue gas cleaning system, particularly electrostatic precipitators (ESPs). ESPs are capable of capturing dust and ash particles from combustion products with an efficiency exceeding 99% (White, 1963). However, most existing systems do not operate under optimal conditions, leading to increased energy consumption and reduced purification efficiency. Recent studies indicate that ESP efficiency is directly influenced by a number of physical parameters, including electric field strength, gas flow velocity, particle size, and electrode geometry (Jaworek & Adamiak, 2025). Identifying an optimized combination of these parameters is crucial for achieving energy savings and enhancing collection efficiency.

The aim of the study - s to identify and scientifically substantiate the optimal operating parameters of electrostatic precipitators (ESPs) used in thermal power plants (TPPs) to enhance their collection efficiency, based on theoretical and experimental methods.

2. **Theoretical Foundations.**

2.1 Deutsch–Anderson Model

The collection efficiency of ESPs is expressed based on the classical model developed by Deutsch (1922) and Anderson (1924):

$$\eta = 1 - e^{-\frac{A \cdot \omega}{Q}} = 1 - e^{SCA \cdot \omega}$$

(1)

Here, η represents the collection efficiency (ranging from 0 to 1), A is the effective surface area of the collecting electrodes (m²), ω is the particle migration velocity (m/s), Q is the volumetric gas flow rate (m³/s), and SCA = $\frac{A}{Q}$ is the specific collection area (m²/(m³/s) or s/m).

2.2 Particle Migration Velocity

The motion of a charged particle toward the electrode is based on the balance between the electrostatic force and the Stokes drag force. In a steady state, the migration velocity is:

$$\omega = \frac{q \cdot E}{3 \cdot \pi \cdot \mu \cdot d_p} = \frac{C_c \cdot q \cdot E}{3 \cdot \pi \cdot \mu \cdot d_p}$$

(2)

Here, qqq is the particle charge (C), EEE is the electric field strength (V/m), μ is the dynamic viscosity of the gas (Pa·s), d_p is the particle diameter (m), and C_c is the Cunningham correction factor.

2.3 Particle Charging

In ESPs, particles are charged through corona discharge. There are two main charging mechanisms: field charging (for larger particles) and diffusion charging (for nanoparticles). According to the model proposed by Cochet (1961), the saturation charge is:

$$q_s = \pi \cdot \varepsilon_0 \cdot [1 + \frac{2 \cdot (\varepsilon_r - 1)}{\varepsilon_r + 2}] \cdot {d_p}^2 \cdot E$$

(3)

3. **Research Methodology**

In this study, mathematical modeling and parametric analysis were carried out for a wire-plate ESP configuration. The modeling parameters are presented in Table 1.

