NOx Removal From Diesel Engine Exhaust Using Low Voltage DC Powered High Voltage Power Supply

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Abstract—In the recent year pollution level has increased due to ever increase in both stationary and automobile diesel engine exhaust. The most harmful pollutant coming out of diesel engine exhaust, NOx need to be controlled due to the recent stringent emission standard. In the recent study, the electric discharge based NOx treatment has gained popularity for both stationary and automobile exhaust cleaning. But controlling the NOx from automobile diesel exhaust using electric discharge has a major concern about the high voltage power supply availability in a vehicle. Thus there is a need of high voltage power supply excited by low voltage DC. This paper describes a low voltage DC powered high voltage power supply. The power supply was fabricated, aiming to retrofit to a vehicle for exhaust treatment. This power supply is tested for the removal of NOx from filtered real exhaust.

The use of electric discharge techniques for pollution control is an active research topic [1]–[5], and it has shown promise in the field of NOx abatement as well [6]–[11]. The advantage of electric discharge as compared to other electric based techniques like electron beam irradiation is that its power consumption is quite low, and this makes it an economically viable option. There are many ways to produce electric discharges; the pulsed corona method [3] and the dielectric barrier discharge (DBD) method [8] are extensively used for the NOx removal process. Both these discharges have the ability to produce sufficient amounts of energetic electrons in the exhaust, which in turn interact with the background gas molecules and give rise to free radicals and ions. These ions have an effect in NOx abatement process. In this paper, we have concentrated on the DBD plasma, as higher electric fields can be achieved when a dielectric barrier is placed between the high voltage and ground of the electric reactor. So far most of the research for control of NOx using dielectric barrier discharge has been studied using conventional transformer based high voltage power supplies [3]–[12]. However, these are not feasible for automobiles, because of the large energy and space required. In order to treat vehicular exhaust, the power supply for the plasma reactor needs to be of a size that can be fitted within the body of the vehicle and ideally should run from a battery. Rajanikanth et al have worked on the portable power supply energized from low voltage DC for possible retrofit onto vehicle [12], [13]. In this paper, a 0–30 VDC power supply is proposed to generate nano-second high voltage pulse using rotary spark gap (RSG). This power source has been used to excite a plasma reactor of cylindrical borosilicate glass tube. Two different steel high voltage electrodes were placed concentric to the glass tube, one having a diameter of 2 mm and the other of 5 mm. The two plasma reactors thus created are referred to as wire cylinder reactor (WCR) and pipe cylinder reactor (PCR) respectively.

In this paper, MS13x is used as an adsorbent in cascade with the plasma reactor. With the use of low voltage DC powered high voltage power supply appreciable amount of NOx was removed. The above experiments were conducted at the laboratory level.

Keywords—Electric discharge, non-thermal plasma, filtered exhaust, NOx removal, flyback

I. INTRODUCTION

The issue of air pollution is widely regarded as one of the most serious problems that need to be curbed to ensure human health and safety. The deleterious effects of air pollution include environmental damage as well. Therefore, stringent measures are being imposed worldwide to limit the pollutant emissions from industries and automobiles. In order to meet these criteria, research on a large scale is being carried out in the field of pollution control. One key area in this research is the mitigation of nitrogen oxides (NOx) from diesel engine exhaust. The NOx in the diesel engine exhaust consists mainly of two components, the nitric oxide (NO) and Nitrogen dioxide (NO\texttextsuperscript{2}). The diesel engine exhaust contains a high proportion of oxygen and hence retards the activity of several commercially available NOx abatement catalysts. Therefore, non-conventional techniques such as the electric discharge based non thermal plasma (NTP) are being evaluated for their effectiveness in NOx abatement.

The use of electric discharge techniques for pollution control is an active research topic [1]–[5], and it has shown promise in the field of NOx abatement as well [6]–[11]. The advantage of electric discharge as compared to other electric based techniques like electron beam irradiation is that its power consumption is quite low, and this makes it an economically viable option. There are many ways to produce electric discharges; the pulsed corona method [3] and the dielectric barrier discharge (DBD) method [8] are extensively used for the NOx removal process. Both these discharges have the ability to produce sufficient amounts of energetic electrons in the exhaust, which in turn interact with the background gas molecules and give rise to free radicals and ions. These ions have an effect in NOx abatement process. In this paper, we have concentrated on the DBD plasma, as higher electric fields can be achieved when a dielectric barrier is placed between the high voltage and ground of the plasma reactor.

