Nanosecond pulse discharge based nitrogen oxides treatment using different electrode configurations

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Abstract: Nowadays, the intensity of air pollution, due to the industries and automobiles, has been increasing continuously. Nitrogen oxides (NO\textsubscript{X}) are one of the most harmful pollutants, which are getting released from both automobile and stationary diesel engines. They essentially need to be removed from the exhaust using after treatment systems. However, the energy required to remove these pollutants is one of the major considerations in selecting the technology for pollutant removal from diesel engine exhaust. A study has been carried out on the non-thermal plasma-based NO\textsubscript{X} removal technique using various combinations of power supply units and electrode configurations. Three different electrode configurations are tested, in which two are cylindrical electrodes with diameters 3 and 5 mm, and the other one is a square electrode with a diagonal of 5 mm. A comparison is made between the results with two different pulse power supply units, PS-I: high-voltage direct current test set based and PS-II: DC–DC converter based. The square electrode with PS-II has been found to be the optimal combination, which has removed 85% of NO\textsubscript{X} from the exhaust at an energy density of 55.5 J/L, when the initial NO\textsubscript{X} concentration in the exhaust is 388 ppm.

1 Introduction

Air pollution leads to harmful effects on environment and then subsequently on human health. Conventional techniques such as selective catalytic reactor, DeNO\textsubscript{X} burners and exhaust gas recirculation have failed to bring down the level of nitrogen oxides (NO\textsubscript{X}) to mandatory limits. Experimenting with the fuel injection timing [1] and the other engine design modifications are also unable to cope up with the future stringent emission regulations, because of the highly oxidising environment inside the diesel engine [2]. To overcome the various disadvantages of these conventional techniques, an emerging technique, i.e. non-thermal plasma (NTP) is introduced by the researchers. The NTP based techniques are best known for their low energy consumption, cost-efficiency and high removal efficiency [3–6]. Various techniques such as surface discharge, pulsed corona discharge have been using since the last four decades and getting good results at laboratory level. Dielectric barrier discharge (DBD) is one of the most efficient and reliable technique, which is also known as silent discharge [7]. In this method, energy from electrical discharge is directed selectively into the production of the electrons, ions and radicals or into molecular excitation, resulting in an efficient reduction of unwanted species or pollutants. When a high voltage power supply is applied to the electrode, breakdown of the gas passing through the gap between the two electrodes occurs [8]. In this process, O species are generated and a homogenous discharge is produced with low energy consumption [9, 10]. AC and pulse energisation have been emerged as effective techniques than DC energisation for NO\textsubscript{X} reduction [11]. In case of DC energisation the average energy gained is insufficient to generate any radicals, failing to avail further oxidation and reduction inside the reactor [7]. Pulse energisation has already been proved to be the best with regards to maximum NO conversion and NO\textsubscript{X} removal efficiency [12]. Apart from the energisation, electrode shape, length and diameter are also the affecting parameters for removal efficiency. NO\textsubscript{X} removal efficiency is also said to be directly proportional to electrode diameter and length [13–17]. In this study, experiments are conducted to know optimal combination of power supply unit and electrode configuration. Results are explained with appropriate figures and comparisons among different cases considered.

2 Experimental setup

The experimental setup used in the laboratory for the proposed research work has been shown in Fig. 1 along with the explanation of its components in detail in the following subsections.

2.1 Exhaust source

The exhaust treated in the experiments has been drawn from a 7.5 kVA diesel generator set using an oil-free pump. This diesel engine is loaded electrically. Concentrations of various pollutants in the exhaust vary depending on the atmospheric conditions.

2.2 Filtering unit

The filtering unit of this experimental setup comprises of steel wool, drierite, and particulate filter. Steel wool, which is made from low carbon steel, has been used to trap the soot particles. The drierite dries the exhaust at very low pressure. During this study, non-indicating drierite, also known as regular drierite, is used. The particulate filter (EG0020) is used to remove the particulates present in the exhaust.

