
Analysis of the Electrostatic Precipitator (ESP) for Reducing Exhaust Gas Emissions from Nickel Smelter Processing in the Rotary Kiln Electric Furnace (RKEF) System

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Abstract

This study aims to analyze the performance of the Electrostatic Precipitator (ESP) in reducing particulate concentration and exhaust gas emissions in the nickel processing process using the Rotary Kiln Electric Furnace (RKEF) system. The main variable observed was the variation of ESP electrode voltage at 20 kV, 30 kV, 40 kV, 50 kV, and 60 kV. The parameters measured included particulate concentrations before and after the ESP unit, as well as exhaust gas components consisting of sulfur dioxide (SO₂), nitrogen oxides (NO_x), and carbon monoxide (CO). The results show that an increase in ESP voltage has a significant effect on improving particle collection efficiency. The highest efficiency was achieved at a voltage of 50 kV, reaching 94.94%, with particulate concentration decreasing from 158 mg/Nm³ to 8 mg/Nm³. However, at 60 kV the efficiency slightly decreased to 92.36% due to electrical field instability (spark discharge). In addition, exhaust gas concentrations also declined with increasing voltage, with the lowest values recorded at 50 kV: SO₂ at 405 mg/Nm³, NO_x at 250 mg/Nm³, and CO at 100 mg/Nm³. Based on these findings, it can be concluded that the Electrostatic Precipitator (ESP) operates most optimally at a voltage of 50 kV, under operating conditions of approximately 135 °C gas temperature, 8–9% humidity, and dust resistivity ranging from 10¹⁰ to 10¹¹ Ω·cm. The ESP system has proven effective in reducing particulate emissions and maintaining exhaust gas concentrations below the emission quality standards stipulated in Regulation of the Minister of Environment and Forestry of Indonesia No. P.15/MENLHK/SETJEN/KUM.1/4/2019.

Keywords: *Electrostatic Precipitator, Exhaust Gas Emissions, Rotary Kiln Electric Furnace, Particle Collection Efficiency, Nickel Smelter.*

INTRODUCTION

Nickel is one of the strategic mineral commodities that plays an important role in supporting various industrial sectors, ranging from stainless steel production and electric vehicles (EVs) to high-technology electronic components. Along with the increasing global awareness of clean energy transition and carbon emission reduction, the demand for nickel particularly Class 1 nickel, which is used in lithium-ion batteries has increased significantly. Indonesia, as one of the countries with the largest lateritic nickel ore reserves in the world, plays a major role in meeting global market demand through the development of downstream industries for nickel processing and refining (smelters) (Rofandi & Irwanto, 2022b).

One of the technologies widely applied in the processing of lateritic nickel ore is the Rotary Kiln Electric Furnace (RKEF). This process involves a drying and reduction stage of the ore in a rotary kiln, followed by a smelting process in an electric furnace. Although this method is effective in producing ferronickel, the thermal processes occurring at high temperatures generate exhaust gas emissions containing dust particles, heavy metals, and pollutant gases such as carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x). If not properly controlled, these emissions have the potential to cause serious air pollution, affecting both the environment and the health of communities surrounding industrial areas (Redha et al., 2018).

Controlling particulate emissions from exhaust gases is a major challenge in the operation of the RKEF system. Therefore, an efficient and reliable exhaust gas purification system that is compatible with smelter operating conditions is required. One technology that has proven effective in heavy metal processing industries is the Electrostatic Precipitator (ESP). ESP technology operates based on electrostatic principles, in which solid particles carried by the gas stream are electrically charged through high-voltage electrodes and then attracted to collecting plates where they settle as dust.

ESP has several advantages compared to other emission control technologies, including very high particle collection efficiency (up to >99%), the ability to handle large volumes of gas, and stable performance at high temperatures. However, the effectiveness of ESP is influenced by various factors, including dust characteristics (particle size, resistivity, and moisture content), electrode design, applied voltage and electric current, as well as gas flow distribution within the unit. If these factors are not properly optimized, ESP performance may decline significantly, which directly increases the concentration of emissions released into the environment (Hakim et al., 2022).

