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| Research Article

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Scientific-Methodological Foundations for Increasing Electrode Efficiency in Electrostatic Filtration Systems through the Application of Ultrasonic Cleaning Method

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Relevance

At present, the removal of harmful dust and particles from industrial gas emissions is one of the most urgent environmental issues. Electrostatic precipitators (ESP) used in thermal power plants, metallurgy, and the chemical industry serve as effective tools for removing such particles[1]. However, the mechanical rapping method used for cleaning ESP electrodes has several drawbacks:

- ✓ high noise levels,
- ✓ electrode wear and tear,
- ✓ high maintenance costs,
- ✓ low efficiency for sticky and high-temperature dust,
- ✓ shortened electrode service life.

Cleaning using ultrasonic vibrators is a modern, contactless, low-energy, and high-precision method that enables effective removal of dust from electrodes via micro-vibrations.

Objective

To develop the scientific basis for cleaning electrofilter electrodes using ultrasonic vibrators in order to improve their performance; to investigate the effectiveness of dust removal based on vibration frequency, amplitude, and resonance conditions; and to confirm findings through practical experiments.

Methods

Theoretical analysis – studying the adhesion forces of dust on electrodes (Van der Waals, electrostatic forces) and the mechanisms of overcoming them using ultrasonic vibrations. Mathematical modeling – physical modeling of the effects of ultrasonic vibrations on surfaces and dust particles.

Experimental approach – Laboratory experiments were conducted to separate dust from electrode surfaces using piezoelectric ultrasonic vibrators.

Comparative analysis – The effectiveness of the ultrasonic method was compared with the traditional rapping (mechanical impact) method[2].

Results

- It was determined that the efficiency of dust removal from electrodes using ultrasonic vibrators can reach 95–98%.
- Maximum dust detachment was observed in the frequency range of 20–35 kHz and amplitude range of 0.2–0.5 mm.
- Ultrasonic cleaning demonstrated no surface wear, quiet operation, and 30–40% lower power consumption compared to the rapping method.
- Under resonance conditions, electrode vibrations overcame the adhesion forces of dust particles.
- This method is particularly effective for sticky, moist, or high-temperature dust-laden gases, making it relevant for modern ESP systems.

Keywords

Electrostatic precipitator, ultrasonic vibrator, dust removal, piezoelectric vibration, resonance, Van der Waals forces, ESP, contactless cleaning, industrial dust emissions, energy efficiency.

Introduction

Electrostatic precipitators (ESPs) are widely used devices for the effective capture of solid particles from industrial gas emissions. However, the performance of existing ESPs strongly depends on operational conditions and tends to be unstable due to fluctuations in dust flow density, pressure, and temperature.

Thus, increasing the efficiency of electrostatic precipitators and automating their operation is one of the key scientific and technical challenges in environmental engineering.

This study proposes methods for controlling the operating frequency of ESPs in accordance with changes in dust flow and pressure to enhance system responsiveness and adaptability. The findings aim to provide recommendations for improving the energy efficiency of industrial gas cleaning systems and reducing their environmental impact.

Literature Review and Methodology

A review of the literature shows that several key technologies are currently used for cleaning industrial gas emissions, including:

- ✓ mechanical filtration,
- ✓ cyclone separation,
- ✓ electrostatic filtration, and
- ✓ chemical sorption.

Despite these options, the electrostatic method remains one of the most effective, especially for fine particulate matter, but its limitations in harsh environments (e.g., sticky or high-temperature dust) necessitate innovative approaches such as ultrasonic cleaning[3].

Despite the availability of various dust filtration technologies, several challenges arise when applying these methods under different operating conditions in industrial enterprises:

1. Factors Reducing the Efficiency of Electrostatic Precipitators (ESPs)

- Non-uniform distribution and low intensity of the electric field inside ESPs, leading to incomplete capture of dust particles.
- A decline in field intensity and performance due to variations in working conditions (e.g., temperature, humidity, gas flow).
- Electrode surface contamination negatively affecting dust collection efficiency.

2. The Issue of Energy Optimization

- ESPs typically have high power consumption, making the efficient use of electrical energy a critical concern.
- There is a growing need to develop automated and adaptive control systems that respond effectively to changing operating conditions.

3. Introduction of New Filtration Technologies

- Implementation of advanced filter elements based on nanotechnology.
- Development of hybrid filtration systems combining mechanical and electrostatic filters.
- Research into environmentally safe filtering materials and enhancing their efficiency over long-term operation[4].

Analysis of the literature confirms the presence of ongoing research and technological developments aimed at addressing these challenges, reinforcing the relevance of this study. The main objective of the research is to develop innovative approaches to enhance the efficiency of ESPs in industrial gas emission treatment systems. This includes:

- ✓ in-depth study of electrodynamic processes,
- ✓ energy consumption optimization, and
- ✓ experimental testing of new filtering materials.

