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Study on the effect of electrode configurations on NO_x removal from diesel engine exhaust

Sankarsan Mohapatro*, Srikanth Allamsetty*, Apeksha Madhukar* and Nikhil Kumar Sharma*

The electrical discharge phenomenon is ubiquitous in various fields of engineering to solve some complex and complicated problems. Applications of electrical discharges also include environmental remediation techniques such as water and air pollution treatments. This paper deals with the application of electrical discharge in non-thermal plasma based depollution of diesel engine exhaust. Experiments are conducted to know the effect of electrode configuration on NO_X removal efficiency. A high voltage AC test set is used as a source for the power required for the plasma reactor. The dielectric barrier discharge technique is used to dissociate the exhaust gas molecules into radicals, which further cause a number of chemical reactions to take place so that the harmful pollutants would get removed or converted into harmless gases. Two cylindrical discharge electrodes with diameters 3 mm and 5 mm, respectively, and one square electrode with a diagonal of 5 mm are tested as high voltage electrodes. Results are discussed considering three cases; in each case, removal of NO_X with one particular discharge electrode is analyzed. As the energy consumed to remove the NO_X is a major consideration, the specific energy (J/L) delivered by the source as well as the energy cost (eV/mol) are calculated for all the cases. A comparison is made among the results to determine the best electrode configuration with respect to $DeNO_X$ efficiency, specific energy consumption and energy cost. The square electrode is found to be the best among the test electrodes, which has removed 84% of NO_X from the exhaust at a specific energy of 51.45 J/L. The energy cost in this case is 54.07 eV/NO_X.

Keywords: *Electrical discharges, NO_X removal, plasma reactor, dielectric barrier discharge, diesel engine exhaust.*

1.0 INTRODUCTION

The electrical discharge plasma has already been proved to be economical compared to conventional techniques for exhaust gas treatments. It can be produced in a number of ways, one of which is the Dielectric Barrier Discharge (DBD). The principle of electrical discharge plasma in cleaning the gaseous pollutants is to produce high energetic electrons with an average energy of around 5 to 20 eV. This energy is sufficient to break the chemical bond of the carrier gas molecules to produce radicals, which selectively react with the pollutant molecules converting them to harmless gas molecules. As the electrons are preferentially excited using the electric discharge phenomenon, leaving more number of massive ions with lower energy, a significant energy savings can be realized. Furthermore, the energy goes into production of energetic electrons rather than into gas heating [1]. Thus, compared to conventional techniques such as selective catalytic reduction, it consumes lesser energy and hence can be a better alternative.

Effects of the amplitude and frequency of voltage, diameter of the electrode, reactor volume and discharge gap on NO_X removal were studied based

*DEI lab, School of Electrical Sciences, Indian Institute of Technology Bhubaneswar, India.

on DBD in [2]. It is found in this study that the NO_X removal rate is increased with increase in the volume of reactor and the diameter of electrode. Effects of electrode length, diameter, material, shape of the inner electrode, and dielectric material were studied in [3] and found that screw shaped electrode improves NO removal efficiency. Coaxial reactors, consisting stainless wire as inner electrode and stainless pipe as outer electrode, are used in [4] to generate streamer discharges. When the spark discharges occurred during this study near the center of the coaxial reactor, the inner wire electrode was gradually attracted to the outer electrode. A tensioned inner wire electrode was introduced to study this phenomenon. Cross-flow DBD reactor is used in [5] for removal of NO_X. Experiments were conducted varying the flow rate and found that the $DeNO_X$ efficiency reduces at higher flow rates. The effect of diameter, length and shape of the electrodes on NO_X removal is investigated in [6]. It is found in this study that NO_X removal efficiency increases with increase in electrode diameter and length. Further, Screw thread electrode was described to be performing better than the rod type electrode due to its ability to get higher production of micro discharges.

Despite the improvement in after treatment technologies and modifications in the design, diesel engines have continued to emit a large amount of NO_X. This study is an attempt to provide a solution for this problem by suggesting the best electrode configuration.