So far most of the research for control of NOx using dielectric barrier discharge has been studied using conventional transformer based high voltage power supplies [3]–[12]. However, these are not feasible for automobiles, because of the large energy and space required. In order to treat vehicular exhaust, the power supply for the plasma reactor needs to be of a size that can be fitted within the body of the vehicle and ideally should run from a battery. Rajanikanth et al have worked on the portable power supply energized from low voltage DC for possible retrofit onto vehicle [12], [13]. In this paper, a 0–30 VDC power supply is proposed to generate nano-second high voltage pulse using rotary spark gap (RSG). This power source has been used to excite a plasma reactor of cylindrical borosilicate glass tube. Two different steel high voltage electrodes were placed concentric to the glass tube, one having a diameter of 2 mm and the other of 5 mm. The two plasma reactors thus created are referred to as wire cylinder reactor (WCR) and pipe cylinder reactor (PCR) respectively.

In this paper, MS13x is used as an adsorbent in cascade with the two repetitive pulse energized plasma reactors and the synergistic effect of the cascaded system is studied. The presence of oxygen in the diesel engine exhaust gives rise to oxygen radicals when subjected to plasma treatment. These radicals favor oxidation reactions, converting a portion of the NO to NO\texttextsuperscript{2}. Therefore, the cascading of adsorbents after the plasma reactor is an effective way to eliminate the excess NO\texttextsuperscript{2} [8].

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup used in this present research work. The source of exhaust here was a 5 kVA diesel
A part of the exhaust was sucked with the help of vacuum pump at a desired flow rate and remaining exhaust was allowed to pass to atmosphere. Steel wool has been used for the removal of soot and oil mist present in the raw diesel exhaust. Then the exhaust was allowed to pass through the 5 micron filter (Make: Ultra Filter) where the particulate gets trapped and filter helps in removing the moisture content present in the exhaust. As per the desired flow rate with the help of flow control the filtered exhaust was then passed through the plasma reactor, where the treatment takes place. For the measurement of pollutant concentration in exhaust a flue gas analyser (Make: Indus Scientific, FGA53) is being used.

The source of high voltage to the reactor is a nano-second pulse power supply powered by low voltage DC. Flyback topology is being used for the development of this power supply. The generated high voltage DC from the power supply is fed to rotary spark gap (RSG) for generation of nano-second high voltage pulse. Fig. 2 shows the schematic diagram of the circuit used for the present work. The ZVS (zero voltage switching) flyback driver popularly known as Mazzilli driver is used for the flyback transformer [14]. The driver uses two MOSFETs in a push-pull configuration; the circuit self-oscillates with an LC tank and switches each MOSFET when there is zero voltage across it. Being a resonant oscillator the frequency that circuit will run is determined by the inductance of the transformers primary coil and the capacitor.

The output of flyback transformer has more ripple, the reason could be the internal capacitor of flyback transformer used is unable to make it ripple free. Thus a capacitor of 0.02 \(\mu F\), 25 kV is being used for reducing the ripple present in the output. The high voltage DC output of the flyback transformer is then fed to the RSG for generation of nano-second high voltage pulse, shown in Fig. 3. The moving electrode was set to speed with the help of external high speed motor operated by a.c. such that the frequency of the pulse output will be 85–90 pulse per second. It is found that the rise time of the high voltage pulse is varying from 10 to 24 nsec.

In the present study two types of electrodes (stainless steel) are studied with cylindrical reactor. One of the electrodes is wire type with 2 mm diameter and the other is of pipe type with 6 mm diameter. The reactor is made of glass with an outer diameter of 18 mm and inner diameter of 15 mm. The discharge area was limited to 28 cm.
Fig. 3. Schematic diagram of the nanosecond high voltage power supply.

Fig. 4. Plasma reactor.

The power supply is then used for the removal of NOx from diesel exhaust. Fig. 4 shows the plasma reactor, where two type of inner electrode as mentioned earlier are used. Fig. 3 shows the variation power fed to the wire cylinder reactor (WCR) and pipe cylinder reactor (PCR) with input DC voltage.

