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Elimination of Gas and Particulate Emissions in Coal Boilers using Plasma Precipitator System

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Abstract

A plasma precipitator reactor is an essential part of the emission treatment. This device removes fine particles, such as dust, smoke, and various toxic gases, using the force of an induced plasma charge, minimally impeding the flow of gases through the unit. In this study, the plasma precipitator combines dust deposition-capture technology by magnetic force and emission gas removal with plasma. The reactor was successfully fabricated and tested in real-world applications of the textile industry to reduce gas and particulate emissions. Using this reactor, SO₂, NO₂, CO, and CO₂ sulfur dioxide (SO₂), nitrogen dioxide (NO₂), carbon monoxide (CO), carbon dioxide (CO₂) gases turned into more environmentally friendly forms, such as O₂, with a decrease of approximately 91.3%, 91.4%, 88.3%, and 89.6% w/w, respectively. Meanwhile, the element and molecular forms, which contain sulfur, carbon, and nitrogen, were deposited as particulates in the electrode channels. Using this technology, the number of particulates decreased up to approximately 93.5% w/w. The plasma precipitator reactor does not require high electricity compared to (conventional) scrubbers that use a blower system. The results indicate that plasma precipitators can be used as an advanced technology to replace conventional gas and particulate emission removal systems from the industries.

Keywords: coal boilers, emission, gases, particulates, plasma precipitator

Introduction

Air pollution, resulting from industrial activities, may produce harmful gases, such as sulfur dioxide (SO₂), nitrogen dioxide (NO₂), carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons, and particulates. Air pollution not only threatens environmental sustainability but also harms the health and well-being of humans. In Indonesia, the problem of industrial waste management has been severe [1]. Existing air emission control technologies have not been completely able to solve this problem. Many industries have installed gas emission controllers, but the emission test results are still high, exceeding the specified threshold values. The failure to control gas and particulate emissions depends on several factors, such as maintaining the controller, operator's competency, and controller's ability to a specific capacity. Furthermore, the difficulty in handling successfully captured emissions remains a big hurdle in the waste disposal problem.

The elimination of gas and particulate in most industries is still limited to the absorber, scrubber, and dust collector

technologies, which are ineffective and require high costs [2]. Meanwhile, a prototype incorporated with plasma technology has achieved excellent reduction results. However, plasma technology has not yet achieved its top performance since coal particulates enter the plasma reactor to accelerate carbon deposits in the electrodes. In response, this study introduces and discusses the utilization of a dust capture technology through electrostatic precipitators and destruction of gas emission with plasma technology.

The main idea of the proposed emission removal system in this work is as follows. Air is an insulator medium, but if sufficient voltage (± 10 kV) is applied to the two electrodes, it will act as a conductor when electric current flows (electrical discharge). The flow of the electric current indicates ionization, which results in the formation of ions and electrons in the air between the two electrodes. The greater the electrical voltage applied to the electrode, the more significant ions and electrons are formed. The reactions that occur between the ions and electrons in large quantities result in plasma.

Plasma precipitator combines the dust deposition-capture technology by magnetic force and emission gas removal with plasma into environmentally friendly ions. In this work, plasma reactor with a dielectric barrier discharge is constructed. The electrodes are arranged to distribute the plasma micro-discharges to the entire electrode surface. This plasma reactor is installed in the gas stack based on coal fuel to break down emission gas and deposit the particulates formed from coal combustion. The key indicators that affect the success of this process include the exhaust gas flow rate, number of electrodes to be used, which must be dependent on the volume of outlet gas, and location of the plasma reactor installation to minimize the energy needed. Overall, there are several advantages of the applications of plasma technology in the industry and they are as follows: saving investment costs because extensive land and high construction costs are not required, saving electricity costs as the power required is less, easy to operate, easy to clean, and can be used longterm [3, 4] The designed electrostatic precipitator with a multilevel control system and flow of electric current plasma will ionize the emission gas and capture the particulates perfectly. The plasma precipitator can be used as a novel technology to replace conventional technology in controlling coal-based emissions.

Materials and Methods

The used equipment included particulate emission sampling equipment, whose main components are vacuum pumps, cable rolls, and rope. The device is equipped with a gas tube detector to analyze SO₂, NO₂, CO, CO₂, and O₂ gas emissions. The equipment used in the gas emission reduction is a dielectric barrier-plasma discharge tube with a length and diameter of 10 and 5 cm, respectively and 16 channels in total. All materials involved in the prototype were mounted upright on a stainless steel plate of 10-mm thickness.

