NO\textsubscript{X} abatement from filtered diesel engine exhaust using battery-powered high-voltage pulse power supply

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Abstract: The dielectric barrier discharge-based non-thermal plasma technique is one of the most prominent techniques which give peerless results in controlling the concentration of NO\textsubscript{X}. However, when it comes to the automobile diesel engine, availability of high-voltage pulse power supply is the major constraint. In this study, battery-powered high-voltage pulse power supply for NO\textsubscript{X} treatment has been proposed. Two types of electrodes: rod type and rod with helical spring type are studied for the treatment of exhaust. Cascaded plasma-adsorbent technique has also been used to enhance NO\textsubscript{X} removal efficiency. Experiments have been conducted with two different gas flow rates, i.e. 4 l and 6 l/min at laboratory level and have got significant results toward removal of NO\textsubscript{X}. When the exhaust has been treated with plasma alone, the reactor with rod-type electrode has shown 85\% NO\textsubscript{X} removal efficiency at a specific energy (SE) of 283 J/l with a flow rate of 4 l/min. When the plasma reactor is cascaded with the adsorbent reactor, both adsorbents: 13x molecular sieve (MS13x) and activated alumina are able to remove 100\% of NO\textsubscript{X} with the proposed power supply at a lesser SE.

1 Introduction

Controlling diesel pollution has become one of the utmost public priorities as diesel exhaust has been presenting major health hazards from the past several years. On the other hand, world diesel engine demand is growing continuously. Diesel engines produce significant amount of NO\textsubscript{X}, which is a harmful air pollutant that constitutes a unique challenge with regard to its reduction. With increased emission standards, there is a strong need for research in controlling NO\textsubscript{X} in the diesel engine emission. Even though there have been different NO\textsubscript{X} reduction techniques, they have not succeeded in limiting the NO\textsubscript{X} completely. Various researchers throughout the globe are investigating the removal of NO\textsubscript{X} from diesel engine exhaust, experimenting with variations in power supply, flow rate, exhaust concentration, temperature, electrode and reactor configurations.

A multipoint-to-plane geometry is proposed as an alternative to parallel plane electrode by Takaki et al. [1] to lower the operating voltage. The power supply used in this paper was composed of rectifier circuits, insulated gate bipolar transistor and pulse transformers. However, the NO\textsubscript{X} in the diesel generator gas exhaust has been reduced up to 10% only with an electrical efficiency of 28 g/kWh. Characteristics of ferro-electric barrier discharge were investigated experimentally by Kawada et al. [2] for the electrode arrangements of wire-rod and wire-quadrupole. The results of this paper proved that a slight decrease in discharge current takes place in each electrode configuration when the corona wire is covered with barium titanate sheath. Another study was carried out by Srinivasan and Rajanikanth [3] using a 25 kV pulse source and investigated experimentally by Kawada and co-workers [4] for the electrode arrangements of cross-flow dielectric barrier discharge. The results of this paper prove that with an increase in discharge current, the NO\textsubscript{X} concentration decreases.

2 Experimental set-up

Experimental set-up used for this present paper has been shown in Fig. 1. Various components of this set-up have been explained in the following sections.

2.1 Source of exhaust, particulate filter, flow controller and gas analyser

A 5 kVA diesel generator set has been used as the source for the exhaust to conduct this experiment. A portion of the exhaust from it has been drawn using an oil-free pump for conducting this experiment. This raw exhaust has been made to pass through a steel wool to remove soot and oil mist before passing through a particulate filter, where the PM along with the moisture content has been removed. Here, a 5 μm particulate filter (make: Ultrafilter; model: EG0200) has been used for this purpose. Flow controller has been used to make this filtered exhaust go with a desired rate of flow before entering the reactor chamber. The exhaust has been made to pass through the gas analyser (make: Indus Scientific; model: FGA-53) after the treatment in reactors, which measures various pollutants, not only NO\textsubscript{X}, but also CO, CO\textsubscript{2} and HCs present in the processed exhaust either in parts per million or in percentage.
2.2 High-voltage pulse generation

High-voltage pulses needed for the reactor process have been generated using a series of equipment as shown in Fig. 1. Schematic diagram of the battery-powered nanosecond high-voltage power supply has been shown in Fig. 2. A 150 W boost converter of input range 10–32 and 12–35 V variable output is connected to the 12 V battery to increase the voltage level to 24 V. This combination is connected to a flyback transformer through a Mazzilli converter. The Mazzilli converter is a derivative of L-C MOS oscillator and Royer oscillator, made to perform better than those two. It overcomes the voltage limitations of L-C MOS by using a combination, pulling power from the supply, yet cross-coupling the gates through a diode to the opposite drain. It operates faster than Royer as it has metal–oxide–semiconductor field-effect transistors instead of bipolar junction transistors (BJTs). This Mazzilli converter self-oscillates at the L-C oscillation frequency.