2.3 Measuring unit

A voltage divider (Make: IWATSU, Model: HV-P60A, DC to 50 MHz, within ±3 dB) of attenuation 2000:1 ± 5% has been used to step down the high voltage to a measurable value. It is connected to a digital storage oscilloscope (DS 1074: 70 MHz, RIGOL) to analyse the signal. The power consumption by the reactor has been measured using the two reactor principle with the help of power meter connected at supply port. In this method, the power delivered by the source would be measured twice: first time, with one reactor and then with two reactors in parallel. The discharge power would be the difference of both these measured powers, assuming that the power supply unit and converters tend to same losses for both the cases [18]. Further, a flue gas analyser (FGA 53X, Indus Scientific)
has been used for analysing the concentrations of various pollutants; it measures the concentration in ppm and percentage using infrared and electro-chemical sensors.

2.4 Plasma reactor

Plasma reactor used for this study is a hollow cylindrical borosilicate glass tube reactor. The anode electrode, made up of stainless steel, is concentric with the glass tube reactor, and the cathode is an aluminium foil, which is wrapped uniformly throughout the reactor and grounded. The electrodes used in these experiments differ in dimension and shape. The inner and the outer diameters of the reactor are 15 and 17 mm, respectively. Even though the length of the anode electrode is 335 mm, the effective discharge region is 260 mm only as the aluminium foil has been wrapped up to that much length only. Schematic diagram of plasma reactor along with the test electrodes has been shown in Fig. 2. In the three test electrodes, two are cylindrical electrodes with diameters 3 and 5 mm, viz. C-3 and C-5 mm; and the other one is square electrode with a diagonal of 5 mm, i.e. S-5 mm.

2.5 High voltage power supply

Details of the two high voltage pulse power supply units used in these experiments have been given below:

- PS-I: HVDC (high-voltage direct current) test set (0–30 kV, 20 mA), 600 VA (make: RE) connected with rotary spark gap (RSG).
- PS-II: Rectifier (230 V AC/0–25 V DC, UNOPOS) connected with zero voltage switch (ZVS) DC–DC converter and RSG.

Fig. 3a shows a picture of HVDC test set used in PS-I. This is a conventional power supply, which generates an output voltage in the range of 0–30 kV DC from 230 V, 50 Hz AC supply. The maximum output current is 20 mA. It has a ripple of <2% at maximum output current for capacitive loads. The schematic diagram of RSG, which is used to generate the high voltage pulses, has been shown in Fig. 3b. RSG consists of four hemispherical ended fixed electrodes and one hemispherical ended rotating electrode as shown in the figure. Fixed electrodes 1 and 2 are short circuited. Fixed electrode 3 is grounded. The plasma reactor is connected between the terminals 2 and 3. Pulses are generated due
to the continuous rotation of moving electrode, which is driven by a high speed motor. While rotating, moving electrode connects fixed electrodes 4 and 2 first, where the high voltage appears across the reactor, then it connects fixed electrodes 1 and 3, where a zero voltage appears across the reactor. As this process continues, pulses required for the plasma treatment would be generated. The frequency of these pulses depends on the speed of the motor and here it is maintained constant at 80 pps with both the power supply units.

Schematic diagram of PS-II is shown in Fig. 3c. Various components used in PS-II can be seen in this figure. The block diagram of PS-II has been shown in Fig. 3d. The ZVS DC–DC converter is a Mazzilli oscillator [19], in which metal–oxide–semiconductor field-effect transistors switch to ON state when they have zero voltage across them, i.e. when carrying least power. Hence, this converter is free from switching losses. Being a resonant oscillator, it runs at the resonant frequency. It also consists of an inductor in the primary side, having an inductance value four times higher than the magnetising inductance of the transformer, which increases the efficiency by acting as a current source. The output of this converter is given to RSG to generate the required pulse supply.

