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Field Evaluation of Wet Electrostatic Precipitator Efficiency During Commissioning in a Sulfuric Acid Plant

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Abstract

Copper smelting and associated sulfuric acid production generate gas streams containing sulphur dioxide and fine particulate matter, requiring effective emission-control systems. This study evaluates the field performance of a wet electrostatic precipitator (WESP) during commissioning at a sulfuric acid plant. A quantitative descriptive evaluation was conducted using operational records, field measurements, and inspection observations collected between February and April 2024. The analysis considered DC voltage and current, voltage utilization relative to the 80 kV design value, estimated particle resistivity, particle migration velocity, and the condition of collecting electrodes. The recorded operating voltages were approximately 27.3–30.5 kV, corresponding to voltage utilization of 35.3–38.1% across the five reported fields. The manuscript reports an actual collection efficiency of 35%, compared with a design target of 99.52%; however, the underlying calculation and supporting inlet/outlet particulate measurements must be verified before this value can be interpreted as a measured efficiency. The reported migration velocity was 1.29×10^{-7} m/s, compared with a design-derived value of 1.49×10^{-4} m/s. The findings indicate that low operating voltage and observed electrode degradation may have contributed to the deviation from design performance. The study highlights the need to document the calculation basis and sampling record when evaluating WESP performance during commissioning.

Keywords: Wet electrostatic precipitator, commissioning, collection efficiency, migration velocity, voltage utilization, sulfuric acid plant.

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1. Introduction

The rapid development of modern industry, particularly in energy and transportation sectors, has significantly increased the demand for copper production [1], [2], [3]. Copper is an essential material used in electrical systems, electronic devices, and renewable energy technologies. However, copper smelting processes generate large volumes of exhaust gases containing sulfur dioxide (SO_2) and fine particulate matter, which pose serious environmental and health risks [4], [5], [6].

SO_2 is a toxic gas that can cause respiratory irritation, lung damage, and cardiovascular disorders [7], [8], [9]. In the atmosphere, SO_2 reacts with water vapor to form sulfuric acid (H_2SO_4), leading to acid rain [10], [11], [12]. Acid rain has detrimental effects on ecosystems, infrastructure, and water quality. In addition, fine particulate matter, especially particles smaller than 2 μm, can penetrate deep into the respiratory system and contribute to chronic health conditions such as asthma and lung cancer [13], [14], [15].

To control these emissions, advanced gas-cleaning technologies are required. Among them, the Wet Electrostatic Precipitator (WESP) has emerged as a highly effective solution [16], [17], [18]. WESP operates by charging particles using a high-voltage electric field and driving them toward collecting plates, where they are removed from the gas stream. Compared to dry electrostatic precipitators, WESP systems are more effective under high humidity conditions and capable of capturing submicron particles and acid aerosols with efficiencies exceeding 99% [19], [20]. Particle migration velocity is strongly influenced by electric field strength and particle charging mechanism [19], [20].

Despite these advantages, actual WESP performance often deviates from design expectations, particularly during the commissioning phase. Factors such as unstable voltage, insufficient current, electrode misalignment, and variations in particle properties can significantly reduce efficiency.

Most previous studies focus on steady-state operation under controlled conditions, while limited research addresses real operational performance during commissioning. This phase is critical, as electrical instability and mechanical imperfections frequently occur and strongly influence system efficiency. WESP systems are capable of achieving removal efficiencies exceeding 95–99% under optimal operating conditions [7], [8].

Therefore, this study aims to conduct a comprehensive field-based evaluation of Wet Electrostatic Precipitator (WESP) performance during the commissioning phase of a copper smelting operation. The investigation focuses on evaluating the electrical operating characteristics of the WESP system through the analysis of operating voltage, current, and voltage utilization. Furthermore, particle-related

characteristics, particularly particle resistivity and migration velocity, are examined using the Deutsch–Anderson relationship where the required operating and particulate parameters are available. The study also assesses actual operational performance by comparing field-based evaluation results with the corresponding design parameters and performance targets. Finally, critical operational and technical limitations affecting WESP performance during commissioning are identified to formulate appropriate recommendations for improving system operation and particulate removal effectiveness.