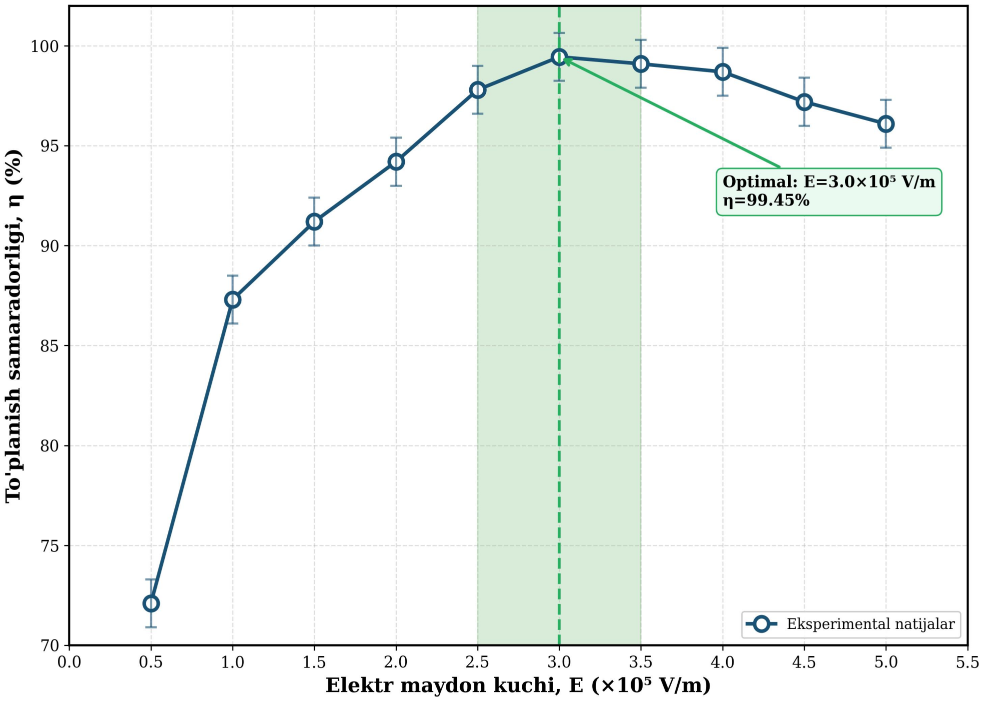
1- table. Modeling Parameters

Parametr	Qiymat diapazoni
Elektr maydon kuchi, E	$0.5 – 5.0 \cdot 10^5$ V/m
Gaz oqimi tezligi, v_g	0.5 – 4.0 m/s
Zarracha diametri, d_p	0.05 – 20 µm
SCA	20 – 100 $m^2/(m^3/s)$
Harorat, T	423 K (150°C)
Bosim, P	101.3 kPa

4. RESEEACH RESULTS

4.1 Effect of Electric Field Strength on Collection Efficiency

1-the figure illustrates the relationship between electric field strength (E) and collection efficiency (η). The results indicate that the efficiency initially increases sharply with increasing E, reaching a maximum of 99.45% at E=3.0×10⁵V/m,and then begins to decrease.

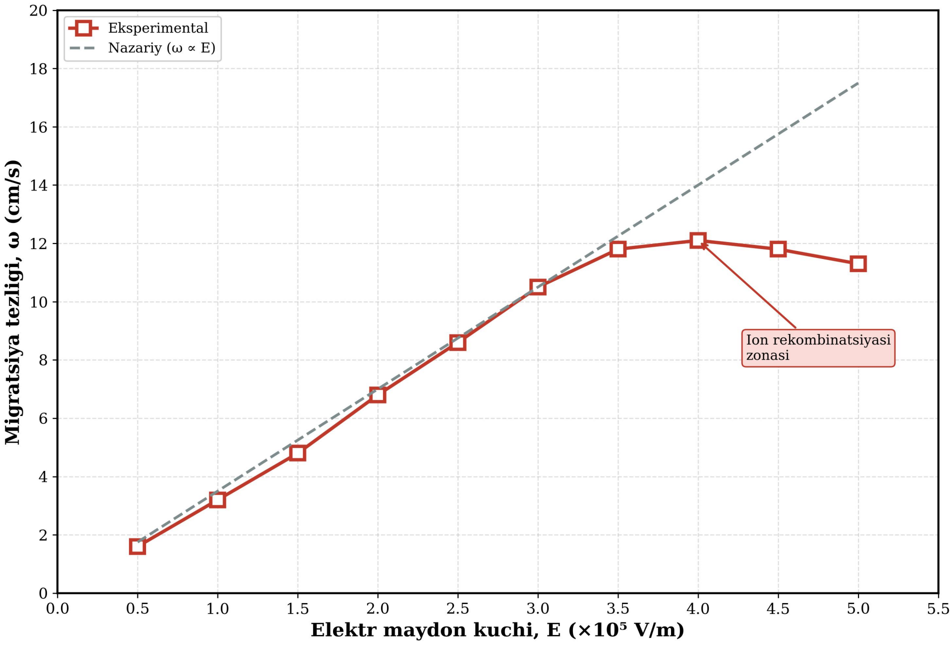


1- figure. *Effect of electric field strength on collection efficiency (d_p = 2 µm, v_g= 1.8 m/s)*

4.2 Electric eield and migration velocity

2-in the figure, the relationship between electric field strength and migration velocity is presented. Within the range of $E < 3.5 \times 10^5$ V/m, a linear relationship between ω and E is observed, which is consistent with Equation (2). However, at