3 Results and discussion

The experiments are conducted at a temperature of 25°C using the setup described in Section 2. The approximate initial concentrations of various pollutants in the diesel engine exhaust (DEE) are given in Table 1. The sum of concentrations of NO and NO₂ measured individually gives the concentration of NOₓ. The DEE also contains many other pollutants: toluene, methanol, phenol, aldehydes and so on, but this study has focused on measuring NOₓ concentration only. Treatment of these gaseous pollutants in the exhaust has been done using the plasma reactor. A constant gas flow rate of 4 l/min is maintained throughout the experiments. When high voltage pulses are applied to the plasma reactor, a strong electromagnetic field is produced, which is capable of generating single-barrier nanosecond discharge. When barrier discharge takes place, it leads to the generation of O and N radicals, initially resulting in oxidation process of NO molecules present in the exhaust [4, 15] as shown in the following equations:

\[
\text{NO} + \text{O} \rightarrow \text{NO}_2; \quad k = 1.4 \times 10^{-12} \text{cm}^3/\text{s} \quad (1)
\]

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2; \quad k = 1.8 \times 10^{-14} \text{cm}^3/\text{s} \quad (2)
\]

Table 1 The initial concentration of pollutants present in DEE

| Pollutant/gas | Initial concentration |
|---------------|----------------------|
| NOₓ           | 388 ppm              |
| NO            | 368 ppm              |
| NO₂           | 20 ppm               |
| CO            | 70 ppm               |
| O₂            | 18.62%               |
| CO₂           | 1.83%                |
These two equations represent NO to NO$_2$ conversion reactions. NO reacts with O and O$_3$ to form NO$_2$ and lead to decrease in the concentration of NO and simultaneous increase in the concentration of NO$_2$. Later, when the ED is increased further, concentration of NO$_2$ also starts decreasing as more number of reactions takes place due to increased density of the radicals. Equations (3)–(6) show the reactions those help in removal of NO$_2$. Equation (3) happens when NO reacts with N radical, which results in harmless N$_2$ molecule and O radical. Equations (4)–(6) represent the reactions, which cause NO$_2$ reduction. It is to be noted from these equations that the molecules present in the exhaust after the treatment in plasma reactor are harmless in their own form. Gases such as NO$_3$, N$_2$O, N$_2$O$_4$ and N$_2$O$_5$ are not harmful compared to NO$_X$ until they again involve in chemical reactions to form NOX. There is a less possibility of decomposition of NO$_3$, N$_2$O$_4$, N$_2$O$_5$, NO$_2$O upon reactions with hydrocarbons, because the exhaust is filtered with particulate filter as well as steel wool before the plasma treatment. These reactions were very few among several possible chemical reactions those can be taken place during plasma process. Complete modelling and simulation of discharge and kinetics of plasma processes have to be done for knowing all those reactions. The chemical kinetics of the NO removal process was simulated in [20] and various probable chemical reactions those can be taken place in plasma reactor were presented along with their rate coefficients.

\begin{align}
\text{NO} + \text{N} & \rightarrow \text{N}_2 + \text{O}; \quad k = 2.1 \times 10^{-11} \text{cm}^3/\text{s} \quad (3) \\
\text{NO} + \text{O} & \rightarrow \text{NO}_2 + \text{O}; \quad k = 1.4 \times 10^{-12} \text{cm}^3/\text{s} \quad (4) \\
\text{NO} + \text{NO}_3 & \rightarrow \text{N}_2\text{O}_5; \quad k = 1.4 \times 10^{-12} \text{cm}^3/\text{s} \quad (5) \\
\text{NO} + \text{N} & \rightarrow \text{N}_2\text{O} + \text{O}; \quad k = 1.4 \times 10^{-12} \text{cm}^3/\text{s} \quad (6)
\end{align}

Results have been explained in this section considering two cases with two types of pulse power supply units. In each case, removal of NO$_X$ with respect to the electrode configuration has been discussed with one particular power supply unit. Further, comparisons have been made among all the cases considered and also with the existing literature.