Fig. 5 also shows the corresponding output voltage across the reactors of input DC voltages. The power input to the reactor was measured from the input side by power difference method using a digital wattmeter [8], [11], [15]. In this method, the power consumed by the reactor is measured at the supply end, and then the power is measured again at these same voltages without reactor. Now the difference between these two powers gives the power consumed within the reactor, assuming all other losses remaining constant. The specific energy can be obtained by using the formula as in Eq. (1).

\[
\text{Specific energy} \left( \frac{J}{L} \right) = \frac{\text{Power input to reactor (watt)}}{\text{Gas flow rate (liter/sec)}} \tag{1}
\]

Once the exhaust has been treated with the pulsed plasma, it is then passed through the MS13x adsorbent reactor as shown in Fig. 6. A small quantity of MS13x is used, so as to allow free flow of exhaust. An adsorbent is a substance, usually porous in nature and with a high surface area that can adsorb substances onto its surface by intermolecular forces. The adsorption in MS13x pellets is caused mainly by Van der Walls forces and electrostatic forces between adsorbate molecules and the atoms that compose the MS13x adsorbent surface. A large specific surface area is preferable for providing large adsorption capacity, but the creation of a large internal surface area in a limited volume gives rise to large numbers of small sized pores known as “micropores” between adsorption surfaces.

The size of the micropores determines the accessibility of adsorbate molecules to the internal adsorption surface, so the pore size distribution of micropores is another important property for characterizing absorptivity of adsorbents. The MS13x is a synthetically produced zeolite (metal alumina silicates) characterized by pores and crystalline cavities consisting of pore size varying from 3 Å to 10 Å. The pores have been engineered to trap molecules of dimensions smaller than them, and will completely exclude larger molecules. The effective surface area of molecular sieves is in the range of 400–800 m²/g [8]. They have been specifically engineered for selectivity in NOx adsorption. The picture of this adsorbent is shown in Fig. 7.
### III. RESULTS AND DISCUSSION

The generated pulsed power supply was tested with plasma reactor fitted with the two different electrodes. As mentioned before, the diesel engine exhaust filtered to remove soot, particulates and moisture and then subjected to plasma treatment. The real diesel exhaust contains a great number of gaseous components which can react in various ways. In fact, more than 200 reactions have been reported in literature [1], [16], [17] and exhaustive studies of those are beyond the scope of this paper.

The main reactions that take place in the plasma related to the formation and dissociation of nitrogen oxides are given as Eqs. (2) to (12):

\[
\begin{align*}
N + O_2 & \rightarrow NO + O \quad \text{(2)} \\
N + O_3 & \rightarrow NO + O_2 \quad \text{(3)} \\
O + NO_2 & \rightarrow NO + O_2 \quad \text{(4)} \\
NO + O & \rightarrow NO_2 \quad \text{(5)} \\
NO + O_3 & \rightarrow NO_2 + O_2 \quad \text{(6)} \\
NO + NO_3 & \rightarrow NO_2 + NO_2 \quad \text{(7)} \\
NO + N & \rightarrow N_2 + O \quad \text{(8)} \\
NO_2 + O & \rightarrow NO + O_2 \quad \text{(9)} \\
NO_2 + O_3 & \rightarrow NO_3 + O_2 \quad \text{(10)} \\
NO_2 + NO_3 & \rightarrow N_2O_5 \quad \text{(11)} \\
NO_2 + N & \rightarrow N_2O + O \quad \text{(12)}
\end{align*}
\]

The presence of O-radicals in the plasma atmosphere is known to favor oxidation, whereas the N-radical favors both oxidation and reduction. In the present study, filtered exhaust was used and therefore the contribution of hydroxyl (OH) and peroxyl (HO\(_2\)) radicals for NO oxidation are minimized. However, depending upon the amount of hydrocarbons present, especially ethylene, the alkyl (C\(_n\)H\(_{2n+1}\)), alkoxy (C\(_n\)OH\(_{2n+1}\)) and acyl (C\(_n\)H\(_{2n+1}\)) radicals may contribute for NO removal, particularly at lower gas temperatures, as shown in Eqs. (13) and (14) [18].

\[
\begin{align*}
\text{CH}_2\text{O}_2 + NO & \rightarrow NO_2 + \text{CH}_3\text{O} \quad \text{(13)} \\
\text{CH}_3\text{O} + NO & \rightarrow \text{HNO}_2 + \text{CH}_2\text{O}_2 \quad \text{(14)}
\end{align*}
\]

The measured initial concentrations of the diesel exhaust are given in Table I.