2.0 EXPERIMENTAL SET UP

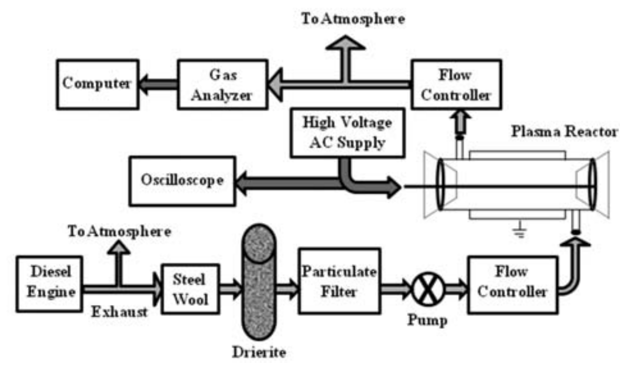

FIG. 1. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup used for the study. The details of the components of this setup are explained in the following subsections.

2.1 Exhaust Source and Filtering Unit

A 7.5 kVA diesel generator set is used as the source for the exhaust where an oil-free pump is used to draw the exhaust. The diesel engine is loaded electrically. Atmospheric conditions also influence the concentrations of various pollutants in the Diesel Engine Exhaust (DEE).

The filtering unit comprises of steel wool, drierite, and particulate filter. Low carbon steel is used to make the steel wool. This is used to trap the soot particles. A non-indicating drierite is used to dry the exhaust. The particulate filter (model: EG0020) is used to remove particulate matter present in the exhaust.

2.2 Plasma Reactor and Test Electrodes

A hollow cylindrical borosilicate glass tube is used as the plasma reactor during these experiments. The inner and the outer diameters of the reactor are 15 mm and 17 mm respectively. The aluminum foil is wrapped on the reactor up to a length of 260 mm and thus the effective length of the corona discharge region is 260 mm only.

The high voltage electrodes are made up of stainless steel and an aluminum foil is wrapped uniformly throughout the reactor to make the ground electrode. Three types of high voltage electrodes are tested during these experiments, which differ in dimension and shape. Those are two cylindrical electrodes with 3 mm diameter and 5 mm diameter, i.e. C-3mm and C-5mm respectively, and one square electrode with a diagonal of 5 mm, i.e. S-5mm.

2.3 High Voltage Power Supply

The high voltage power supply unit used in these experiments is a 900 VA HVAC test set (make: RE). The voltage can be varied from 0 to 30 kV and the maximum current that can be supplied is 30 mA. NO_X removal using power frequency HVAC supply is a feasible option in terms of simplicity and robustness. The standard power frequency AC transformer is easily available and also has the capability of generating high voltage plasma.

2.4 MEASURING UNIT

The output of a voltage divider of ratio 2000:1 is connected to a digital storage oscilloscope (model: DS1074; 70 MHz, make: RIGOL). The power consumption by the reactor is measured using the single reactor principle. In this method, the power delivered by the source would be measured first without connecting the reactor at the load and then again after connecting the reactor. The discharge power would be the difference of both these measured powers, assuming that the power supply unit and converters are lossless [7]. A gas analyzer (model: FGA 53X, make: Indus Scientific) is used to analyze the concentrations of various pollutants. It measures the concentrations in both ppm and percentage using infrared and electro-chemical sensors.

3.0 RESULTS AND DISCUSSION

In this study, HVAC supply is applied to the plasma reactor and three types of mentioned electrodes are tested one after the other. The experiments have been conducted at a temperature of 25 ^oC and flow rate is maintained as constant, i.e. 4 l/min. The approximate initial concentrations of various pollutants in the exhaust are given in Table 1.