### 3.1 Removal of NO$_X$ using PS-I

In this subsection, results with the PS-I consisting of HVDC test set and RSG have been explained with appropriate figures. High voltage pulses required for the plasma exhaust treatment are generated using this power supply unit with the help of RSG.

Experiments are conducted using PS-I and treated the exhaust in the plasma reactor with three types of mentioned electrodes one after the other. The maximum NO$_X$ removal efficiency with each electrode has been recorded with corresponding voltage at which it occurred. The discharge power is measured at different voltages using the single reactor principle. The power delivered by the source is measured first without connecting the reactor. Then it is measured again after connecting the reactor as the load. The discharge power is taken as the difference of the powers measured in both these cases, assuming that the power supply unit and converters are supplying power with same losses in both the cases.

The instantaneous power consumption in plasma reactor is inversely proportional to the discharge gap length, assuming all the losses as negligible. The electrode diameter and discharge power are directly proportional to input voltage. Thus, the electric field intensity is inversely proportional to discharge gap length [13, 14]. It can be calculated using the equation below:

\[ E_g = \frac{V}{\ln((r_d/r_i)) - \left((\epsilon_d - \epsilon_g)/(\epsilon_d/\epsilon_g)\right)(l_g/l_{di})} = \frac{V}{l_g} \quad (7) \]

Here $\epsilon_d$ and $\epsilon_g$ are dielectric constants of dielectric barrier layer and gap, respectively, $r_i$ is radius of high voltage electrode, $r_d$ and $r_{di}$ are inner and outer radii of dielectric barrier layer, respectively, $l_g$ is dielectric thickness ($l_g = r_d - r_i$), $l_{di}$ is discharge gap length ($l_{di} = r_{di} - r_i$) and $V$ is the input voltage.

From (7), it can be said that, electric field intensity increases with the decrease in discharge gap length, i.e. with the increase in electrode diameter. Higher electric field intensity causes more number of chemical reactions to take place. So, removal efficiency is also higher for the electrodes having a higher diameter. However, edge effects, which also cause increase in the electric field intensity, have been ignored in this formula. Further, energy density (ED), NO and NO$_X$ removal efficiencies are calculated using the following equations:

\[ \text{ED (J/L)} = \frac{\text{Discharge power (W)}}{\text{Flow rate (l/s)}} \quad (8) \]

\[ \text{NO removal efficiency} = \frac{C_{\text{in,NO}} - C_{\text{out,NO}}}{C_{\text{in,NO}}} \times 100 \quad (9) \]

\[ \text{NO}_X \text{ removal efficiency} = \frac{C_{\text{in,NO}_X} - C_{\text{out,NO}_X}}{C_{\text{in,NO}_X}} \times 100 \quad (10) \]

Here $C_{\text{in}}$ and $C_{\text{out}}$ terms represent the concentrations of pollutants mentioned as their suffixes at inlet and outlet of plasma reactor, respectively.

Fig. 4a shows the nanosecond high voltage pulse output of PS-I. The rise time is found to be <25 ns. The discharge powers are measured as 12.66, 16.42 and 16.84 W for the test electrodes C-3, C-5 and S-5 mm, respectively, at an input voltage of 30 kV. It can be stated from (7) that the electric field increases as the discharge gap decreases. Discharge gap would be lesser when an electrode with larger diameter is used. Thus, test electrodes C-5 and S-5 mm resulted in higher discharge powers than C-3 mm as shown in Fig. 4b.

Fig. 5a shows the variation in concentrations of NO and NO$_2$ with respect to ED. As said earlier, during the treatment of the exhaust, very high energetic electric field is produced in the reactor. It can be observed from the figure that the concentration of NO has been decreased, while that of NO$_2$ has been increased with the increase in applied voltage. The oxidation reactions those took place in the plasma reactor due to the electric field causes NO to NO$_2$ conversion as shown in (1) and (2). In this case, S-5 mm has taken comparatively smaller ED for complete removal of NO compared to other two test electrodes. However, all the three test electrodes have shown 100% removal or conversion of NO, as NO$_2$ concentration has increased significantly. Even though there is no NO present in the exhaust, the concentration of NO$_2$ is increased further with the increase in ED. Increased intensity of single-barrier nanosecond discharge due to increase in ED causes further reactions to take place with the N, O molecules those are still present in the reactor, resulting in formation of NO$_2$.