#### TABLE I

**CONCENTRATIONS OF EXHAUST COMPONENT**

<table>
<thead>
<tr>
<th>Pollutant/Gas</th>
<th>Concentration</th>
</tr>
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<tbody>
<tr>
<td>NO(_x)</td>
<td>316ppm</td>
</tr>
<tr>
<td>NO</td>
<td>280ppm</td>
</tr>
<tr>
<td>CO</td>
<td>1251ppm</td>
</tr>
<tr>
<td>O(_2)</td>
<td>16.2%</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Fig. 8. Variation of NO and NO\(_2\) in wire cylinder plasma reactor at different specific energies under pulse energization.

A. The effect of the pulsed power supply on diesel engine exhaust

#### 1) Wire cylinder reactor

Fig. 8 shows the variation of NO and NO\(_2\) for the three different flow rates with the increase in specific energy in the wire cylinder plasma reactor. It is clear that NO reduces continuously, but a portion of it gets converted to NO\(_3\) and this leads to an increase of NO\(_3\) concentration. However, beyond a certain level of specific energy, the concentration of NO\(_2\) comes down as well. This trend is borne out in all the three flow rate cases.

It is noted that with increase in flow rate, the residence time of the exhaust in the plasma reactor comes down, leading to a lesser efficiency of NO removal. Interestingly, greater production of NO\(_2\) has also been noted for higher flow rates. This is because of the availability of greater volume of the exhaust and hence greater NO molecules are present which are getting converted to NO\(_2\). Fig. 9 shows the DeNO efficiency. It can be seen that the efficient conversion of NO to NO\(_2\) in the plasma atmosphere ensures almost complete elimination of NO, thus achieving a removal efficiency of more than 90% in all three cases.

The DeNO\(_x\) efficiency achieved in this process with the wire cylinder reaction is around 83% at 2 l/min and 45% at 6 l/min, as shown in Fig. 10. The sharp increase in efficiency at a particular specific energy (such as 250 J/L for 2 l/min) corresponds to the non-uniform geometry of the reactor, which gives rise to a non-uniform field distribution. This leads to the corona being sporadic at lower voltages and becoming steady beyond a certain power input/voltage.

#### 2) Pipe cylinder reactor

We now come to the performance of the pipe cylinder reactor when energized with this novel low voltage DC operated High voltage power supply. The NO and NO\(_2\) variation at different gas flow rate with respect to SED is shown in Fig. 11. It can be observed that about 200ppm of NO\(_2\) was produced when the gas flow rate was 6 l/min, which can further be minimized by using a good adsorbent. As can be seen from the Fig. 12, the NO removal is achieved fairly completely at even
low specific energies, and the overall NO removal efficiency in this case is higher than 90%. There is a slight increase in NO₂ production as compared to the wire cylinder case, and this can be attributed to the close to uniform field in the pipe cylinder reactor, which gives rise to larger corona volume and hence converts the NO to NO₂ more efficiently. The larger corona volume also corresponds to larger power consumption as is evident from the Fig. 5.

Beyond a certain power input to the reactor, the tendency of NO₂ dissociation becomes stronger as most of NO is removed from the exhaust. However, there is some NO₂ still remaining within the exhaust even at higher specific energies, and this needs to be eliminated from the exhaust stream by means of adsorbent. This will be dealt with in the next section.

The DeNOx efficiency is displayed in Fig. 13. It is more than 80% in the case of 2 l/min flow rate, but comes down to about 60% at the higher flow rate of 6 l/min. It may be noted that as DeNO efficiency is close to 90%, the fall in efficiency can be solely attributed to the increase in NO₂ concentration in the exhaust, and it is seen that though the uniform treatment tends to create more NO₂ in the first place, subsequently with increased specific energy the NO₂ starts to fall, leading to a better DeNOx efficiency. Comparing the DeNOX efficiency to that of the wire cylinder, it can be seen that at similar specific energies, the wire cylinder performs better. This can be attributed to its non-linear geometry which gives rise to a more intense electric field at lower voltages. This limits the power input but gives a better DeNOx efficiency.