TABLE 1
INITIAL CONCENTRATIONS OF POLLUTANTS PRESENT IN DEE

Pollutant/ Gas	Initial Concentration
NO_X	388 ppm
NO	368 ppm
NO_2	20 ppm
CO	70 ppm
O_2	18.62%
CO_2	1.83%

The concentration of NO_X is the sum of concentrations of NO and NO_2 measured individually. The exhaust also contains some other pollutants, but as this study is focused on reducing NO_X concentration only, remaining are unobserved while measuring. Treatment of the exhaust is done using the plasma reactor applying high voltage AC supply. This leads to the corona discharge and then to the generation of O and N radicals. These radicals initially cause oxidation process of NO molecules present in the exhaust [7]. Due to this most of the NO converts into NO_2. So a significant increase in the concentration of NO_2 can be observed. Later, when the Specific Energy (SE) is increased further, concentration of NO_2 also starts decreasing as more number of reactions takes place due to increased density of the radicals [8]. Some major reactions from all the reactions take place in the plasma reactor [9] has been mentioned below along with their corresponding rate constants (k) in cm^3/s.

$$NO + O \rightarrow NO_2\ ;k=1.4\times10^{-12} \quad (1)$$

$$NO + O_3 \rightarrow NO_2 + O_2;\ k=1.8\times10^{-14} \quad (2)$$

$$NO + N \rightarrow N_2 + O;\ k=2.1\times10^{-11} \quad (3)$$

$$NO_2 + O_3 \rightarrow NO_3 + O_2;\ k=1.4\times10^{-12} \quad (4)$$

$$NO_2 + NO_3 \rightarrow N_2O_5;\ k=1.4\times10^{-12} \quad ...(5)$$

$$NO_2 + N \rightarrow N_2O + O;\ k=1.4\times10^{-12} \quad ...(6)$$

When NO_2 also starts reducing it can be said that NO_X removal is started. The concentration of NO_X in each case, i.e. with each electrode, is recorded with the voltage at which it is present. Then the SE, DeNO and $DeNO_X$ efficiencies are calculated using the following equations.

$$SE(J/L) = \frac{\text{Discharge power (W)}}{\text{Flow rate(l/sec)}} \quad (7)$$

$$\text{DeNO Efficiency}(\%) = \frac{\text{Initial NO} - \text{Final NO}}{\text{Initial NO}} \times 100 \quad (8)$$

$$\text{DeNO}_X\ \text{Efficiency}(\%) = \frac{\text{Initial NO}_X - \text{Final NO}_X}{\text{Initial NO}_X} \times 100 \quad (9)$$

Here, flow rate is measured in l/min using flow controller, but converted to l/sec to get SE in J/L. initial NO, initial NO_X, final NO and final NO_X are the concentrations measured. Figure 2 shows the variation of discharge power with respect to the input voltage for all the test electrodes. For the same input voltage, C-3mm draws more power compared to C-5mm. The instantaneous power consumption in plasma reactor is inversely proportional to the discharge gap length assuming all the losses are negligible.

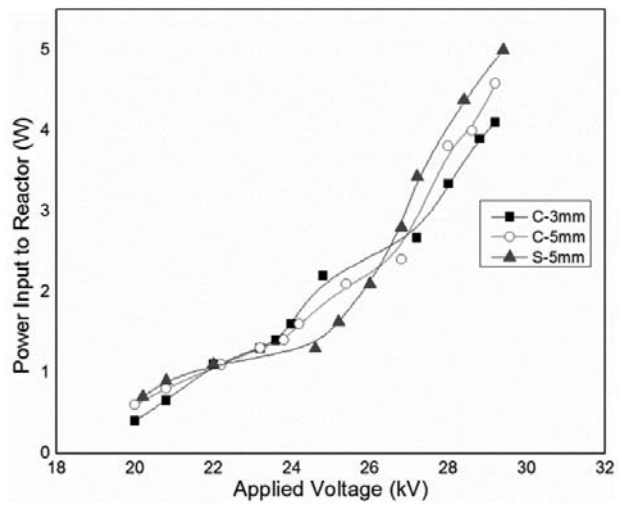

FIG. 2. DISCHARGE POWER PROFILE WITH RESPECT TO THE APPLIED VOLTAGE.