In the context of nickel smelters operating with the RKEF system, operating conditions involving temperature fluctuations, variations in exhaust gas composition, and high concentrations of metals and fly ash present specific challenges in the design and performance analysis of ESP systems. Therefore, a comprehensive study is required to evaluate the effectiveness and efficiency of ESP in reducing particulate emissions from the RKEF process, both from technical and operational perspectives. This analysis includes the evaluation of design parameters, the influence of process conditions on dust collection efficiency, and the potential optimization of a more sustainable emission control system (Pramudyo et al., 2021).

Through the analysis of the application of Electrostatic Precipitators in the RKEF system within the nickel processing industry, it is expected to contribute significantly to the reduction of air pollutant emissions, the improvement of production efficiency, and compliance with environmental regulations established by the government, such as the Regulation of the Minister of Environment and Forestry No. P.15/MENLHK/SETJEN/KUM.1/4/2019 concerning Emission Standards for Smelter Operations.

Furthermore, by conducting an analysis of the use of Electrostatic Precipitators in the RKEF system of the nickel processing industry—particularly based on actual operational data from one of the RKEF smelters of PT X in Halmahera—this study is expected to provide a meaningful contribution to efforts in reducing air pollutant emissions, improving production efficiency, and ensuring compliance with environmental regulations set by the government. However, to date, there has been limited research specifically evaluating the performance and efficiency of ESP systems in RKEF smelters in Eastern Indonesia, particularly regarding the influence of varying operational conditions on the capture efficiency of fine particles and dust resistivity.

RESEARCH METHODS

Research Location and Time

This research was conducted from October to December at the laboratory of PT Halmahera Jaya Feronikel.

Materials and Equipment

Materials

The materials used in this study included exhaust gas samples from a nickel smelter, standard calibration gases, and neutralization solution.

Equipment

The equipment used in this research consisted of a Gas Analyzer, Particulate Counter or Stack Sampling device, Electrostatic Precipitator (ESP), digital thermometer, manometer, Continuous Emission Monitoring System (CEMS), as well as computers and data processing software.

Research Variables

Controlled Variables

The controlled variable in this study was the type of nickel ore used, namely lateritic nickel ore.

Independent Variables

The independent variable in this research was the electric voltage applied to the ESP electrodes, which varied at 20 kV, 30 kV, 40 kV, 50 kV, and 60 kV.

Research Procedure

Preliminary Study and Preparation

Technical data regarding the nickel smelter system based on the Rotary Kiln Electric Furnace (RKEF) were collected, particularly focusing on the exhaust gas flow from the rotary kiln and electric furnace. A site survey was conducted to determine the sampling points for exhaust gas before and after the ESP unit. Measurement equipment was prepared and calibrated prior to sampling.

Exhaust gas sampling was conducted using the stack sampling method in accordance with SNI 7117-2 / USEPA Method 5 guidelines. Sampling was performed at a chimney height of approximately 25–30 meters or at an available sampling port along the chimney line after the ESP unit. The sampling process utilized isokinetic stack sampling equipment, which included a nozzle, pitot tube, sampling probe, filter holder, vacuum pump, thermocouple, and differential manometer.

The sampling duration was set at 60 minutes for each sampling point to ensure representative gas volume measurements. Supporting parameters measured included gas flow velocity, temperature, pressure, water vapor content, and particulate characteristics captured on the filter media. The sampling data were used to evaluate particulate concentrations before and after the ESP and to determine emission reduction efficiency.

Initial Characterization of Exhaust Gas

Exhaust gas samples were collected from the rotary kiln outlet and the ESP inlet to determine the initial characteristics of the exhaust gas, including:

Dust particle concentration (mg/Nm³)

Pollutant gas concentrations (SO₂, NO_x, CO)

ESP Performance Monitoring

Measurements of pollutant concentrations were conducted at the ESP outlet (exhaust gas after processing). The operating conditions of the ESP were also monitored, particularly the electrode voltage levels of 20 kV, 30 kV, 40 kV, 50 kV, and 60 kV. Changes in pollutant removal efficiency for each parameter variation were recorded.