The installed plasma tubes are coated on the inside by Pyrex glass so that the results of the gas reduction process, which were in the form of substantial deposits, are easy to clean. The function of the tube is to limit the flow of electricity. A metal rod is inserted in the middle of the tube as a high voltage electrode. High voltage cables connect all circuits. This system works by incorporating plasma technology to reduce gas and electrostatic dust (the particulates). This collaborative control system works using high voltage electricity and large magnetic forces. The advantages of this technology are that it is economical, clean, and environmentally friendly. Figure 1 illustrates the developed plasma precipitator reactor and its panel box (system controller).

The real-world applications of the developed plasma precipitator reactor were conducted in a textile industry located in Semarang, Central Java. The work includes



Figure 1. Design of Plasma Precipitator Reactor and its Panel Box with Electrical Components

primary and secondary data collection. Primary data collection includes the measurement of flue gas stack discharge, maximum discharge of 25,000 m³ per hour, initial concentration of SO₂, NO₂, CO₂, CO, and O₂, initial concentration of particulate emission, voltage used for the optimization of the emission reduction, and emission gas reduction test after being passed into the plasma precipitator reactor. The secondary data collection includes fuel specification data, which is 4500 Kcal low-grade coal, boiler operational data, which is operated for a week, daily fuel requirements, characteristic test of the existing system, voltage test on each channel, and distribution of electricity on each module in the reactor.

Experiments are conducted by assembling the device into two parts, namely the mechanical and electrical components. Mechanical components are designed with materials (stainless steel and pyrex glass) that are heat resistant at temperatures above 200 °C. This component is installed outside the gas stack by letting the emission airflow into the reactor. The reactor cable is connected to a panel installed in a safe place and free of water to prevent a short circuit. Before conducting the characteristic plasma test, the exhaust gas output from the boiler outlet is analyzed with a gas analyzer to determine the concentrations of SO₂, NO₂, CO₂, CO, and O₂ gases before reacting with the plasma reactor [5,6]. After determining the initial concentration of these gases, the reactor's performance on each channel is measured. This measurement aims to determine the amount of power (voltage) of each channel and ensure that all

channels are in good condition. Each channel is operated in the maximum position because the exhaust gas discharge condition can reach 25,000 m³ per hour, which requires considerable power. The changing variable of this research is the voltage, i.e., each channel has a different maximum voltage [7], and the fixed variables are the flow rate of the flue gas stack, emission temperature, and distance between the electrodes.

Following the abovementioned steps, the measurement of gas and particulate emission was conducted after switching the plasma precipitator reactor on. The capability test of the plasma precipitator reactor was conducted for approximately 6 h using a gas analyzer. Measurement of the oxygen content was performed and aimed to detect an increase in the oxygen levels after the ionization of the emission gases [8, 9]. The system also included dust setters (precipitators), which consisted of two main components, namely the mechanical and electrical components. The mechanical component consisted of a cascade that functions as a particulate precipitator, while electrical components were designed to generate a high voltage. The particulate that passes through the cascade will stick to the cascade with a magnetic field. The cascade will vibrate to drop or release the dust every 10 min and be collected in a dust container.

The operating voltage of the plasma precipitator reactor is greater than 10 kV and requires a power source of 100 W. All measurements were done at a peak load condition (approximately 80% of the production capacity). The final concentration of the gas and number of particulate emissions were recorded after the first 150 min from the initial measurement. Figure 2 describes the general procedure of this work.

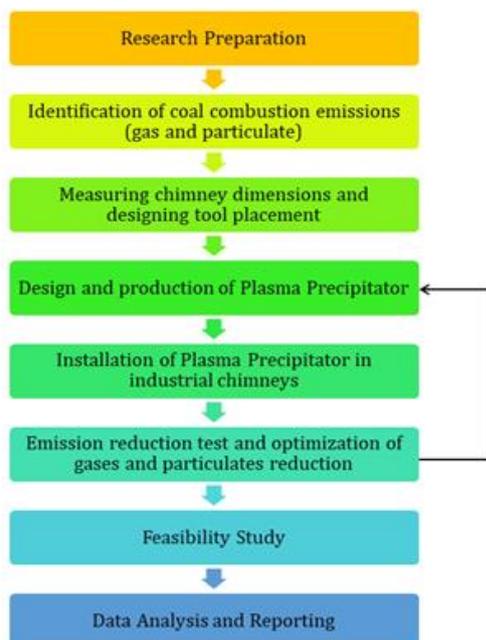


Figure 2. Application Procedure of the Plasma Precipitator

Results and Discussion

Sampling was performed when the coal boiler was operated at a production capacity of 8 tons per hour (installed capacity of 10.5 tons per hour) and under a peak load condition of 80%. Measurements with an analyzer were conducted for 6 h, with data recording every 30 min to determine the concentration changes in gas emissions. The reactor was operated at a maximum voltage of 20 kV in each channel with 16 channels. Concentrations of SO₂, NO₂, CO, CO₂, and O₂ under the initial conditions and after being controlled by the plasma reactor are discussed below.