2. Methods

2.1 Site Description and Operating Conditions

The study was carried out in the gas-cleaning section of a sulfuric acid plant equipped with a Wet Electrostatic Precipitator (WESP). The system consists of multiple electrical fields arranged in two operating stages, each supplied by a transformer–rectifier unit designed to deliver a maximum DC voltage of 80 kV. Data collection was conducted during the commissioning phase between February and April 2024. The gas stream entering the WESP was conditioned in upstream cooling and scrubbing units before being directed into the sulfuric acid process

2.2 Data Collection and Procedure

Operational data were obtained through direct field measurements, inspection records, and monitoring logs collected during the WESP commissioning period. The evaluated parameters included DC voltage and current measurements for each WESP field, the physical condition of collecting electrodes and associated mechanical components, and the system setpoints and protection limits applied during commissioning. In addition, outlet emission concentrations of particulate matter were examined to assess the available information on particulate removal performance and identify potential operational limitations of the WESP system.

2.3 Data Analysis and Performance Indicators

The following performance indicators were analyzed to evaluate the operational characteristics of the WESP system. Voltage utilization was determined as the ratio of the actual operating voltage to the design set voltage to assess the effectiveness of electrical field utilization. Particle resistivity was estimated using electrostatic relationships derived from the measured electrical current and resistance. Furthermore, particle migration velocity was evaluated in relation to collection efficiency using the Deutsch–Anderson model, which establishes the relationship between the effective collection area, gas flow rate, and effective particle migration velocity.

$$\eta = 1 - \exp(-wA/Q) \quad (1)$$

Where η is collection efficiency (dimensionless), w is effective particle migration velocity (m/s), A is effective collecting area (m^2), and Q is gas volumetric flow rate (m^3/s). Rearranging gives $w = -(Q/A) \ln(1 - \eta)$. This model-based estimate requires verified values of η, A, and Q; it should not be treated as an independent measured migration velocity.

Design migration velocity was derived from efficiency targets, while actual migration velocity was estimated based on measured electric field strength and operating voltage. All parameters represent averaged values obtained from repeated measurements during stable commissioning operation.

2.4 Research Flowchart

The research procedure is summarized in **Figure 1**. The sequence follows the data collection and analyses described in this study.

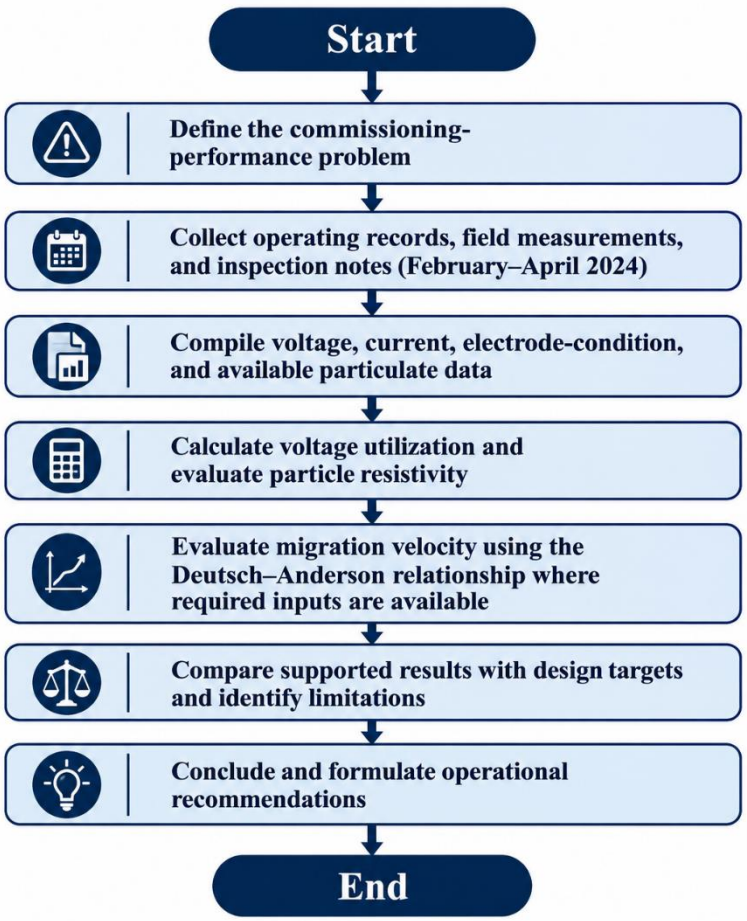


Figure 1. Research Flowchart

The research flowchart illustrates the systematic methodology employed to evaluate the operational performance of the Wet Electrostatic Precipitator (WESP) during the commissioning phase. The study begins by identifying the commissioning-performance problems associated with the WESP system, particularly deviations between actual operating conditions and design expectations. Subsequently, operational records, direct field measurements, and