Results and Discussion

To maintain the long-term efficiency of ESPs, timely and effective removal of accumulated dust particles from electrode surfaces is essential. Traditionally, this is achieved through mechanical rapping systems. However, this approach often results in:

- ✓ lower cleaning efficiency,
- ✓ increased operational noise,
- ✓ significant wear on components,
- ✓ and high maintenance costs.

As a modern technological solution, the application of ultrasonic vibrators is proposed. In this method, vibrations in the 20–40 kHz frequency range weaken the adsorption forces between particles and the electrode surface, causing particles to detach and fall[5].

Physical Mechanisms Involved:

- ✓ Acoustic cavitation
- ✓ Resonant vibration
- ✓ Sound pressure gradient

Mathematical Expression

The acoustic force required to detach a particle is expressed as:

$F_a = (4/3)\pi r^3 \rho_p a \omega^2$

Where:

- ✓ F_a= acoustic force acting on a particle (N)
- ✓ r = particle radius (m)
- ✓ ρ_p = particle density (kg/m³)
- ✓ a = vibration amplitude (m)
- ✓ ω = angular frequency ω = 2πf, f – where f = frequency (Hz)

Experimental findings demonstrate that at a frequency of 28 kHz and an amplitude of 5×10^{-6} m, over 90% of dust particles were successfully detached from electrode surfaces.

International Contributions and Technological Integration

Numerous international researchers have made valuable contributions to improving ESP technologies. Notably:

- ✓ Dr. J.R. White (USA),
- ✓ Dr. E. L. Cussler (University of Minnesota, USA),
- ✓ Dr. Jianhua Guo (China),
- ✓ and Arvind Kumar have conducted significant work in this field.

Currently, many global research efforts continue to advance electrostatic filtration systems.

Integration of the ultrasonic cleaning system with automated control systems enables:

- ✓ real-time detection of dust buildup,
- ✓ selection of optimal vibration frequency,
- ✓ and enhanced energy efficiency through adaptive regulation[6].

Discussion

The efficiency of electrostatic precipitators (ESPs) is directly dependent on the cleanliness of the electrode surfaces. Although conventional mechanical cleaning systems (rappers) have been used for decades, they present several significant limitations, including:

- ✓ strong mechanical impacts on the surface,
- ✓ high noise levels,
- ✓ mechanical wear of components,
- ✓ and the need for frequent maintenance.

These limitations become especially problematic when handling sticky, moist, or high-temperature dust particles, where the effectiveness of traditional cleaning methods drops significantly.

To overcome these challenges, ultrasonic vibrators based on piezoelectric elements were introduced. These devices generate high-frequency micro-vibrations that facilitate the detachment of dust particles from electrode surfaces without direct contact.

Laboratory experiments demonstrated that:

- Adhesive forces (Van der Waals, electrostatic) are effectively overcome through ultrasonic vibration;
- Optimal resonance frequencies were observed in the 20–35 kHz range;
- Energy consumption was reduced by 30–40% compared to traditional methods;
- Dust removal efficiency reached 95–98%;
- No mechanical impact on surfaces resulted in a prolonged electrode lifespan.

Furthermore, the non-contact nature of this technology makes it highly suitable for automation. By integrating a microcontroller-based system (e.g., STM32), the following capabilities were achieved:

- ✓ real-time identification of resonance frequencies,
- ✓ adaptive control of ultrasonic vibrator operation,
- ✓ continuous monitoring of system performance.

This approach is especially relevant for industrial ESPs operating under high-temperature conditions, such as those used in circulating fluidized bed (CFB) boilers or metallurgical plants.

Conclusion

Ultrasonic cleaning of ESP electrodes represents a modern, energy-efficient, and contactless technology that plays a vital role in improving the effectiveness of industrial gas filtration systems. Based on experimental results, the following conclusions can be drawn:

- Ultrasonic vibrations in the 20–35 kHz range are highly effective in dislodging dust particles from electrode surfaces;
- Cleaning efficiency increases to 95–98%, demonstrating a clear advantage over traditional rapping systems;
- The wear and tear of electrodes are significantly reduced, extending maintenance intervals;
- Overall energy consumption is decreased by 30–40%;
- Implementation of an STM32 microcontroller-based control system allows for real-time operation, optimal resonance frequency detection, and continuous efficiency monitoring.

This technology is particularly promising for use in high-temperature, sticky, or complex dust-laden gas environments. Given the limited research in Uzbekistan on this subject, it opens opportunities for the development of a novel scientific and technological direction within the field.

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