Flyback transformer is used to step up the voltage level to a high-voltage which is then applied to the RSG. This RSG, which consists of a moving electrode, has been made to rotate with the help of an external motor to generate high-voltage pulses. The frequency of these pulses depends on the rotational speed of the motor, which is operated by AC supply. In the present paper, the high voltage is stepped down to a measurable value using a voltage divider (make: IWATSU, model: HV-P60A, DC to 50 MHz, within −3 dB) of attenuation 2000:1 ± 5%. A digital storage oscilloscope (make: RIGOL; model: DS 1074: 70 MHz) is connected to analyse the signal. The frequency of the pulse output is observed to be varying from 88 to 92 Hz and the rise time, from 12 to 20 ns. The nanosecond high-voltage pulses generated here have been shown in Fig. 3, when the plasma reactor is connected as the load. These pulses are then applied to the plasma reactor for the removal of NO\textsubscript{X}. Fig. 4 shows the variation of power consumed by the plasma reactor with rod-type electrode (RTE) and rod with helical spring (RHTE) with respect to DC input voltage from the boost converter. Fig. 4 also shows the corresponding output voltages in kilovolts across both these reactors at different DC input voltages.
2.3 Plasma and adsorbent reactors

Diesel exhaust, with the desired flow rate, has been made to pass through the plasma reactor first and then adsorbent reactor, which have been shown in Figs. 5a and 5d, respectively. The plasma reactor used here is made up of glass with a wall thickness of 3 mm and inner diameter of 15 mm. The discharge length is limited to 28 cm. Experiments have been conducted using two types of electrodes as mentioned before. First electrode is RTE with a rod of 4 mm diameter and the second is RHTE with a rod of 4 mm diameter having a helical spring wound on it. These electrodes have been shown in Figs. 5b and 5c. Adsorbent reactors with two different adsorbent pellets, i.e. MS13x and alumina (Al₂O₃) have been cascaded separately with plasma reactors. These cascaded plasma and adsorbent reactors, with two different electrodes, are tested one after the other, to know a better combination with respect to the NOₓ removal efficiency and the specific energy (SE).

3 Exhaust treatment

Initial concentrations of various pollutants present in diesel engine exhaust have been given in Table 1. The concentration of NOₓ is the sum of the concentrations of NO and NO₂ measured individually. Despite the pollutants mentioned, there are different types of hydrocarbons: aldehydes, methanol, phenol, toluene etc., also present in the exhaust which is not measured as the objective of this present paper is restricted to the NOₓ removal only. High-voltage pulses have been applied to the high-voltage electrode present in the plasma reactor while the ground electrode is connected to common ground terminal. The applied voltage has been increased gradually and when it crosses the minimum breakdown voltage, micro-discharges start to take place. High energetic electrons generated in this process react with the gas molecules, which are passing through the reactor. Thus, the production of various radicals takes place in the plasma environment causing several numbers of chemical reactions to take place in the reactor [13]. Some of the reactions those that take place in the plasma reactor [6] have been mentioned in equations (1) to (11) along with their corresponding rate constants (k).

NO–NO₂ conversion reactions involving O/O₃/NO₃ radicals

\[ O_2 + e \rightarrow O + O + e; \quad k = 1.1 \times 10^{-12} \text{ cm}^3/\text{s} \]  
(1)

\[ NO + O \rightarrow NO_2; \quad k = 1.4 \times 10^{-12} \text{ cm}^3/\text{s} \]  
(2)

\[ O_2 + O \rightarrow O_3; \quad k = 1 \times 10^{-14} \text{ cm}^3/\text{s} \]  
(3)

\[ NO + O_3 \rightarrow NO_2 + O_2; \quad k = 1.8 \times 10^{-14} \text{ cm}^3/\text{s} \]  
(4)

\[ NO + NO_2 \rightarrow NO_2 + NO; \quad k = 1.5 \times 10^{-11} \text{ cm}^3/\text{s} \]  
(5)