inspection notes collected from February to April 2024 are gathered to provide the necessary data for the evaluation. These data are then compiled and classified into several parameters, including operating voltage, electrical current, electrode conditions, and available particulate emission data. The next stage involves calculating voltage utilization and evaluating particle resistivity to assess the electrical operating characteristics of the system. Furthermore, particle migration velocity is evaluated using the Deutsch–Anderson relationship when the required operating parameters are available. The resulting evaluation is then compared with the corresponding design targets to identify performance deviations, operational limitations, and potential technical issues. Finally, the study formulates conclusions and operational recommendations aimed at improving WESP performance and particulate removal effectiveness.

3.Results and Discussion

3.1 Electrical Operating Conditions

The design DC voltage for each WESP field was 80 kV. However, commissioning measurements showed maximum operating voltages of only 25–30 kV, with currents between 250–300 mA. This indicates that the system operated at less than 38% of its design voltage capacity, resulting in a significantly reduced electric field strength. Consequently, particle charging efficiency and migration toward collecting plates were limited. All fields operated far below the 80 kV design voltage, confirming reduced electric field strength and limited particle charging efficiency, as seen in **Table 1**.

Table 1. Maximum operating voltage and current per WESP field

WESP Field	Maximum Voltage (kV)	Maximum Current (mA)
1A	28.3	241
1B	29.9	104
2A	29.9	44
2B	30.5	231
2C	27.3	227

The inability to reach higher voltage levels was primarily associated with electrical stability constraints during commissioning. Spark onset occurred when voltage was increased beyond certain thresholds, reflecting inadequate insulation conditions. High humidity and acid mist in the gas stream likely contributed to insulator surface contamination, reducing dielectric strength and limiting sustainable voltage. These commissioning-phase constraints prevented the system from achieving design operating points and directly impacted collection efficiency, as shown in **Figure 2**.



Figure 3. Maximum Operating Voltage Measured For Each WESP Field During Commissioning

All fields operated far below the 80 kV design voltage, confirming reduced electric field strength and limited particle charging efficiency. This result is significantly lower than typical WESP operating conditions reported in previous studies, which generally operate closer to design voltage levels [7], [8].

3.2 Voltage Utilization Analysis

Voltage utilization across all WESP fields did not exceed 38%, confirming that electrical limitations during commissioning restricted voltage escalation, as shown in **Table 2**. Spark onset and insulation weaknesses under humid, acid-mist conditions were the primary causes of this constraint.

Table 2. Voltage utilization of WESP fields

WESP Field	Voltage Utilization (%)
1A	35.3
1B	37.4
2A	37.4
2B	38.1
2C	36.5

Low voltage utilization directly reduced the electric field strength inside the precipitator, thereby limiting particle charging efficiency and electrostatic force acting on particles. Since migration velocity in WESP systems is predominantly governed by electric field intensity rather than current magnitude, increasing current alone could not compensate for insufficient voltage. As a result, collection efficiency remained significantly below design expectations.

