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Sub-atmospheric Tubular Electrostatic Precipitator for Efficient Reduction of Methane and Carbon Monoxide

Hadeer A. Abbas*
Qusay A. Abbas

Department of Physics,
College of Science,
University of Baghdad,
Baghdad, IRAQ
* Corresponding author email:
hadeer.abass1204@sc.uobaghdad.edu.iq

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This study uses a sub-atmospheric pressure spark electrostatic precipitator (ESP) to examine the reduction of carbon monoxide (CO) and methane (CH_4) from atmospheric air. The process operates in the voltage range of 15–25 kV at a constant pressure of 380 Torr. Gas concentrations inside and outside the deposition unit were measured using MQ-2 and MQ-4 sensors mounted on an Arduino-based data acquisition module. The results showed that negative spark discharge significantly improves removal efficiency compared to positive discharge, with maximum removal efficiencies of 88% for methane and 87% for CO at 25 kV with a negative bias. Scanning electron microscope (SEM) images revealed the deposition of round-shaped carbon nanoparticles and agglomerates on the electrode surface. At the same time, EDS analysis confirmed the high carbon deposition, demonstrating the efficient decomposition of CO and CH_4 molecules within the plasma discharge chamber.

Keywords: Tubular electrostatic precipitator; Spark discharge; Carbon monoxide; Collection efficiency

1. Introduction

The incessant increase in industrial pollutants and carbon emissions has pushed engineers, scientists, and researchers towards finding more sophisticated techniques for purifying deleterious gases, particularly in industries with high emission rates such as energy plants and heavy industries [1]. A top-rated technology amongst them is electrostatic precipitators (ESPs), which work on charging particles suspended in the air with electricity and driving them to collection electrodes using a high electric field.

ESPs have traditionally been counted on for the elimination of fine particulate matter from combustion gases [2]. Notably, subsequent work suggests a broader perspective: under certain circumstances, the devices might also help eliminate some gaseous pollutants via surface adsorption or a soft electrochemical impact.

The advantage of ESPs is that they can capture smoke and microscopic particles without the involvement of conventional mechanical filters. This is another important factor contributing to the reduction in pressure loss and long-run maintenance costs [3]. It is very important to point out that conventional ESP systems are not very effective in the control of complex gas transformations. Now is the time for new ideas to emerge. Recently, various methods involving electrical discharge generating very powerful electrons have drawn considerable attention from researchers with regard to breaking the chemical bonds in gases like carbon monoxide (CO) and methane (CH_4). This mechanism partially or completely breaks down these substances into ions [4,5]. Plasma experiments with DC spark discharge have only recently been employed in this field. These have shown that methane can be broken down at atmospheric pressure to release solid carbon and hydrogen without releasing CO_2, which is a significant environmental benefit. And that the conversion efficiency increases with increasing voltage and spark frequency [6]. The new plasma technologies have also been employed in the conversion of carbon gases such as CH_4 and CO into desirable end-use products without the need for elevated heat, hence making them a likely prospect in clean energy applications [7]. For carbon monoxide (CO), experiments have demonstrated that the gas is partially thermoelectrically dissociated at high vacuum, giving rise to gaseous CO_2 and solid carbon based on the reaction $2CO + C \rightarrow 2CO$.

Furthermore, it has also been seen that the occurrence of repeated sparks inside a volume that has CO results in a slight deposition of carbon on the metal electrode [8]. Therefore, putting the concepts of electrostatic precipitators together with plasmas could give a hybrid system a dual role: differentiation of charged particles and differentiation or breaking apart gaseous molecules of carbon under suitable circumstances. This work focuses on observing the motion of gases, such as methane and carbon monoxide, inside a high-voltage electric field in an electrostatic-type precipitator during a spark discharge, examining the carbon deposition capacity, the efficiency of ionization, and its performance impact on the entire system [9]. This mechanism not only lowers the level of bad gases in the air but also helps deposit carbon on the surfaces of the ESPs. Spark discharge, or electrical discharge or plasma discharge, is at least a state where a high voltage between the electrodes makes the gas ionize [10].

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2. Experimental Part

The experiments were conducted using a tubular electrostatic precipitator (ESP) with two coaxial cylindrical electrodes enclosed within a Pyrex tube as shown in Fig. (1). The outer electrode functions as the collecting electrode, and the inner electrode as the discharge electrode. By applying a high DC voltage between the electrodes, a strong electric field is created that facilitates gas molecule charging and encourages the chemical breakdown of CO and CH_4, resulting in both positive and negative spark discharge. A rotary vacuum pump maintains the gas flow, generating a flow rate of roughly 50 L/min. An enough interaction between the gas molecules and the produced plasma is made possible by the chamber volume (1.8 liters), which yields a residence time of 2.2 seconds. Four sensors were used to measure the gas concentrations at the ESP chamber's inlet and outlet: two MQ-2 sensors for CO and two MQ-4 sensors for CH_4. The sensor signals were digitized using an Arduino microcontroller and sent, in real time, to a computer to continuously monitor and evaluate the ESP removal efficiency. A high-voltage DC power supply (DY10, Cloudray, China) was applied to maintain voltages for the desired electric field level up to 25 kV. Table (1) summarizes the most important technical information about the ESP, and figure (2) shows the experimental setup used in this work.