NO reduction reactions

\[ N_2 + e \rightarrow N + N + e; \quad k = 3.0 \times 10^{-16} \text{ cm}^3/\text{s} \]  
(6)

\[ NO + N \rightarrow N_2 + O; \quad k = 2.1 \times 10^{-10} \text{ cm}^3/\text{s} \]  
(7)

NO₂ conversion reaction

\[ NO_2 + O \rightarrow NO + O_2; \quad k = 1 \times 10^{-11} \text{ cm}^3/\text{s} \]  
(8)

\[ NO_2 + O_3 \rightarrow NO_3 + O_2; \quad k = 1.4 \times 10^{-12} \text{ cm}^3/\text{s} \]  
(9)

\[ NO_2 + NO \rightarrow N_2O_5; \quad k = 1.4 \times 10^{-12} \text{ cm}^3/\text{s} \]  
(10)

Table 1 Initial concentrations of various components present in the diesel exhaust

| Pollutant/gas | Concentration |
|--------------|--------------|
| NOₓ          | 290 ppm      |
| NO           | 255 ppm      |
| NO₂          | 35 ppm       |
| CO           | 1348 ppm     |
| O₂           | 16.2%        |
| CO₂          | 0.1%         |

Fig. 4 Variation of power fed and output across the reactor for different DC input voltage

Fig. 5 Reactors and electrodes
(a) Plasma reactor, (b) RTE, (c) RHTE, (d) Adsorbent reactor
Initial NO concentration − final NO concentration

DeNO efficiency (%) = \frac{\text{initial NO concentration} - \text{final NO concentration}}{\text{initial NO concentration}} \times 100

DeNO\text{X} efficiency (%) = \frac{\text{initial NO}_X\text{ concentration} - \text{final NO}_X\text{ concentration}}{\text{initial NO}_X\text{ concentration}} \times 100

4 Results and discussion

The results of the experiments carried out at laboratory level during the present paper have been discussed in this section. These experiments have been conducted at 25°C for two different flow rates, i.e. 4 and 6 l/min.

4.1 Case 1: performance of plasma reactor with RTE for NO\text{X} removal

Change in the concentrations of NO and NO\text{2} in the plasma reactor with RTE with the SE under pulse energisation with the flow rates of 4 and 6 l/min has been shown in Fig. 6. It can be said from this figure that NO reduces continuously with both the flow rates; even reduces to zero with the flow rate of 4 l/min. The fact is that a portion of NO gets converted to NO\text{2} as a result of chemical reactions leading to an increase in NO\text{2} concentration. However, the concentration of NO\text{2} also starts reducing when the SE is increased beyond a certain level. In this case, electric field intensity in the reactor chamber increases, and thus the number of chemical reactions that take place would increase further, causing NO reduction and NO\text{2} conversion reactions. So, the concentration of NO\text{2} first increases and then decreases, which can be seen in Fig. 6.

DeNO\text{efficiency of plasma reactor with RTE, which has reached 100% with both the flow rates, has been shown in Fig. 7a. However, when the flow rate is increased, the plasma reactor would accommodate the exhaust for comparatively less time leading to a lesser NO removal efficiency. Even though the SE needed is comparatively less with the flow rate of 6 l/min as shown in Fig. 7a, the reactor needs more power input to achieve 100% DeNO\text{efficiency when compared with that with 4 l/min. About 100% DeNO\text{efficiency is achieved at 16.5 W when the flow rate is 4 l/min, whereas it is at 18.3 W when the flow rate is 6 l/min. Conversion of NO--NO\text{2} is also a reason for the 100% DeNO\text{efficiency.}

This also affects DeNO\text{X}\text{efficiency, which has been shown in Fig. 7b; no much increase takes place till a certain SE. Then, a sudden increase in DeNO\text{X} efficiency can be seen in this figure, e.g. at 228 J/l from 28.28 to 58.96% with the flow rate of 4 l/min, which might be due to the non-uniform field distribution in the reactor. A maximum efficiency of 85% is achieved with the flow rate of 4 l/min, but only 58% with the flow rate of 6 l/min at SE densities of 283 and 189 J/l, respectively. So, it can be said that the maximum DeNO\text{X} efficiency achieved is decreased with an increase in flow rate. However, by that instant the DeNO\text{X} efficiency reached 58% efficiency with the flow rate of 6 l/min, the applied voltage has already reached its maximum value, i.e. 29.6 kV and the power drawn by the reactor is 19 W. At this same power consumption, the DeNO\text{X} efficiency is 85% with the flow rate of 4 l/min.