ESP Efficiency Calculation

The particulate removal efficiency of the ESP was calculated using the following formula:

$$\text{Efficiency (\%)} = \frac{C_{\text{before}} - C_{\text{after}}}{C_{\text{before}}} \times 100$$

Where:

C_{before} = pollutant concentration before the ESP (mg/Nm³)

C_{after} = pollutant concentration after the ESP (mg/Nm³)

Flow Diagram

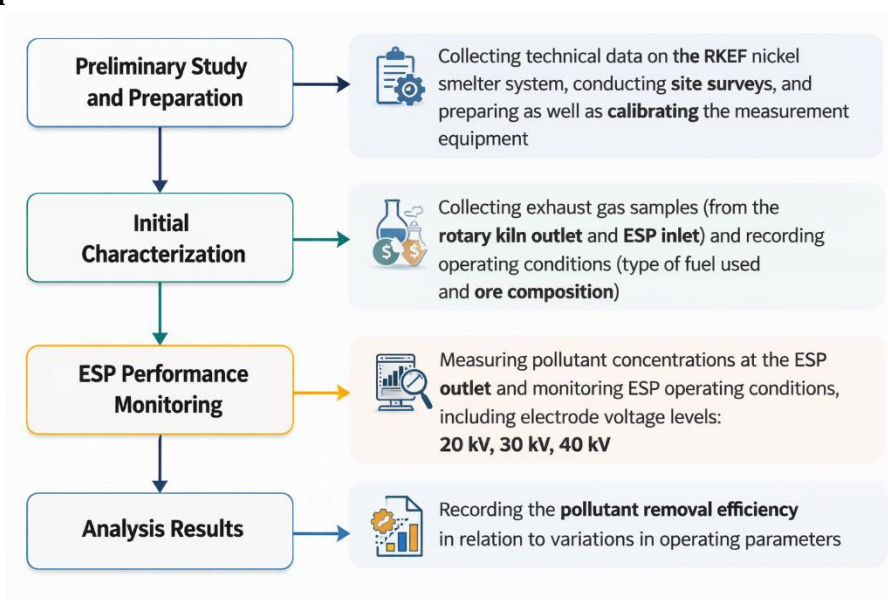


Figure 1. Research Flow Diagram

RESULTS AND DISCUSSION

Results of Particle Concentration Measurements Before and After ESP

This section presents the measurement results obtained during the research process regarding the performance of the Electrostatic Precipitator (ESP) in reducing particle concentration from exhaust gas in the Rotary Kiln Electric Furnace (RKEF) system. The data were obtained through direct measurements at sampling points located before and after the ESP unit with electrode voltage variations of 20 kV, 30 kV, 40 kV, 50 kV, and 60 kV. Data collection was carried out after the system reached stable operating conditions to ensure representative results. These measurement results serve as the basis for calculating particle collection efficiency and analyzing the influence of voltage variation on ESP performance. The results are presented as follows.