The NO removal efficiency with its corresponding ED for the three electrode configurations considered has been plotted and shown in Fig. 5b. It can be seen from this figure that the increase in the ED accelerates the NO conversion reactions. Fig. 5c shows the variation in NO$_X$ removal efficiency with respect to ED. While plotting this graph, results beyond an ED of 160 J/L have not been taken into consideration as the NO$_X$ removal efficiency decreased with the increase in ED. This is because of the increase in the concentration of NO$_2$ as discussed earlier. In this case, S-5 mm has shown the maximum NO$_X$ removal efficiency among the three test electrodes, i.e. 82% at an ED of 144.15 J/L.

A comparison has been made among the test electrodes with respect to their maximum NO and NO$_X$ removal efficiencies as shown in Fig. 6. The maximum NO$_X$ removal efficiency of 81% is achieved with C-3 mm at an ED of 155.1 J/L. C-5 mm has shown better performance compared to C-3 mm achieving a maximum NO$_X$ removal efficiency of 86% at an ED of 111 J/L. However, S-5
mm has proven to be best in this case, achieving 100% NOX removal efficiency at an ED of 144.5 J/L. Thus, it can be said that S-5 mm shows better performance towards achieving maximum NO and NOX removal efficiencies when compared to the other two test electrodes. This is because of its capability to attain more intensified electric field at a lesser input voltage. The surface of the electrode also plays an important role in its performance. As the square electrode consists of edged surface, probability of particle collision increases, which tends to intensify the plasma reactions.

3.2 Removal of NOX using PS-II

In PS-II, a rectifier set is used to feed ZVS DC–DC converter. The output of this converter has been fed to RSG to generate the high voltage pulses. This results in highly concentrated energetic electric field [21]. The energy generated by this field is sufficient to obtain the perfect single-barrier nanosecond discharge inside the plasma reactor. Fig. 7a shows the nanosecond high voltage pulse output of PS-II. The rise time is found to be <12 ns. This low rise time denotes the faster response of the system. Fig. 7b shows the variation in discharge power with respect to the voltage applied to the plasma reactor. The power consumption inside the plasma reactor is found to be inversely proportional to the discharge gap.
Fig. 8 Experimental results with PS-II
(a) Variation in concentrations of NO and NO\textsubscript{2} with respect to ED when PS-II is used,
(b) NO removal efficiency with respect to ED when PS-II is used,
(c) NO\textsubscript{X} removal efficiency with respect to ED when PS-II is used

has achieved a NO\textsubscript{X} removal efficiency of 85% at an ED of just 55.5 J/L. C-3 mm and C-5 mm have also achieved NO\textsubscript{X} removal efficiencies of 86 and 84%, respectively, but at comparatively higher SEs of 100.5 and 79.05 J/L, respectively.

3.3 Comparison among the two power supply units

Experiments have been conducted at ambient temperature and pressure, with a constant gas flow rate of 4 l/min, considering various combinations of power supply units and test electrodes. A comparison has been made among all the cases considered in this study and shown in Table 2. Energy cost per one NO or NO\textsubscript{X} molecule has also been mentioned in this table along with the NO and NO\textsubscript{X} removal efficiencies. This energy cost has been calculated using the following equations:
Energy cost/mol(eV/mol) = \frac{P \times 6.25 \times 10^{18} \text{eV/s}}{\text{Number of molecules removed}} \quad (11)

\text{Number of molecules removed} = \eta \times C_i \times 10^{-6} \times R \times J \quad (12)

Here, \(P\) is the discharge power, \(\eta\) is molecule removal efficiency, \(C_i\) is initial concentration of the molecule in ppm, \(R\) is flow rate in l/s and \(J\) is the molecule density in mol/l. First, the number of molecules removed has been calculated using (12) based on its relation with removal efficiency. Then, using (11), energy consumed for removing each pollutant molecule from the exhaust has been calculated in eV.