4.2 Case 2: performance of plasma reactor with RHTE for NO\text{X} removal

Change in the concentrations of NO and NO\text{2} in the plasma reactor with RHTE with the SE has been shown in Fig. 8. It can be seen from this figure that NO reduces continuously and even comes to zero with both the flow rates at almost same SE, i.e. just after 150 J/l. When compared with the previous case, i.e. plasma reactor with RTE, the SE required to reduce the concentration of NO to zero is very less regardless of the flow rates. When comes to the concentration of NO\text{2}, it increases first due to the NO--NO\text{2} conversion, and then starts decreasing after a certain level of SE. Interestingly, it again starts increasing even when there is no NO at all in the exhaust. This might be happening because of the presence of other N, O radicals in the exhaust. Owing to this, the concentration of NO\text{2} has been decreased up to some extent, i.e. 188 ppm when the flow rate is 4 l/min and 209 ppm when the flow rate is 6 l/min.

DeNO\text{efficiency of plasma reactor with RHTE, which also has reached 100% with both the flow rates, has been shown in Fig. 9a. DeNO\text{X} efficiency, which has been shown in Fig. 9b, is less compared with that with RTE; a maximum efficiency of 36% is achieved with the flow rate of 4 l/min.
4.3 Case 3: performance of adsorbent reactors for NO\textsubscript{X} removal

In this case, the performance of adsorbent reactors with two different adsorbents MS13x and Al\textsubscript{2}O\textsubscript{3}, when they are operated alone, has been analysed. Change in the concentrations of NO and NO\textsubscript{2} in MS13x adsorbent reactor with time has been shown in Fig. 10a. The concentrations of NO and NO\textsubscript{2} are reduced to a minimum of 148 and 5 ppm, respectively, with the flow rate of 4 l/min. Change in the concentrations of NO and NO\textsubscript{2} in Al\textsubscript{2}O\textsubscript{3} adsorbent reactor with time has been shown in Fig. 10b. The concentrations of NO and NO\textsubscript{2} are reduced to a minimum of 215 and 11 ppm, respectively, with the flow rate of 4 l/min and then remained constant for a while and again started increasing slowly. These slight increases at the end are because of the oxidation processes in the reactor. When it is with 6 l/min, the reduction is a little lesser than that with 4 l/min. However, it can be said that there is no much reduction in the NO\textsubscript{X} concentrations with any of these adsorbent reactors, but comparatively the reduction is better with MS13x adsorbent reactor. This is because of the internal surface area and pore size of the adsorbent material. The data corresponding to these two parameters for the two adsorbents considered in this paper has been tabulated in Table 2. As the pore size of Al\textsubscript{2}O\textsubscript{3} is too large (30–1000\textdegree), with relatively lesser internal surface area, it does not allow Van der Waal collisions to occur, resulting in a lesser adsorption compared with that observed with MS13x [6].

DeNO\textsubscript{X} efficiencies of both adsorbent reactors have been plotted with time and shown in Fig. 11. It can be seen from this figure that the maximum DeNO\textsubscript{X} efficiency achieved by the MS13x adsorbent reactor is 49% with the flow rate of 4 l/min. Similarly, the maximum DeNO\textsubscript{X} efficiency achieved by Al\textsubscript{2}O\textsubscript{3} adsorbent reactor is 23% with the flow rate of 4 l/min. This shows that the adsorbent reactors alone are not so effective in NO\textsubscript{X} removal when compared with those cases when these are cascaded with plasma reactors. So, it can be understood that the exhaust should be treated in plasma reactor first by applying high-voltage...
pulses to reduce the NO\textsubscript{X} concentration to the maximum possible extent, and then sending it through adsorbent reactor gives provision to remove the NO\textsubscript{X} completely.

4.4 Case 4: performance of cascaded plasma and adsorbent reactors for NO\textsubscript{X} removal

The plasma-treated exhaust contains more amount of NO\textsubscript{2} compared with NO. Thus, it will have less DeNO\textsubscript{X} efficiency and more DeNO\textsubscript{X} efficiency. To improve the DeNO\textsubscript{X} efficiency, adsorbents such as MS13x and Al\textsubscript{2}O\textsubscript{3} are being used here in this present work in cascading with plasma reactor. The results of these experiments have been discussed in the following sections.