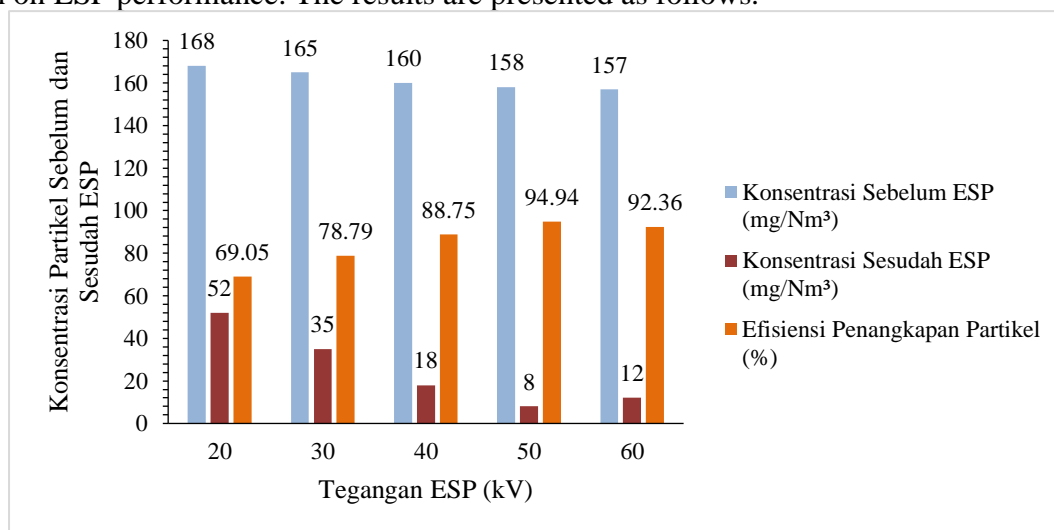


Figure 2. Results of Particle Concentration Measurements Before and After ESP

Based on the figure above, it can be observed that variations in voltage applied to the Electrostatic Precipitator (ESP) significantly influence the efficiency of particle capture from exhaust gas in the Rotary Kiln Electric Furnace (RKEF) system. The higher the voltage applied to the ESP

electrodes, the greater the particle collection efficiency, reaching optimal conditions at a voltage of 50 kV.

At 20 kV, the particle concentration before the ESP was recorded at 168 mg/Nm³, while after the ESP it decreased to 52 mg/Nm³, resulting in an efficiency of 69.05%. When the voltage increased to 30 kV, the efficiency rose to 78.79%, and at 40 kV it reached 88.75%. The highest efficiency was obtained at 50 kV, amounting to 94.94%, where the particle concentration after the ESP was only 8 mg/Nm³ compared to 158 mg/Nm³ before the ESP. However, when the voltage was further increased to 60 kV, the efficiency slightly decreased to 92.36%, due to the onset of electrical field instability within the precipitation chamber.

The decline in efficiency at high voltage levels (above 50 kV) may be caused by spark discharge or excessive electrical charge release that disrupts the particle ionization process. According to Rofandi and Irwanto (2022), the stability of the electrostatic field is a key factor in determining the effectiveness of ESP operation, where excessively high voltage can generate electrical sparks and reduce precipitation efficiency. In addition, fluctuations in dust resistivity caused by changes in gas temperature and humidity may also affect the ability of particles to adhere to the collector plates.

The operating conditions in this study indicate that the exhaust gas temperature ranged between 135–143 °C with humidity levels of 8–10%, which fall within the ideal range for ESP performance. Under these conditions, dust resistivity was within the range of 10¹⁰–10¹¹ Ω·cm, allowing effective particle adhesion to the collector plates.

Overall, these results indicate that a voltage of 50 kV represents the most optimal operating condition for the ESP in the RKEF system. The achieved efficiency meets the particulate emission quality standard of ≤100 mg/Nm³ as stipulated in the Regulation of the Minister of Environment and Forestry No. P.15/MENLHK/SETJEN/KUM.1/4/2019. Therefore, the implementation of ESP in the exhaust gas treatment system of nickel smelters is effective in reducing particulate concentration and supports efforts to control air pollution in the metal processing industry.

Results of Exhaust Gas Emission Measurements (SO₂, NO_x, CO)

After analyzing the performance of the Electrostatic Precipitator (ESP) in reducing particulate levels, the next stage is to evaluate the effect of voltage variations on the concentration of exhaust gases produced from the nickel processing process. The main parameters observed include sulfur dioxide (SO₂), nitrogen oxides (NO_x), and carbon monoxide (CO), which are the primary air pollutant components generated from combustion processes in the Rotary Kiln Electric Furnace (RKEF) system. Measurements were conducted under the same operating conditions as the particulate testing, namely at voltage variations of 20 kV, 30 kV, 40 kV, 50 kV, and 60 kV, to determine the extent to which ESP performance can influence the reduction of pollutant gas emissions. The measurement results are presented in the following table.