It has already been mentioned that removal efficiency is improved with the increase in electrode diameter. Hence, C-5 mm performs better than C-3 mm, which can be seen in this table; C-5 mm requires smaller energy compared to C-3 mm. When comes to the shape, S-5 mm can be said to be superior in performance in terms of \(\text{NO}_X\) removal efficiency. Among the power supply units used, performance of PS-II is superior in terms of maximum \(\text{NO}_X\) and \(\text{NO}_X\) removal efficiencies as well as energy efficiency.

It can also be noted that the S-5 mm with PS-II is the best among all combinations, with 85% \(\text{NO}_X\) removal efficiency at an energy cost of 58.15 eV/\(\text{NO}_X\) mol. The major difference between the outputs of both the pulse power supply units is nothing but their respective rise times. The rise time of the output of PS-I is found to be <25 ns, whereas that of PS-II is <12 ns. The unit, which generates pulses with lesser rise time, is able to achieve more \(\text{NO}_X\) removal efficiency at a smaller ED [22]. Thus, PS-II performed better than PS-I in this study. Further, the results of this study have been compared with the previous literature and shown in Table 3.

Equipment or components used to generate high voltage pulses in their respective studies have been mentioned in Table 3 along with the electrode configurations tested. In this study, maximum \(\text{NO}_X\) removal efficiency is achieved at smaller ED when compared to other studies considered. Energy costs have also been mentioned for those studies in which the data is available. Gas temperature was maintained at 260°C for the study mentioned in [24] and thus the energy cost is just 30 eV/\(\text{NO}_X\) mol. A significant difference in the energy cost for this study can be observed with the remaining studies.

4 Conclusion

This research work is a study to know the best combination of pulse power supply unit and electrode configuration for the efficient removal of \(\text{NO}_X\) from DEE using NTP-based DBD at the laboratory level. Experiments are carried out with a purpose of understanding the possibility of using the method in automobile vehicles. Results have shown that the PS-II has achieved maximum \(\text{NO}_X\) removal efficiency at a smaller ED when tested with S-5 mm. It can be noted from this that the low voltage DC powered high voltage pulse power system is good enough to get better results than the unit containing with HVDC test set and RSG. The reason for this is the lesser rise time of PS-II compared to that of PS-I. PS-II is also less expensive than the PS-I. Among the electrode configurations considered, S-5 mm has shown better performance because of the intensified electric field due to the sharp edges of the square electrode. Thus, it can be concluded that the combination of PS-II and S-5 mm is efficient in terms of energy consumption for removing pollutants, which has shown 85% \(\text{NO}_X\) removal efficiency at an ED of just 55.5 J/L. Results are also compared with previous studies and can be said as higher \(\text{NO}_X\) removal efficiencies are achieved at smaller ED consumptions.

### Table 2 Comparison among all the cases considered

| Power supply unit | C-3 mm | C-5 mm | S-5 mm |
|-------------------|--------|--------|--------|
|                   | DeNOa, %/eV/NO | DeNOXb, %/eV/NO | DeNOa, %/eV/NO | DeNOXb, %/eV/NO | DeNOa, %/eV/NO | DeNOXb, %/eV/NO |
| PS-I              | 100/179.85 | 69/182.45 | 100/125.93 | 74/111.74 | 100/167.15 | 82/155.30 |
| PS-II             | 100/86.79 | 86/103.72 | 100/88.18 | 84/79.92 | 100/64.35 | 85/58.15 |