As shown in Figure 3 (red curve), the initial concentration of SO₂ emission from the coal boiler stack reaches a concentration of approximately 3,000 mg m⁻³. This value significantly exceeds the permissible level of 750 mg m⁻³ SO₂. This result may be due to the high activity of the boiler to meet the needs of the generated steam in the process of making textiles. Note that coal has a typical sulfur content of around 2.5%–3.2% (coal manifest data). Moreover, the boiler unit is not equipped with a gas emission control device, resulting in a high level of SO₂ concentration.

Following this, the plasma precipitator reactor was switched on through the panel box (Figure 1. Note that 16 channels were operated in this plasma precipitator reactor, and each channel is connected to one tube. The voltage generated in one channel can completely deposit and ionize the air passing through each tube. The data was recorded subsequently after the first 150 min from the initial measurement. Figure 3 (blue curve) shows that the final concentration of SO₂ reaches 198–321 mg m⁻³ with an average emission discharge of 20,000 m³. The result indicates a 75%–90% reduction in the SO₂ emission gas.

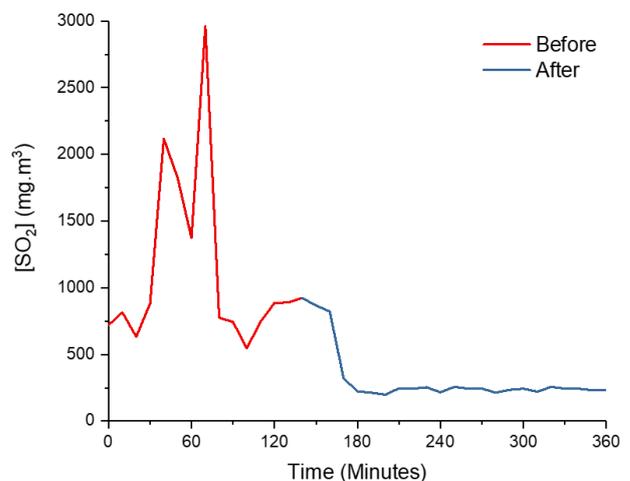


Figure 3. Initial (Red Curve) and Final (Blue Curve) Concentration of SO₂ Emission

The initial nitrogen dioxide (NO_2) gas concentration before reduction by the plasma precipitator reactor was also observed (Figure 4, red curve). Initially, the NO_2 concentration of the coal boiler did not show any significant increase in the first 2.5 h. This is influenced by the minimal amount of nitrogen content in the coal fuel (approximately 0.5%). The NO_2 level in the exhaust gas emissions is also insignificant. The highest initial NO_2 concentration is about 5.8 mg m^{-3} . Similar to the previous procedure, the data was recorded subsequently after 150 min from the initial measurement. Figure 4 (blue curve) shows the NO_2 gas reduction for up to 4 h after the initial concentration in the first 2 h. The observed NO_2 gas reduction is very significant, decreasing to approximately 0.5 mg m^{-3} (80%).

Carbon monoxide (CO) gas emission monitoring is needed to determine the combustion efficiency. To assess this, the initial and final concentrations of CO are measured continuously for 6 h. Figure 5 (red curve) shows the initial concentration of CO gas before reduction by the plasma precipitator. The highest initial CO gas concentration reached approximately 90.0 mg m^{-3} . This high CO gas content may be caused by the coal quality. The high humidity and high carbon content of the coal can affect CO gas concentrations during the combustion process.

Figure 5 (blue curve) shows the CO gas reduction trend after the first 150 min from the initial measurement. The resulting CO gas reduction is found to be significant, down to a concentration of approximately 10.5 mg m^{-3} . This is likely due to CO gas being ionized into solid carbon, which is attached to the electrode tubes, and the oxygen gas exiting the reactor outlet.

In addition to the CO gas, carbon dioxide (CO_2) gas is also formed from coal combustion. The measurement of the CO_2 emission gas is an important parameter that reflects the combustion condition and the energy used.