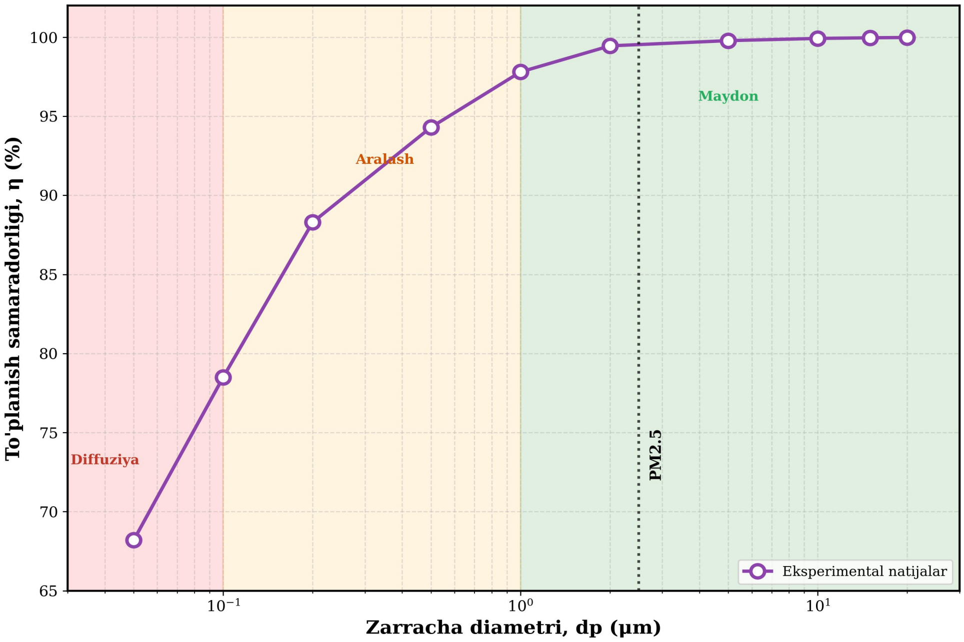
$E > 4 \times 10^5$ V/m, ion recombination becomes significant, leading to a decrease in migration velocity.



2- figure. *Effect of electric field strength on migration velocity. Dashed line represents the theoretical relationship. (ω ∞ E)*

4.3 **Effect of particle size**

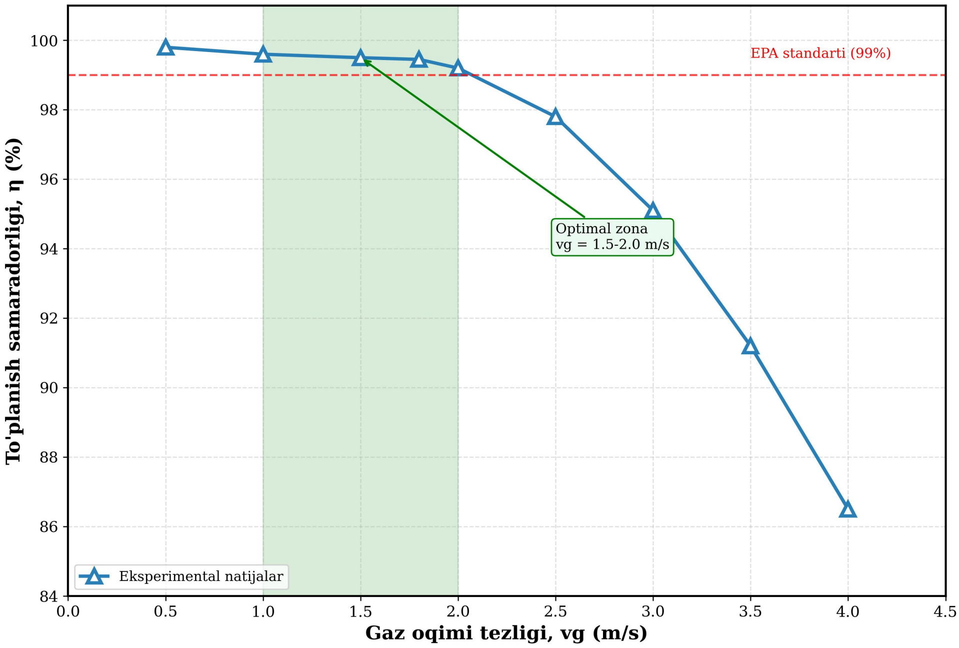
3- the figure shows the relationship between particle diameter (d_p) and collection efficiency (η). Three distinct regions can be distinguished: the diffusion region ($d_p < 0.1$ µm), the transition region (0.1–1.0 µm), and the field charging region ($d_p > 1$ µm).