4.4.1 Plasma reactor with RTE cascaded with adsorbent reactors: DeNO\textsubscript{X} efficiencies, when the plasma reactor with RTE has been cascaded with adsorbent reactors MS13x and Al\textsubscript{2}O\textsubscript{3} have been plotted with respect to SE and shown in Fig. 12a. It can be seen from this figure that 100% DeNO\textsubscript{X} efficiency has been achieved with both the adsorbents and with both the flow rates considered. However, a significant difference in SE required for getting 100% DeNO\textsubscript{X} efficiency can be observed with respect to the adsorbent type.

When the MS13x adsorbent reactor is cascaded, NO\textsubscript{X} has totally been removed at an SE of 216 J/l with the flow rate of 4 l/min. However, it is just 90 J/l of SE with the flow rate of 4 l/min when it is cascaded with Al\textsubscript{2}O\textsubscript{3} adsorbent reactor. The reasons for

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**Table 2** Surface area and pore size of the adsorbents

| Adsorbents | Surface area, m\textsuperscript{2}/g | Pore size, Å |
|------------|----------------------------------|-------------|
| MS13x      | 400–800                          | 10          |
| Al\textsubscript{2}O\textsubscript{3} | 100–300                          | 30–1000     |

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**Fig. 10** Variations of NO and NO\textsubscript{2} in adsorbent reactors with MS13x with respect to time

(a) Adsorbent reactors with MS13x, (b) Adsorbent reactors with Al\textsubscript{2}O\textsubscript{3}

**Fig. 11** DeNO\textsubscript{X} efficiencies of both adsorbent reactors with respect to time

**Fig. 12** DeNO\textsubscript{X} efficiency in plasma reactor cascaded with adsorbent reactors under pulse energisation

(a) With RTE, (b) With RHTE
better performance of the MS13x adsorbent reactor when operating alone have already been mentioned in the previous section, i.e. due to its lesser pore size. However, it can be observed from here that Al$_2$O$_3$ adsorbent reactor is performing better than MS13x adsorbent reactor when they are cascaded with plasma reactors with both the flow rates. As said earlier, due to the oxidation reactions those took place in plasma reactor, most of the NO would get converted to NO$_2$. So, the exhaust that is entering the adsorbent reactor would be rich in NO$_2$. As the molecular weight of NO$_2$ is larger than NO, Al$_2$O$_3$ adsorbents perform better than MS13x adsorbents here due to their larger pore size.

### 4.4.2 Plasma reactor with RHTE cascaded with adsorbent reactors

DeNO$_X$ efficiency, when the plasma reactor with RHTE has been cascaded with adsorbent reactors MS13x and Al$_2$O$_3$ have been plotted with respect to SE and shown in Fig. 12b. It can be seen from this figure that in this case also 100% DeNO$_X$ efficiency has been achieved with both the adsorbents with both the flow rates considered as in the previous case. When the MS13x adsorbent reactor is cascaded, NO$_2$ has totally been removed at an SE of 72 J/l with the flow rate of 4 l/min, and when it is Al$_2$O$_3$ adsorbent reactor the SE required is 94 J/l.

Maximum DeNO$_X$ efficiencies achieved for all the cases considered in the present paper with both exhaust flow rates are tabulated in Table 3 along with the power consumption by the reactor at that instance. The corresponding DeNO efficiency at the same power consumption has also been mentioned. About 100% DeNO$_X$ efficiency has been achieved with all four sub-cases of the case 4 when the plasma reactor is cascaded with adsorbent reactors. Comparatively less power consumption has taken place, i.e. 4.8 W, when the plasma reactor with RHTE is cascaded with MS13x adsorbent reactor with the flow rate of 4 l/min. When the flow rate is 6 l/min, lesser power consumption is 7.5 W for the plasma reactor with RHTE cascaded with Al$_2$O$_3$ adsorbent reactor. The negative percentage values of change in NO$_2$ indicate the increase in NO$_2$ concentration compared with the initial value, at the same power input to the reactor, where the maximum DeNO$_X$ efficiency takes place. Similarly, positive percentage values indicate a decrease in the NO$_2$ concentration, thus 100% indicates total removal of the NO$_2$. From this table, it can be said that the best combination among the considerations is the plasma reactor with RHTE cascaded with the adsorbent reactor containing MS13x with a flow rate of 4 l/min. Furthermore, a comparison with previous studies has been provided in Table 4 with respect to maximum DeNO$_X$ efficiencies achieved. The studies, in which pulse power supply was used, have only been considered here. It can be observed from this table that more DeNO$_X$ efficiency can be achieved when more SE is spent during the plasma treatment. It can also be understood that the DeNO$_X$ efficiency can be increased further by cascading the plasma reactor with the adsorbent or catalytic reactors. In the present paper, as the plasma reactor is provided with sufficient SE and also cascaded with adsorbent reactor, 100% DeNO$_X$ efficiency has been achieved.