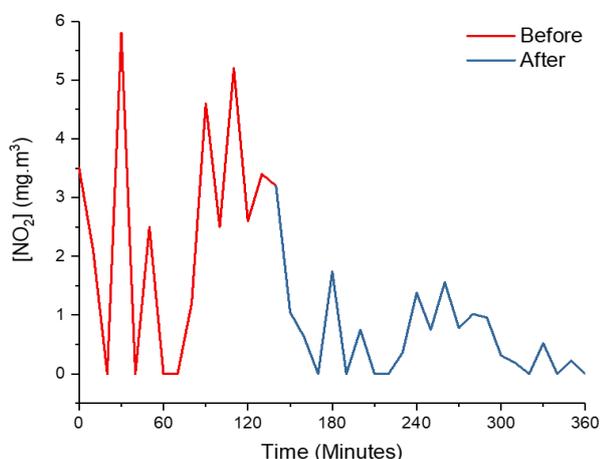


Figure 4. Initial (Red Curve) and Final (Blue Curve) Concentration of NO_2 Emission

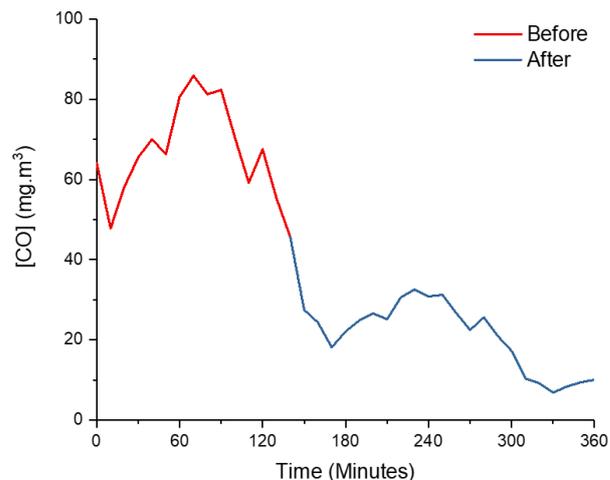


Figure 5. Initial (Red Curve) and Final (Blue Curve) Concentration of CO Emission

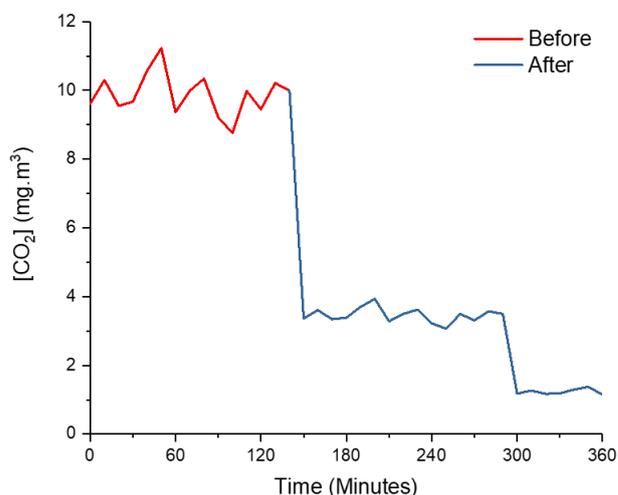


Figure 6. Initial (Red Curve) and Final (Blue Curve) Concentration of CO_2 Emission

From Figure 6 (red curve), the initial concentration of CO_2 gas is approximately 11.5 mg m^{-3} . This value is influenced by the amount of energy or coal used.

The CO_2 emission gas concentration shows a significant decrease after being reduced by a plasma precipitator reactor, reaching a percent reduction (efficiency) of 80–90% as revealed in Figure 6 (blue curve). The lowest CO_2 gas concentration at the final concentration is approximately 1.2 mg m^{-3} , which is likely due to the CO_2 gas being completely ionized into a solid that is deposited on the electrode.

Note that oxygen (O_2) gas was also formed and increased along with the formation of solids deposited in the electrode tube during the combustion process. The initial concentration of O_2 emission gas before reduction by plasma precipitator reactor during the first 150 min

of measurement is approximately 10.5 mg m^{-3} (Figure 7, red curve). This is likely influenced by the amount of air blowing from the combustion system in the coal boiler. The plasma precipitator reactor was then switched on and the data was observed until the next 3.5 h. The final concentration of O_2 emission gas increased gradually up to approximately 20.0 mg m^{-3} , which is possibly due to the production of O_2 gas from the ionization stages of other gases in the system.

Besides these gases discussed above, particulates (or fly ash) are also the most important and major components of the emissions in the industry. The particulate concentration was found to exceed the permissible level of 230 mg m^{-3} as declared by the Ministry of Industry of the Republic of Indonesia. This is possibly influenced by the low-grade coal or fuel quality, producing a high number of particulates and fly ashes. Generally, the simplest particulate emission control devices are usually in the form of a water scrubber that is installed after the coal boiler and before the outlet gas stack, making its release less controllable [10–12].