The variations in concentrations of NO and NO_2 with respect to SE is shown in Figure 3. Very high energetic electric field is produced in the reactor during the treatment of the exhaust. It can be observed from the figure that the concentration of NO decreased while that of NO_2 increased with the increase in applied voltage. This is due to the oxidation reactions those took place in the plasma reactor when electric discharge takes place and leads to NO to NO_2 conversion.

When the C-3mm diameter is used, NO concentration has decreased to 28 ppm and NO_2 concentration has increased to 61 ppm at an SE of 61.5 J/L. When C-5mm is used, NO concentration has fallen down to 0 ppm and NO_2 concentration has increased to 129 ppm at an SE of 60 J/L. But, when the S-5mm is used, NO concentration has fallen down to 0 ppm at an SE of just 31.5 J/L.

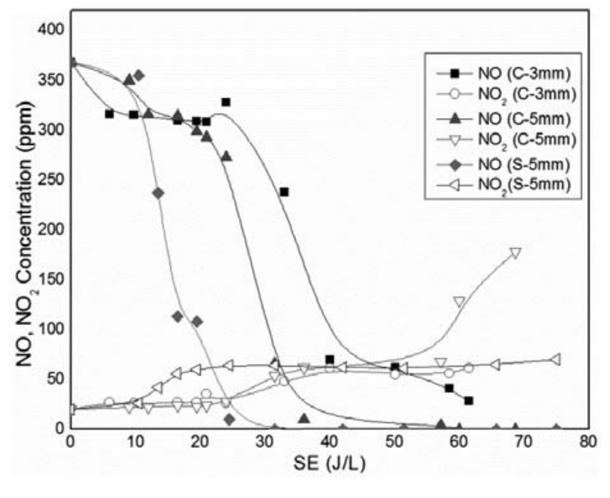

FIG. 3. VARIATION IN CONCENTRATIONS OF POLLUTANTS WITH RESPECT TO SE.

From this, it can be said that S-5mm is performed well when compared to the other two electrodes considered in terms of SE. However, NO_2 concentration is noted to be increased in this case also to 64 ppm. The DeNO efficiency with its corresponding SE for different electrode configurations is plotted and shown in Figure 4. It can be seen from this figure that the increasing SE causes increase in the DeNO efficiency.

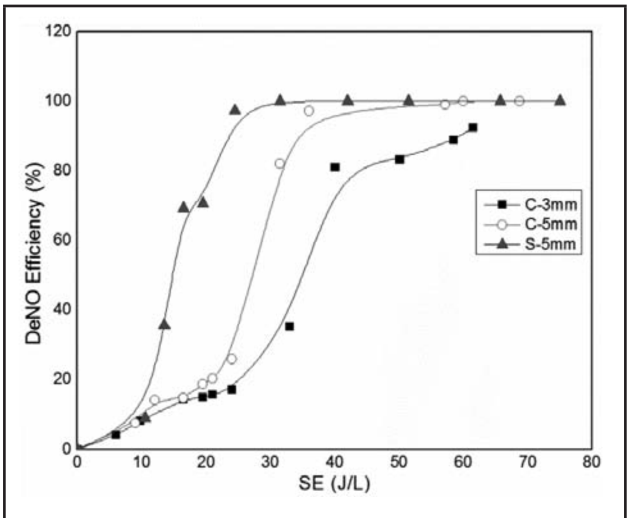

FIG. 4. DENO EFFICIENCY WITH RESPECT TO SE.

Maximum DeNO efficiency with C-3mm is 92.39% at an SE of 61.5 J/L and that with C-5mm is 100% at an SE of 68.7 J/L. For S-5mm, it is 100% at an SE of 31.5 J/L. So S-5mm is found to be taking lesser SE than the other two electrodes.

The trend of $DeNO_X$ efficiency of test electrodes with its corresponding SE is shown in Figure 5. As explained earlier, increase in discharge power and thus SE, results in intensified electric field inside the reactor, and finally leads to the increase in $DeNO_X$ efficiency.