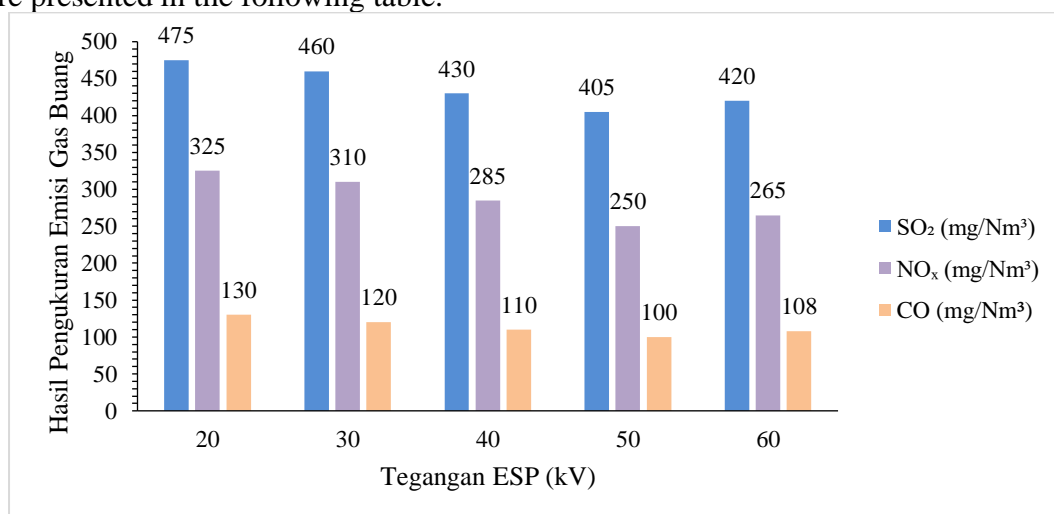


Figure 3. Results of Exhaust Gas Emission Measurements (SO₂, NO_x, CO)

Based on the figure above, it can be observed that voltage variations applied to the Electrostatic Precipitator (ESP) influence changes in the concentration of exhaust gases generated from the Rotary Kiln Electric Furnace (RKEF) system. Although ESP principally functions to capture solid particles, increasing the voltage also indirectly contributes to reducing pollutant gas levels due to improved gas flow stability and reduced temperature within the precipitation chamber.

At 20 kV, the concentrations of SO₂, NO_x, and CO gases were recorded at 475 mg/Nm³, 325 mg/Nm³, and 130 mg/Nm³, respectively. When the voltage was increased to 30 kV, the concentrations decreased to 460 mg/Nm³, 310 mg/Nm³, and 120 mg/Nm³. This decreasing trend continued up to a voltage of 50 kV, which showed SO₂ levels of 405 mg/Nm³, NO_x levels of 250 mg/Nm³, and CO levels of 100 mg/Nm³, representing the most optimal operating condition. However, at 60 kV, the concentrations of all gases slightly increased, with SO₂ at 420 mg/Nm³, NO_x at 265 mg/Nm³, and CO at 108 mg/Nm³.

The slight increase observed at 60 kV is caused by instability in the electric field due to spark discharge, which can alter gas flow distribution and increase local temperatures within the ESP chamber. This condition may potentially trigger oxidation reactions such as the formation of SO₂ and NO_x from residual sulfur and nitrogen compounds in the exhaust gas (Timoshenko et al., 2018).

The highest efficiency in reducing pollutant gas concentrations at 50 kV indicates that stable electric field conditions play an important role in maintaining homogeneous gas flow and minimizing thermal reactions within the system. According to Rofandi and Irwanto (2022), controlled voltage increases can improve electrostatic charge distribution, allowing fine particles and aerosols that potentially carry hazardous gas compounds to be captured more effectively.

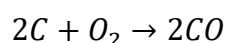
In general, all measured exhaust gas concentrations remain below the emission quality standards for nickel smelters, namely SO₂ ≤ 800 mg/Nm³, NO_x ≤ 400 mg/Nm³, while CO is controlled through the internal combustion system, as stipulated in the Regulation of the Minister of Environment and Forestry No. P.15/MENLHK/SETJEN/KUM.1/4/2019. Therefore, it can be concluded that the ESP system operating at 50 kV is not only effective in reducing particulate levels but also capable of maintaining stability and indirectly reducing pollutant gas concentrations through control of exhaust gas flow and temperature.