The highest initial concentration reached approximately 400.0 mg m^{-3} with an average flow rate of $20,000 \text{ m}^3$ per hour. Note that the condition of the coal boiler process at peak load condition is 80%. At the time of reduction with the plasma precipitator reactor, the particulate concentration gradually decreased up to about 26.0 mg m^{-3} , which shows a significant decrease of particulates and fly ashes by approximately 93.5%. Particulates that flow through the plasma precipitator reactor's electric field will hit or collide with the scattering electrons. This process leads to the loss of electrons in gas molecules, turning them into positively charged molecules. In this case, one electron hits one gas molecule, consequently producing two electrons. The longer this process occurs, the greater the number of negative gas ions attach to the

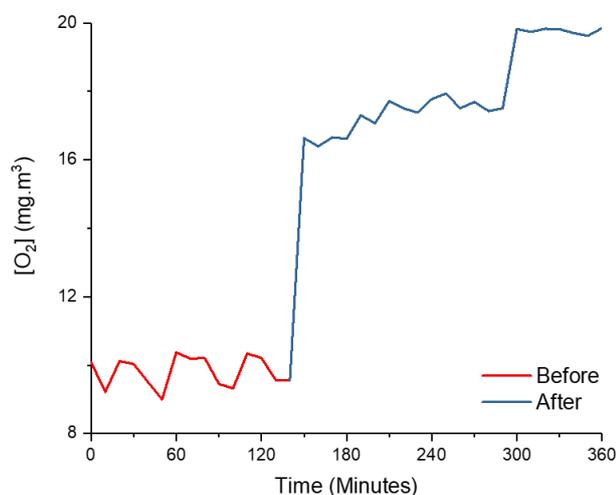


Figure 7. Initial (Red Curve) and Final (Blue Curve) Concentration of O_2 Emission

particulates. The particulates become saturated (saturated charged particles) [13, 14], subsequently sticking to the fins of the reactor system.

In this work, the economic impact analysis is discussed. The calculation of electrical energy used to operate the plasma precipitator reactors is 960 W. Equation (1) shows the calculation of the total cost (in Indonesia Rupiah, IDR).

$$\begin{aligned}
 &= \frac{\text{Watt} \times \text{Time} \times \text{Industrial Electric Price per KWH}}{1000} \\
 &= \frac{(100 \text{ W} \times 16 \text{ Channels}) \times 24 \text{ Hours} \times \text{IDR } 1112}{1000} \\
 &= \text{IDR } 42.700 \text{ per Day per Boiler} \quad (1)
 \end{aligned}$$

Compared to conventional methods, which use a cyclone, the concentration of emission gas cannot be reduced optimally. It is only diluted using the air from the blower and the concentration of the gas and particulate emissions remains high. The utilization of cyclones only minimizes the deposited particulates and reduces fly ashes to the environment but cannot solve the gas emission problem [15, 16]. The use of a plasma precipitator reactor is more efficient and consumes less energy. Generally, many industries use a huge blower of around 60.7 HP (horsepower) where the performance of the motor can only reach 90% or approximately 68 HP. Therefore, the blower electricity cost is IDR 1.342.940 per day according to Equation (2).

$$= \frac{(68 \text{ HP} \times 0.74 \frac{\text{KWH}}{\text{HP}} \times 1000) \times 24 \text{ Hours} \times \text{IDR } 1112}{1000} \quad (2)$$

The industrial electricity costs per KWH are IDR 1112, and the conversion factor of HP to KWH is 0.74. This value suggests that using electricity in a plasma precipitator reactor is very economical compared to using a huge blower. In addition, gas and particulate emission reduction using the developed plasma precipitator reactor can reach up to 80%–90% efficiency. Meanwhile, gas and particulate emission reduction using a conventional blower (cyclone) can go down to a maximum of only 60%, which comes from the dilution of air coming from the blower.

Conclusion

The plasma precipitator reactor developed in this study reduced gas and particulate emissions by approximately 90%. Using this reactor, SO_2 , NO_2 , CO, and CO_2 gases turned into more environmentally friendly forms, such as O_2 . Elements and bonding groups in the form of solids, such as sulfur, carbon, and nitrogen, were found deposited in the electrode. The plasma precipitator reactor does not require high electricity and operational

costs compared to (conventional) scrubbers that use blowers. However, the electrode surface must be cleaned periodically for the gas dissociation process to be executed perfectly. Further developments can be made to increase the resilience of the electrical equipment to reduce coal gas emissions. Further observation is required regarding the durability and reliability of this plasma equipment in the mechanical and electrical components.

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The authors have no competing financial interests to declare.

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