B. Plasma cascaded with MS13x adsorbent system for NOx removal

In this section, the effect of the addition of a column of MS13x adsorbent in cascade with the plasma treatment is observed on NOx treatment. Fig. 14 shows the NO and NO₂ variations with this system at various flow rates. The level of NO₂ is much lower in this case as compared to the plain plasma case due to adsorption of NO₂ on the MS13x pellets. In turn the DeNOX efficiency has been increased to more than 72% for the flow rate at 6 l/min, at 180 J/L. At 2 l/min, more than 90% DeNOx efficiency has been achieved. This is displayed in Fig. 15.
Similar results are obtained for pipe cylinder plasma reactor as well. In fact, in Fig. 16, at 2 l/min, the total NO was removed from the system, thus showing that the MS13x is capable of removing both NO and NO\textsubscript{2} from the exhaust. Greater overall DeNOx efficiency is obtained in the wire cylinder cascaded with MS13x case (70%), than in the pipe cylinder case (71%) at 6 l/min, at a lower specific energy of around 110 J/L as compared to the pipe cylinders 148 J/L and is shown in Fig. 17.

C. Comparison of the wire cylinder and pipe cylinder plasma reactor’s performance at the same specific energy

Fig. 18 and 19 show the performance of the two reactors at 145 J/L. Each graph displays the initial ppm, the removal due to plasma at 145 J/L, the effect of MS13x alone (at zero J/L) and the effect of the combination of the plasma obtained from the novel pulsed power supply and cascaded MS13x.

The results shown here by no means display the best case scenario for both the reactors, and are merely for comparison at a common specific energy. It is clear from the graphs that at similar specific energies, the wire cylinder performs better compared to the pipe cylinder for NOx removal. Also interesting to note is that once the exhaust is treated with...
The new high voltage power supply powered by low voltage energy sources for control of NOx in diesel engine exhaust, "IEEE Transactions on Dielectrics and Electrical Insulation, vol. 17, pp. 1543–1550, 2010.


REFERENCES

IV. CONCLUSION

A DBD reactor with two different electrodes has been designed built and studied with filtered diesel engine exhaust. The dimensions of both the reactors are kept same for the performance evaluation. It has been seen from the results, the removal efficiency decreases as the gas flow rate increases. The new high voltage power supply powered by low voltage DC has been tested successfully for the removal of NOx from filtered diesel exhaust for a possible retrofit into vehicle. It was found that the wire reactor shows better removal efficiency compared to pipe reactor at low SED level. With increase in SED the wire reactor does not show any increase in removal efficiency whereas the pipe reactor shows considerable removal efficiency. A maximum of 87% DeNOx efficiency is obtained with PCR at 570 J/L whereas in case of WCR it is 80% at 330 J/L.

TABLE II

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Wire cylinder reactor (l/min)</th>
<th>Pipe cylinder reactor (l/min)</th>
</tr>
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<tbody>
<tr>
<td>Plasma</td>
<td>80 at 330 J/L</td>
<td>87 at 570 J/L</td>
</tr>
<tr>
<td>Plasma + MS13x</td>
<td>89 at 330 J/L</td>
<td>95 at 570 J/L</td>
</tr>
<tr>
<td>Plasma + MS13x</td>
<td>79 at 165 J/L</td>
<td>95 at 570 J/L</td>
</tr>
<tr>
<td>Plasma + MS13x</td>
<td>70 at 110 J/L</td>
<td>81 at 285 J/L</td>
</tr>
<tr>
<td>Plasma + MS13x</td>
<td>70 at 110 J/L</td>
<td>76 at 190 J/L</td>
</tr>
</tbody>
</table>

plasma, going over the surface of MS13x causes a slight back conversion of NO₂ to NO, but more pronounced is the adsorption of NO₂ on the surface. This trend can be seen clearly in both the graphs. A significant improvement in energy consumption vs output is also seen when the adsorbent is used in the system. Maximum DeNOx efficiency obtained for both WCR and PCR at different exhaust flow rate with plasma and with plasma cascaded with MS13x is shown in Table II.

Fig. 18. NO and NO₂ variation at 145 J/L for the wire cylinder reactor with plasma, adsorbent and cascaded plasma adsorbent cases. 

Fig. 19. NO and NO₂ variation at 145 J/L for the pipe cylinder reactor with plasma, adsorbent and cascaded plasma adsorbent cases.