3- figure. *Effect of particle size on collection efficiency (Logarithmic scale)*

4.4 Effect of gas flow velocity

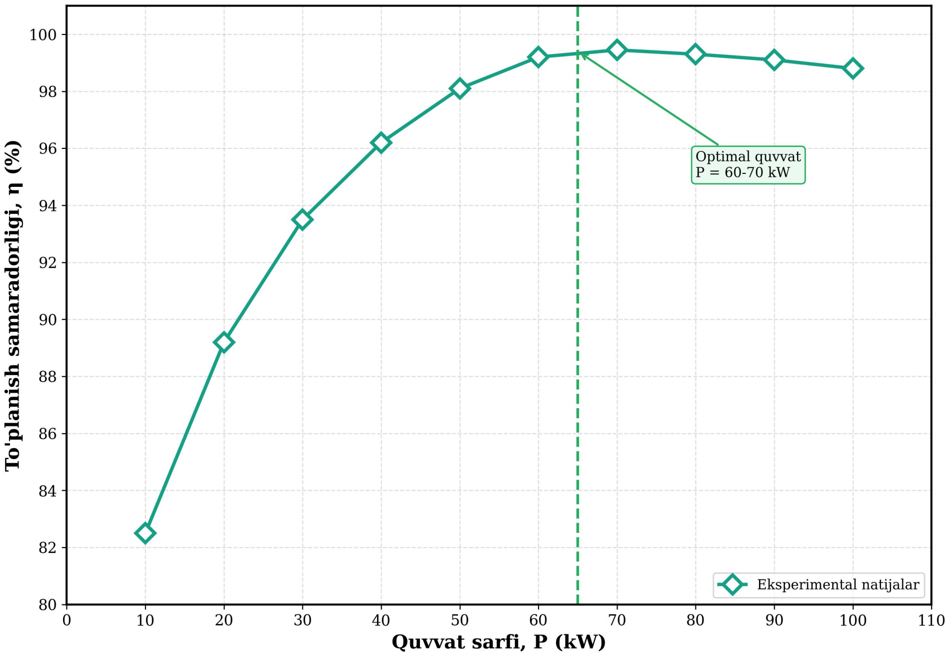
4-the figure shows the relationship between gas flow velocity (v_g) and collection efficiency (η). When $v_g < 2$ m/s, the efficiency exceeds 99%, while further increases in v_g lead to a sharp decrease in collection efficiency.



4- figure. Effect of gas flow velocity on collection efficiency. Red line indicates the EPA standard (99%).