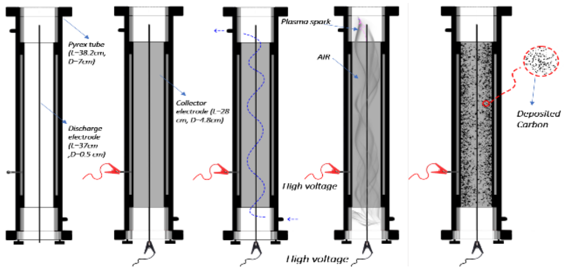

Fig. (1) Tubular electrostatic precipitator

Table (1) Information about the apparatus components without repeating details already mentioned in the text

Component / Parameter	Specification / Description
ESP Type	Tubular electrostatic precipitator
Outer Electrode	aluminum cylinder
Inner Electrode	Metallic rod, discharge electrode
Outer Tube	Pyrex tube
Voltage Supply	DY10 high-voltage DC power supply
Vacuum Pump	Rotary vacuum pump, Yangyi VP115
Gas Sensors	2 × MQ-2 (CO), 2 × MQ-4 (CH_4)
Data Acquisition	Arduino microcontroller

The experimental study was designed to investigate the applied voltage effect on carbon removal efficiency from CO and CH_4 in ambient air through a tubular ESP in negative spark discharge. This analysis tests three different DC voltages: 15 kV, 20 kV, and 25 kV. The pressure within the chamber was controlled with a rotary vacuum pump to about 380 Torr. Each experimental run was conducted for 120 seconds to ensure sufficient operational time to achieve measurable gas removal.

The gas sensors were used to measure the CO and CH_4 concentrations at the ESP chamber's inlet and outlet for each voltage condition.

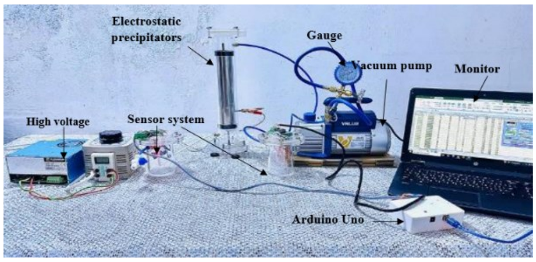

Fig. (2) Experimental setup used in this work

3. Results and Discussion

The following formula was used to determine the carbon removal efficiency based on the variation in gas concentrations before and after the treatment [11]:

$$\eta = 1 - \frac{C_L}{C_0} \qquad (1)$$

C_0 is the concentration of gas coming in, and C_L is the concentration of gas going out after treatment [12]. This setup lets you measure how well the ESP works at getting rid of carbon species from CO and CH_4 at different voltages, in a controlled vacuum, and for a set amount of time of 120 seconds.

The curve shows that the current also goes up when the voltage goes up. This is what you would expect to happen when you discharge a spark. The relationship between current ΔI and voltage ΔV in spark discharges is not completely linear, but typically shows an approximate increase in current with increasing voltage, as shown in Fig. (3).

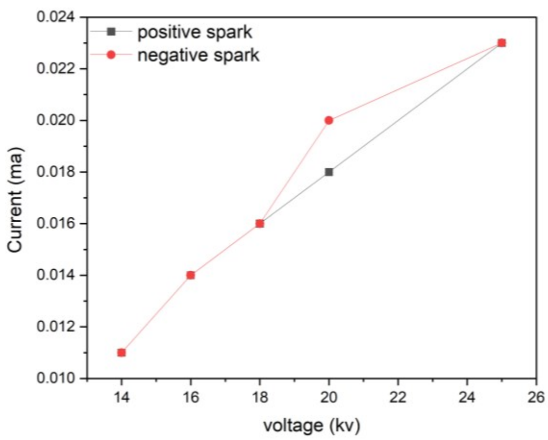

Fig. (3) Voltage-current Characteristics for spark discharge in 380 Torr

As the voltage goes raised, the gas between the electrodes moves electrons and ions faster. This makes

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the charge density between the electrodes go up [13,14]. As the voltage increases, the electric field's ability to accelerate charges and generate new ions increases, leading to increased ionization and partial discharge processes, and consequently, an increase in the current passing between the electrodes. This behavior is in line with models of spark discharge, which show that the intensity of the current is proportional to the strength of the electric field and the quantity of ions generated [15,16]. The positive and negative curves converge at higher voltages (2.5 kV), suggesting that polar effects lessen as the field energy readily surpasses the ionization barrier for both positive and negative discharges, resulting in a more uniform discharge [17].