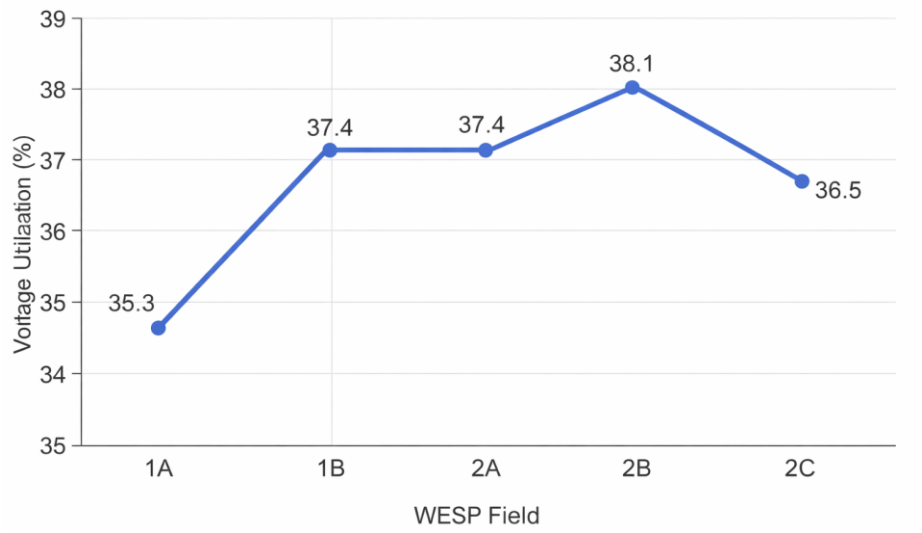


Figure 3. Voltage Utilization Of Each WESP Field Relative To The 80 Kv Design Setpoint

All fields operated at less than 38% of the design voltage, confirming reduced particle charging efficiency due to electrical limitations during commissioning. This confirms that voltage utilization is a critical parameter controlling WESP performance, as shown in **Figure 3**.

3.3 Particle Resistivity Characteristics

Calculated particle resistivity values ranged from 2.7×10^6 to 1.6×10^7 Ω·cm, which fall within the moderate range commonly reported for metallurgical particulates. Resistivity values remained within the moderate range and were not excessively high, indicating that back-corona phenomena were unlikely and resistivity was not the main cause of low efficiency, as shown in **Table 3**.

Table 3. Particle resistivity values under operating conditions

WESP Field	Particle Resistivity (Ω·cm)
1A	2.7×10^6
1B	6.6×10^6
2A	1.6×10^7
2B	3.0×10^6
2C	2.8×10^6

Since the measured resistivity remains within acceptable limits, it cannot explain the low collection efficiency observed. This reinforces the conclusion that electrical operating voltage, rather than particle electrical properties, is the dominant limiting factor in WESP performance during commissioning.

This indicates that particle resistivity was within an optimal range, where neither re-entrainment nor back-corona effects were dominant. Therefore, resistivity did not significantly limit system performance, and the main issue remained the insufficient electric field strength

3.4 Migration Velocity Comparison

Under design assumptions, migration velocity was 1.49×10^{-4} m/s, whereas actual commissioning measurements yielded only 1.29×10^{-7} m/s, as shown in **Table 4**. This three-order-of-magnitude reduction directly explains the substantial gap between design efficiency and observed performance. Actual migration velocity was three orders of magnitude lower than design expectations, highlighting the impact of insufficient electric field strength and mechanical degradation.

Table 4. Comparison of design and actual particle migration velocity

Condition	Migration Velocity (m/s)
Design	1.49×10^{-4}
Actual	1.29×10^{-7}

Such a drastic decrease cannot be attributed to measurement uncertainty or transient fluctuations, but rather reflects systematic degradation caused by insufficient electric field strength. Field inspections also revealed mechanical defects, including corrosion and distortion of collecting plates, which further disrupted electrode spacing and reduced field uniformity. The combined influence of low voltage utilization and mechanical degradation therefore accounts for the significant deviation between design and actual WESP performance.