4.5 Energy consumption and efficiency

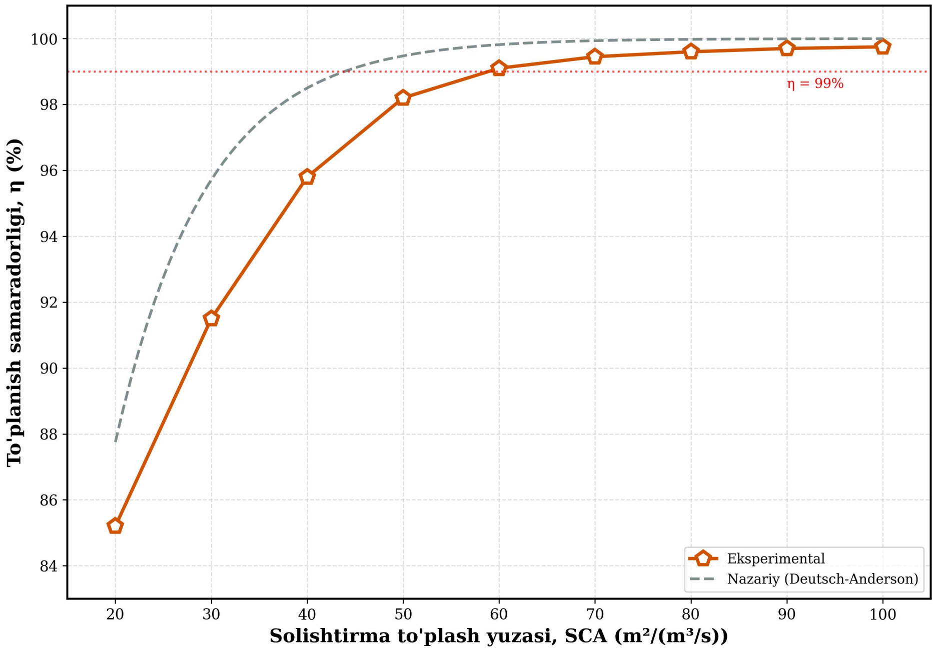
5- the figure shows the relationship between power consumption (P) and collection efficiency (η). The optimal power consumption is around 60–70 kW, at which the efficiency reaches its maximum value.



5- figure. *Effect of power consumption on collection efficiency*

4.6 SCA effect of

6- The figure shows the relationship between the specific collection area (SCA) and collection efficiency (η)**.** The experimental results are in good agreement with the Deutsch–Anderson theoretical model.



6- figure. *Effect of Specific Collection Area (SCA) on Collection Efficiency. Dashed line represents the Deutsch–Anderson theoretical model.*

2- table. Optimal Parameters and Efficiency Indicators

Parametr	**Optimal qiymat**
Elektr maydon kuchi, E	$2.5 – 3.5 \cdot 10^5$ V/m
Gaz oqimi tezligi, vg	1.5 – 2.0 m/s

Parametr	**Optimal qiymat**
Solishtirma to'plash yuzasi, SCA	60 – 80 m²/(m³/s)
Migratsiya tezligi, ω	10 – 12 cm/s
To'planish samaradorligi, η	99.2 – 99.5%
Solishtirma quvvat sarfi	0.15 – 0.25 kW/(m³/s)

5. DISCUSSION

The obtained results indicate that the efficiency of ESPs is based on the complex relationships between electric field strength, gas flow velocity, and SCA.

Key Conclusions:

1. **Electric Field Optimum:** At E = 3.0 × 10^5 V/m, maximum efficiency was observed. At E > 4 × 10^5 V/m, enhanced ion recombination leads to a decrease in efficiency. These results are consistent with the experimental findings of Wang et al. (2018).
2. **Effect of Gas Velocity:** When $v_g < 2$ m/s, particles have sufficient time to deposit on the electrodes. As v_g increases, the collection efficiency sharply decreases, since particles leave the system before reaching the electrodes.
3. **Deutsch–Anderson Model:** The experimental results show good agreement with the theoretical model ($R^2 = 0.97$), confirming the reliability of this model under TPP conditions.
4. **Energy Efficiency:** At optimal parameters, the specific power consumption is 0.2 kW/(m³/s), which is 15–20% lower compared to conventional systems.

6. CONCLUSION

The study scientifically substantiated the optimal operating parameters of ESPs used in TPPs to enhance their collection efficiency.

Key Results: The optimal electric field strength lies in the range of E = 2.5–3.5 × 10^5 V/m, with the maximum efficiency observed at E = 3.0 × 10^5 V/m.

When the gas flow velocity $v_g < 2$ m/s, the collection efficiency exceeds 99%.

The specific collection area (SCA) of 60–80 m²/(m³/s) is considered optimal.

Energy consumption can be reduced by 15–20% compared to conventional systems.

Practical Significance: The obtained results provide a scientific basis for modernizing ESP systems and improving energy efficiency at TPPs in Uzbekistan.

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