As shown in Fig. (4), the collection efficiency of a cylindrical electrostatic precipitator (ESP), which is collected during operation using a spark discharge under both negative and positive electrodes and was calculated using Eq. (1), is strongly influenced by the discharge voltage, internal pressure, and operating polarity. In particular, for methane (CH_4), the maximum collection efficiency was achieved with a negative spark discharge of 88% at 380 Torr and 20-25 kV. Similarly, carbon monoxide (CO) achieved an efficiency of 87% under the same conditions. This voltage dependence is expected based on electrostatic theory, where it is believed that voltage increases the electric field strength and is therefore important for enhancing ionization and particle charging, both of which are important for pollutant removal in ESPs [18].

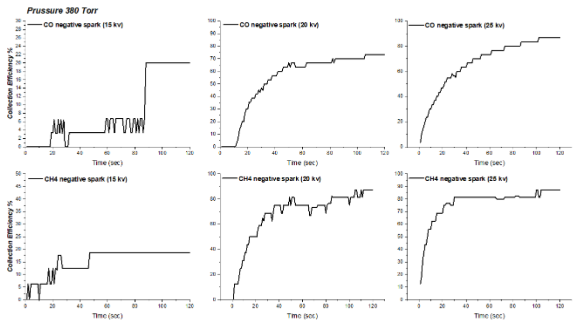


Fig. (4) The collection efficiency of CO and CH_4 for a negative spark at a pressure of 380 Torr

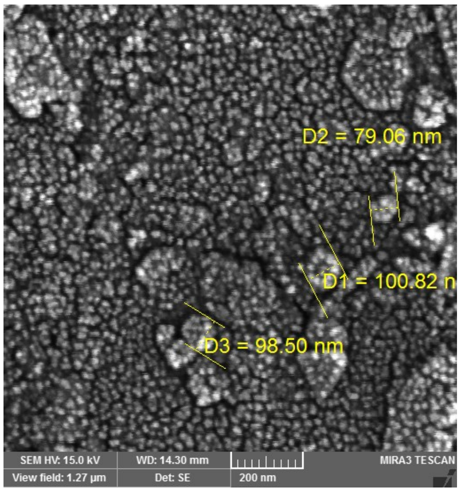
Table (1) describes the highest collection efficiency of methane (CH_4) and carbon monoxide (CO) for different applied polarities and voltages for a 120-second time of treatment.

The data present that the most effective condition for the elimination of pollutants by a cylindrical electrostatic precipitator (ESP) with spark discharge is by negative polarity, at a higher voltage of 25 kV, and at a higher pressure of 380 Torr. Such a condition ensured the highest reduction of concentrations of CH_4 and CO throughout the plasma treating process.

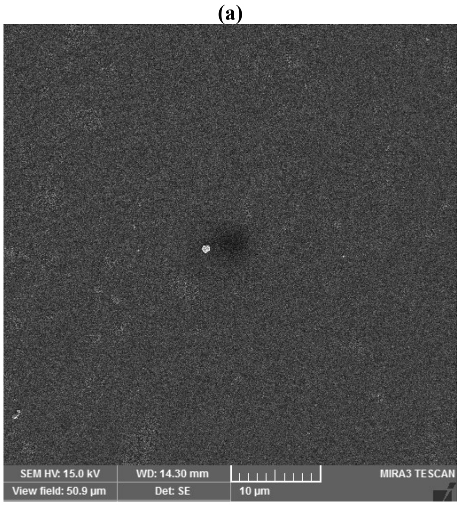
All the experiments were repeated three times for each condition to be reproducible. Mean value and standard deviation were calculated accordingly. The statistical analysis also confirmed the significance of variation of collection efficiency and plasma parameters between positive and negative polarity, which indicates better performance under negative discharge conditions.

They agree on the need to set both the electrical conditions (such as voltage and polarity) and the physical conditions (for example, pressure) correctly for the utmost performance of the ESP-based systems for treating gaseous pollutants

Figure (5) shows imaging of the particles deposited on the inner surface of the cylinder, which was performed after operating the device at various voltages (15, 20, and 25 kV) using a discharge, with room air as the input gas containing organic pollutants such as methane (CH_4) and carbon monoxide (CO). Images were taken from different regions of the cylinder surface to analyze the distribution, shape, and morphological density of the resulting particles.