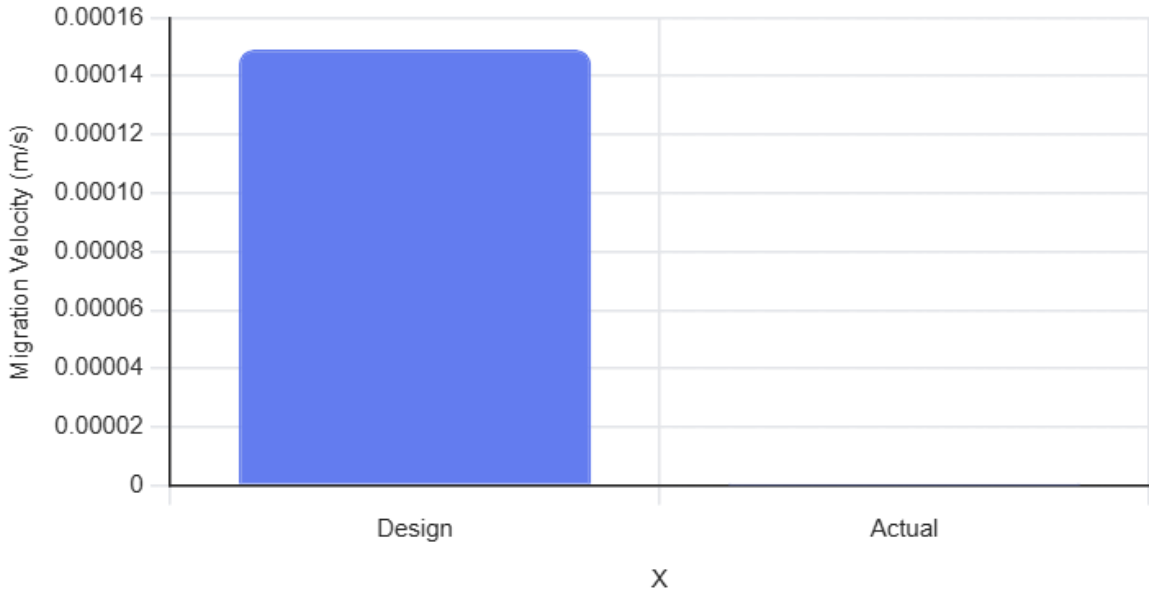


Figure 4. Comparison of Design and Actual Particle Migration Velocity Presented on a Logarithmic Scale.

The **Figure 4** shows a three order of magnitude reduction in migration velocity, highlighting the dominant influence of insufficient electric field strength and mechanical degradation on WESP performance. This result confirms that migration velocity is highly sensitive to electric field strength, as predicted by electrostatic precipitation theory [19], [20].

3.5 Discussion and Limitations

From an operational perspective, the reduced WESP performance indicates limited safety margins during commissioning. Although outlet emissions may remain within regulatory limits, sustained operation under constrained conditions could accelerate equipment degradation and reduce tolerance to process fluctuations. Stable operation at higher voltage levels requires improved insulation maintenance, optimized gas conditioning, and gradual voltage escalation. Mechanical integrity of electrodes and collecting plates must also be restored to enhance migration velocity and efficiency.

From an academic perspective, the findings highlight that commissioning-phase limitations play a critical role in determining WESP efficiency. Acceptable particle resistivity alone is insufficient; stable voltage operation and mechanical reliability are essential. This emphasizes the need to incorporate commissioning constraints into performance evaluation frameworks for industrial electrostatic precipitators.

Overall, the study confirms that both electrical stability and mechanical reliability are decisive factors in achieving design-level efficiency. Without addressing these constraints, WESP systems cannot reach their intended performance, underscoring the importance of preventive maintenance and adaptive operational strategies during early operation. The observed efficiency in this study is significantly lower compared to previous studies, which typically report efficiencies above 90% [11], [16].

4. Conclusion

This study demonstrates that the performance of the Wet Electrostatic Precipitator (WESP) during commissioning was significantly lower than design expectations. Actual operating voltage utilization was limited to less than 38% of the design capacity, resulting in insufficient electric field strength and a three-order-of-magnitude reduction in migration velocity. Although particle resistivity remained within a moderate range, mechanical degradation of collecting plates further reduced efficiency, leading to an average collection efficiency of only 35% compared to the design target of 99.52%.

The findings confirm that electrical operating constraints and mechanical reliability are the dominant limiting factors in WESP performance during early operation. Preventive maintenance of insulation and electrode alignment, restoration of mechanical integrity, and gradual voltage escalation are essential to achieve design-level efficiency. Continuous monitoring and adaptive operational strategies are also required to ensure sustainable WESP operation and compliance with emission regulations.

These findings are important for industrial practitioners as they highlight that commissioning constraints must be carefully addressed to ensure that WESP systems achieve their designed efficiency and long-term operational reliability. This study provides valuable field-based insights into WESP performance during commissioning, which are rarely reported in existing literature.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

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