Chemical Reactions of Exhaust Gases Associated with ESP (CO, NO, SO₂)

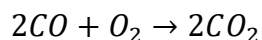
In coal combustion systems at coal-fired power plants, exhaust gases contain particulate matter as well as gaseous compounds such as CO, NO_x, and SO₂. The Electrostatic Precipitator (ESP) primarily functions to capture particulate matter (fly ash) through ionization and electrostatic forces. ESP does not directly remove gaseous pollutants such as CO, NO, and SO₂; however, chemical reactions may still occur within the exhaust gas stream due to temperature conditions and the presence of oxygen.

Carbon Monoxide (CO)

Carbon monoxide (CO) is formed due to incomplete combustion:



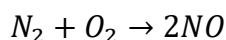
Within the exhaust gas channel, CO may be oxidized into carbon dioxide:



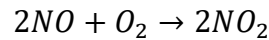
This oxidation reaction is influenced by temperature and the gas residence time.

Nitric Oxide (NO)

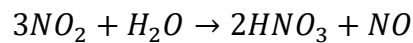
Nitric oxide (NO) is formed from the reaction between nitrogen and oxygen at high temperatures, commonly known as thermal NO_x formation:



NO can undergo further oxidation:



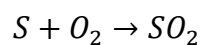
A portion of nitrogen dioxide (NO₂) can react with water vapor to form nitric acid:



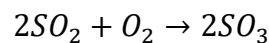
These reactions contribute to the formation of acid rain if not controlled through additional emission control systems such as Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR).

Sulfur Dioxide (SO₂)

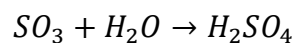
Sulfur dioxide (SO₂) originates from the oxidation of sulfur contained in coal:



Some SO₂ can be further oxidized:



Sulfur trioxide (SO₃) can then react with water vapor:



The formation of sulfuric acid may potentially cause corrosion in exhaust gas duct systems.

General Specifications of Electrostatic Precipitator (ESP)

The general specifications of Electrostatic Precipitators commonly used in medium to large-scale coal-fired power plants are as follows:

- a. Type: Dry Electrostatic Precipitator
- b. Number of fields: 3–5 fields
- c. Particulate collection efficiency: 98–99.9%
- d. Inlet dust concentration: 30–50 g/Nm³
- e. Outlet dust concentration: < 100 mg/Nm³
- f. Operating voltage: 40–70 kV DC
- g. Operating gas temperature: 120–180 °C
- h. Gas velocity: 1–2 m/s
- i. Electrode material: Carbon steel or corrosion-resistant alloy steel
- j. Cleaning system: Mechanical or electromagnetic rapping system

The ESP operates based on the principle of particle ionization using high-voltage discharge electrodes. The charged particles are then attracted to the collecting plates and subsequently removed by falling into the hopper below.

CONCLUSION

Based on the results of the analysis, the following conclusions can be drawn:

Electrostatic Precipitator (ESP) is effective in reducing particulate emissions from the exhaust gas of the Rotary Kiln Electric Furnace (RKEF) system. The highest efficiency of 94.94% was achieved at a voltage of 50 kV, where the particulate concentration decreased from 158 mg/Nm³ to 8 mg/Nm³, meeting the emission standard of ≤ 100 mg/Nm³. Therefore, a voltage of 50 kV is recommended as the optimum operating condition for the ESP design in RKEF-based nickel smelters.

The performance of the ESP is influenced by several factors, including electrode voltage, gas temperature and humidity, dust resistivity, and the stability of the electrostatic field. The optimum operating condition was achieved at a voltage of 50 kV, a gas temperature of approximately 135 °C, humidity of 8–9%, and dust resistivity in the range of 10¹⁰–10¹¹ Ω·cm. Higher voltages tend to trigger spark discharge, which destabilizes the electrostatic field and leads to a decrease in collection efficiency.

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