(a)



(b)

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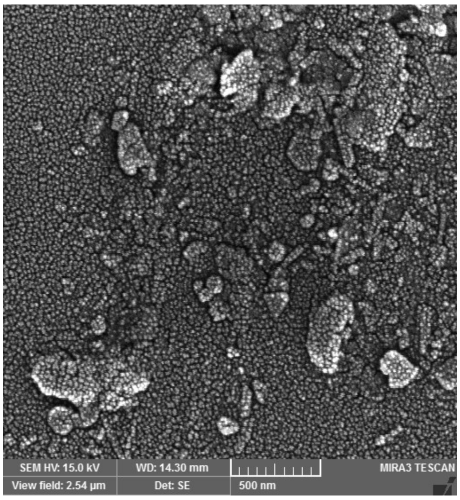
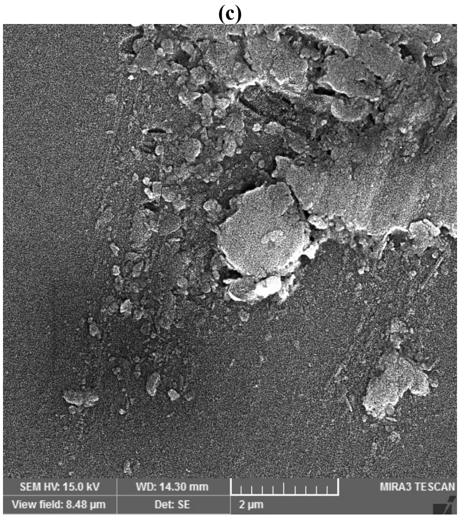


(c)



(d)

Fig. (5) SEM images of the surface of the cylinder

Figure (5a) shows spherical nanoparticles with a regular nanometer diameter, with slight localized clustering. Figure (5b) shows clear nanoscale agglomeration. Figure (5c) shows an inhomogeneous particle distribution, with a high sedimentation density in the center. Figure (5d) shows irregular and rough surface deposits, likely representing undissolved residues of gaseous pollutants or heavy materials that have not fully reacted within the plasma environment.

The chemical composition of the particles deposited on the cylindrical surface of the precipitator was examined using energy-dispersive X-ray spectroscopy (EDS). Figure (6) shows that EDS spectroscopy revealed the presence of several elements, including carbon, oxygen, nitrogen, and silicon, indicating the chemical dissociation of the gases entering the cylinder and being treated by electrical discharge, specifically CO and CH_4. Nitrogen is a component of atmospheric air. The analysis revealed high percentages of carbon (47%), oxygen (33%), and nitrogen (10%), with small percentages of silicon in the silicon used for the analysis. Since the EDS analysis was performed on the entire sample, the elemental interpretation of the particles in the SEM images is a possible explanation based on the general EDS data and discharge conditions. These observations support the view that carbon-oxygen nanoparticles arise from the dissociation of CH_4 and CO within the electrical discharge plasma environment.

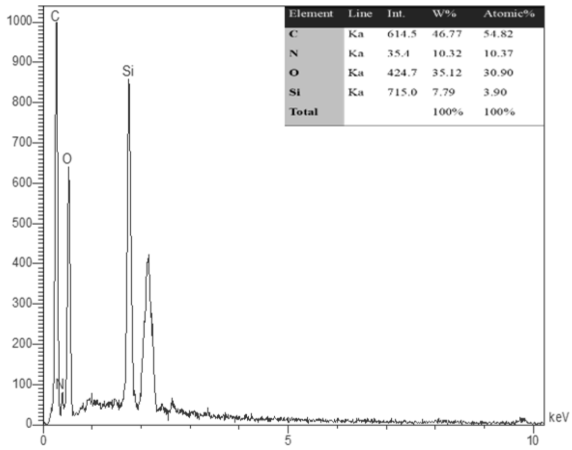


Fig. (6) EDS spectrum

Table (2) The highest collection efficiency for CH_4 and CO with different polarities

	Highest collection efficiency% for CH_4		
P=380 torr	Voltage kV	Negative spark	Positive spark
	15	19	19
	20	88	81
	25	88	81
	Highest collection efficiency% for CO		
P=380 torr	Voltage kV	Negative spark	Positive spark
	15	20	20
	20	73	73
	25	87	83

4. Conclusion

Tubular electrostatic precipitators were found to be an efficient device for the removal of gaseous pollutants, especially CO and CH_4. The most effective negative discharge at high voltage up to 25 kV was found to assure high methane (88%) and carbon monoxide (87%) removal. This shows how important it is to balance the voltage and polarity for the best performance. Carbon nanoparticle deposition on the electrodes was confirmed by investigations utilizing scanning electron microscopy (SEM) and electrostatic scanning electron imaging (EDS), which offered direct evidence of gas breakup and precipitation in a plasma environment. This study shows that plasma-enhanced ESP technology could be used to treat both gaseous and particulate pollutants. This makes it a promising way to improve air quality in places with a lot of pollution, like cities and factories.

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