\(a\)DeNO (%) is \(\text{NO}_X\) removal efficiency.  
\(b\)DeNOX (%) is \(\text{NO}_X\) removal efficiency.
Table 3: Comparison of maximum NO\textsubscript{X} removal efficiencies achieved with some of the previous studies with pulse power

| S. no. | Author name and year of publication | Source of exhaust/plasma reactor type/adsorbents/catalysts used | Equipment/ components used to generate pulses | Electrode configuration | Gas flow rate, l/min | Peak voltage, frequency | Initial NO\textsubscript{X} concentration, ppm | Energy cost, eV/NO\textsubscript{X}, mol | ED, J/L | Maximum NO\textsubscript{X} removal efficiencies achieved, % |
|-------|-----------------------------------|---------------------------------------------------------------|---------------------------------------------|------------------------|---------------------|----------------------|-----------------------------------------------|---------------------------------|--------|-------------------------------------------------|
| 1     | Khacel et al., 2002 [24]          | synthetic exhaust gas, DBD reactor, catalyst, adsorbent       | cable transformer and high voltage ceramic capacitors | tungsten wire, 0.5 mm diameter | 16                  | 20 kV, 200 Hz        | 520                                           | 30                                             | 27     | 43                                              |
| 2     | Srinivasan and Rajanikanth 2007 [25] | simulated diesel exhaust, surface discharge reactor, adsorbent | 25 kV pulse power source                   | stainless steel rod, 1 mm thickness | 4                   | 25 kV, 130 pps       | 220                                           | —                                              | 150    | 88                                              |
| 3     | Yoshida et al. 2008 [26]          | high voltage pulse generator (PPCP Pulsar SMC-30/1000)       | high voltage transformer, rectifier, charging capacitor and RSG | stainless steel rod, 1 mm thickness | 1                   | 35 kV, 420 Hz        | 2000                                          | —                                              | 1440   | 80                                              |
| 4     | Srinivasan et al. 2009 [11]       | DEE, DBD reactor, catalyst, adsorbent                        | static induction semiconducting switches    | stainless wire, 1.5 mm diameter | 2                   | 31.6 kV, 530 Hz      | 350                                           | —                                              | 97     |                                                  |
| 5     | Okubo et al. 2010 [27]            | DEE, packed bed DBD reactor, catalyst                        | static induction semiconducting switches    | stainless wire, 1.5 mm diameter | 2                   | 12 kV, 2000 pps      | 158                                           | —                                              | 54     | 45                                              |
| 6     | Wedaa et al. 2011 [28]            | simulated gas, DBD reactor, catalyst                         | pulse generator (ECG-KOKUSAI model PPS-5000) | stainless wire, 0.2 mm diameter | 5                   | 25 kV, 75 pps        | 130                                           | 1120                                           | 500    | 86                                              |
| 7     | Mohapatro et al., 2011 [7]        | DEE, cross-flow DBD reactor, adsorbent                       | stepping transformer, diode rectifier unit, smoothing capacitor and RSG | straight wire, 0.5 mm thickness | 2                   | 30.4 kV, 80 Hz       | 380                                           | 510                                            | 445    | 55                                              |
| 8     | Bhattacharyya et al., 2013 [16]   | DEE, DBD reactor, catalyst, adsorbent                        | solid state switches, IGBT system and magnetic switches | straight wire, 0.5 mm thickness | 2                   | —, 80 Hz            | 250                                           | 150                                            | 38     |                                                  |
| 9     | Mohapatro and Bhattacharyya 2015 [23] | DEE, cross-flow DBD reactor, adsorbent                        | low voltage DC supply, ZVS flyback transformer and RSG | straight wire, 0.5 mm thickness | 2                   | 25 kV, 85 pps        | 316                                           | —                                              | 570    | 95                                              |
| 10    | present study                     | DEE, DBD reactor, catalyst, adsorbent                        | HVDC test set and RSG                      | C-3 mm, C-5 mm, S-5 mm, C-3 mm, C-5 mm, S-5 mm | 4                   | 28.8 kV, 80 pps      | 388                                           | 182.45                                         | 155    | 69                                              |

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