### 5 Conclusion

This paper described the treatment of NO$_X$ from diesel engine exhaust using a battery-powered nanosecond high-voltage power supply. Here, the power supply is fabricated aiming for retrofitting to automobile vehicle. Results have been discussed with appropriate figures showing the variation of NO and NO$_2$, DeNO and DeNO$_X$ efficiencies with respect to specific energies under pulse energisation for four different cases, with variation in electrodes used and type of adsorbent. Out of the two electrodes used in the present paper, the RITE showed a better performance than RHTE when exhaust is treated with plasma alone. The plasma reactor with RHTE showed better performance compared with RITE when the exhaust was treated with cascaded plasma-adsorbent reactors.

It is observed that with the increase in exhaust flow rate, the removal efficiency decreases at the given power input to the reactor. The best combination of electrode and adsorbent has been found to be RHTE with MS13x. However, 100% NO$_X$ was removed using cascaded plasma-adsorbent technique with both the electrodes at a lesser power input with the newly built power supply compared with previous studies. The power supply proposed in this paper may perform better also for a higher exhaust flow rate with a proper scaling of the reactor.
Table 4  Comparison with previous studies with pulse power supply with respect to maximum DeNO\textsubscript{X} efficiencies achieved

| Sl. no. | Author name and year of publication | Source of exhaust/plasma reactor type | Adsorbents/catalysts used | Gas flow rate, l/min | Peak voltage, kV | Frequency, SE, J/l | Maximum DeNO\textsubscript{X} efficiencies achieved, % |
|--------|-------------------------------------|-------------------------------------|--------------------------|---------------------|-----------------|------------------|---------------------------------------------|
| 1      | Puchkarev et al. [14]               | diesel engine exhaust, corona reactor | —                        | 240                 | 49              | 1 kHz            | 3                                          |
| 2      | Takaki et al. [1]                   | diesel engine exhaust, DBD reactor  | —                        | 1.2                 | 10              | 2000 pps         | 10                                         |
| 3      | Khacef et al. [13]                  | synthetic exhaust gas, DBD reactor  | —                        | 16                  | 20              | 200 Hz           | 27                                          |
| 4      | Srinivasan and Rajanikanth [3]      | diesel engine exhaust, DBD reactor  | catalyst                 | 4                   | 25              | 130 pps          | 150                                         |
| 5      | Yoshida et al. [15]                 | simulated diesel exhaust, DBD reactor | adsorbent            | 1                   | 35              | 420 Hz           | 24                                          |
| 6      | Srinivasan et al. [16]              | diesel engine exhaust, DBD reactor  | —                        | 2                   | 25              | 130 pps          | 114                                         |
| 7      | Mohapatro and Rajanikanth [6]       | diesel engine exhaust, DBD reactor  | adsorbent               | 2                   | 25              | 75 pps           | 270                                         |
| 8      | Okubo et al. [5]                    | diesel engine exhaust, packed bed DBD reactor | adsorbent            | 2                   | 31.6            | 530 Hz           | 97                                          |
| 9      | Wedaa et al. [17]                   | simulated gas, DBD reactor          | catalyst                | 5                   | 12              | 2000 pps         | 54                                          |
| 10     | Bhattacharyya and Rajanikanth [18]  | diesel engine exhaust, DBD reactor  | —                        | 2                   | 30.4            | 80 Hz            | 445                                         |
| 11     | Mohapatro and Rajanikanth [19]      | diesel engine exhaust, duct type DBD reactor | —                       | 2                   | 25              | 74 pps           | 183                                         |
| 12     | present paper                       | diesel engine exhaust, DBD reactor  | adsorbent               | 4                   | 26              | 92 Hz            | 216                                         |

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