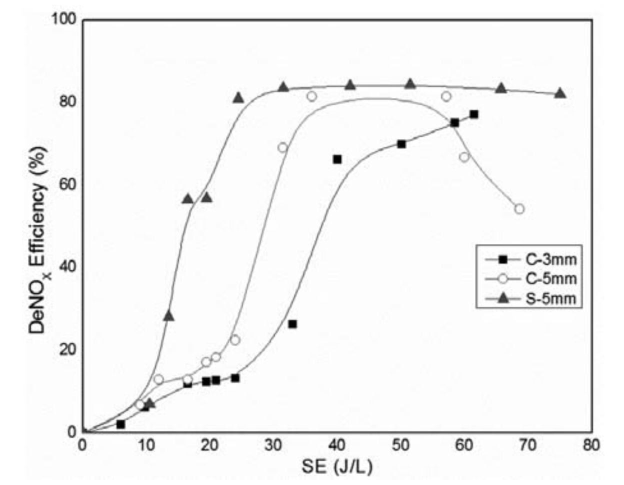

FIG. 5. $DENO_X$ EFFICIENCY WITH RESPECT TO SE.

Further, maximum removal efficiencies of the test electrodes are compared as shown in Figure 6. It can be observed that the maximum $DeNO_X$ efficiency with S-5mm is 83.5 % at an SE of 31.5 J/L and the corresponding DeNO efficiency at the same SE is 100%. When compared to the other two test electrodes, S-5mm shows better performance towards achieving maximum removal efficiency. It can be said that the shape of the electrode plays an important role in its performance. As the square electrode consists of edged shape, it attains more intensified electric field at a lesser input voltage. So the possibility of particle collisions increase, which tends to intensify the plasma reactions.

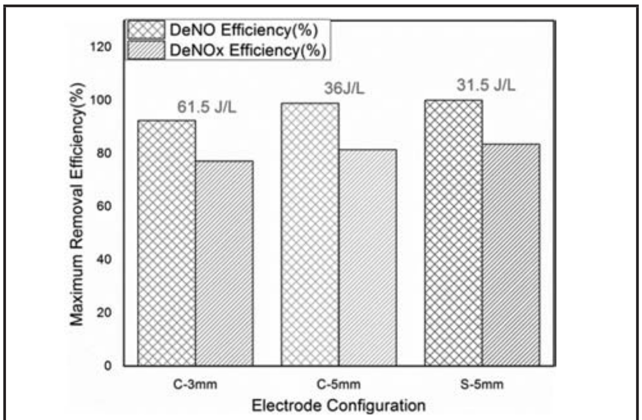

FIG. 6. MAXIMUM REMOVAL EFFICIENCIES WITH RESPECT TO ELECTRODE CONFIGURATION.

Table 2 presents a comparison among the test electrodes with respect to their removal efficiencies as well as energy efficiencies. Here, the units of energy efficiency are in eV/mol. The values given represent the energy consumed, in electron volts, in the work done for removing one pollutant molecule. As already been mentioned, removal efficiency increases with the increase in electrode diameter. So, C-5mm performs better than C-3mm, which can be seen from this table in terms of energy consumption. When comes to the shape, S-5mm can be said to be superior in performance in terms of removal efficiencies.

TABLE 2

COMPARISON AMONG THE ELECTRODE CONFIGURATIONS CONSIDERED

Test electrode	DeNO efficiency (%)	eV/NO mol	$DeNO_X$ efficiency (%)	eV/NO_X mol
C-3mm	92	77.19	77	77.19
C-5mm	100	69.57	81	42.91
S-5mm	100	36.52	83.5	33.41

4.0 CONCLUSION

The present study is performed to know the better configuration of the electrode for the efficient removal of NO_X from the exhaust using NTP based DBD technique. Objective of conducting these experiments is to suggest this method to get used in automobile diesel engines. Results have shown that the maximum $DeNO_X$ efficiency can be achieved with S-5mm at a lesser SE as well as at a lesser energy cost. The reason for the better performance of S-5mm over the other two electrode configurations is the intensified electric field due to its sharp edges. S-5mm has achieved 83.5% $DeNO_X$ efficiency at a SE of 31.5 J/L with an energy consumption of 33.41 eV/NO_X mol.

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