Non-Thermal Plasma Activated deNOx Catalysis

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Abstract

The combination of non-thermal plasma (NTP) with catalyst systems as an alternative technology to remove NOx emissions in the exhaust of lean-burn stationary and mobile sources is reviewed. Several factors such as low exhaust gas temperatures (< 300 °C), low selectivity to N2 and the presence of impurities make current thermally activated technologies inefficient. Various plasma-catalyst systems have been examined and shown to have a synergistic effect on the de-NOx efficiency when compared with NTP or catalyst alone systems. The NTP is believed to form oxygenated species such as aldehydes, nitrogen-containing organic species and convert NO to NO2, which improves the reduction efficiency to N2 during hydrocarbon-selective catalytic reduction reactions. The NTP has been used as a pretreatment to convert NO to its higher oxidation states such as NO2 to improve NOx reduction efficiency in the subsequent processes e.g. NH3-selective catalytic reduction. It has been applied to the lean phase of the NOx storage to improve the adsorption capacity of the catalyst by conversion of NO to NO2. Alternatively, a catalyst with high adsorption capacity is chosen and the NTP is applied to the rich phase to improve the reduction activity of the catalyst at low temperature.

Keywords: Catalyst, Plasma, NOx removal, SCR, NSR
1. Introduction

The treatment of the high levels of NOx emissions in lean-burn automotive engines exhaust is a challenge. While several gas after-treatments systems have been reported [1–3], in all cases the issues of low temperature activity, selectivity to N2 and resistance to impurities in the exhaust gas feed, for example SOx, are problematic. In an attempt at addressing such issues, alternative approaches such as hybrid non-thermal plasma (NTP)-catalyst systems have been explored. In these systems, the effect of the plasma can be related to:

- Gas heating (Joule effect) by vibrational excitation and dissociation of molecules, which proceed much faster than in any conventional heat exchanger due to electronic and ionic collision [4].
- Electronic excitation of molecules
- Formation of short lived radicals. In the case of diesel and lean-burn engines atomic (N), excited nitrogen (N2*), electronically excited oxygen (O(D)) (due to high reactivity) may be formed [5]
- Formation of long lived intermediate species (100µs): ground state atomic oxygen (O), hydroxyl (OH), peroxy radicals (R-OO) [6]
- UV emission
- Surface modification of the catalyst.

The present review compares the various hybrid NTP-catalyst approaches that have been reported for the removal of NOx. In these hybrid systems, the reactor configuration can be very important and two main configurations are used namely the ‘In Plasma Configuration’ (IPC) and the Post-Plasma Configuration (PPC). The IPC involves placing the catalyst in the discharge area since this potentially allows making use of the short lived intermediates created by the plasma for reaction on the catalyst surface. In the PPC, the catalyst is placed downstream of the plasma and in this case the lifetime of
the intermediates formed by the plasma must be sufficiently long to influence the reaction on the catalyst surface [4]. These configurations are shown in Figure 1.

Figure 1. Two main reactor configurations are used in the hybrid plasma-catalyst systems.

2. Hydrocarbon-selective catalytic reduction (HC-SCR) using NTP

Pan et al. [7] reported a synergistic effect of the NTP on NOx reduction by CH4 over an In/H-BEA catalyst using a post-plasma hybrid system (i.e. an enhancement in de-NOx efficiency using PPC system compared to NTP or catalyst system alone). A gas mixture containing 540 ppmv NO, 60 ppmv NO2, 600 ppmv CH4, O2 with a balance of Ar was introduced to the system while varying the plasma energy density and temperature. A significant promotion effect on NOx removal by the hybrid system was observed at 250-550 °C. Further increases in temperature had a detrimental effect on the NOx removal i.e. an increase in plasma energy density from 0 to 135 J L⁻¹ increased the NOx removal below 550 °C while higher temperatures decreased the NOx removal. The Ts, i.e. temperature at 50\% NOx conversion, decreased from above 380 °C at 0 J L⁻¹ (no NTP present) to ~325 °C at 135 J L⁻¹, revealing higher efficiency of the hybrid system at low temperatures. The promoting effect of the NTP on CH₄-SCR was studied by product analysis after the NTP-alone. In the low temperature region, it was attributed to the NO oxidation and CH₄ conversion into helpful intermediates such as HCHO, CH₃NO and CH₃NO₂. However, at high temperatures, the combustion of the intermediates with O₂ became the dominant reaction and decreased the NOx removal efficiency. Introduction of CH₄
separately to SCR and DBD reactors at different ratios in order to widen the operational temperature was also examined. A wide temperature window was observed when 400 ppmv and 200 ppmv CH₄ was injected to the DBD and SCR reactors, respectively [7]. The removal of NO and CH₄ using a PPC system over Cu-based catalysts on different supports has also been reported. A plasma with an energy density of 1800 J L⁻¹ was shown to promote the NO and CH₄ removal within 25-500 °C. NO removal efficiency was also significantly affected by the type of catalyst support and decreased in the following order: CuO/CeO₂/TiO₂/Ɣ-Al₂O₃ > CuO/TiO₂/Ɣ-Al₂O₃ > CuO/Ɣ-Al₂O₃ > CuO/TiO₂. The characterization results indicated that CuO/CeO₂/TiO₂/Ɣ-Al₂O₃ catalyst, with respect to other catalysts, had larger amount of Cu²⁺ incorporated within CeO₂ and TiO₂ species which could possibly be correlated to its relative higher catalytic activity [8].

Rajanikanth et al. reported a series of studies examining the deNOₓ efficiency of a stationary 4.4 kW diesel engine exhaust at no load and 50% load conditions, using NTP-catalyst or adsorbent processes [9–13]. The filtered exhaust before the aftertreatment system included NO, NO₂, CO, hydrocarbons, aldehydes and CO₂. Using a two-stage plasma-activated alumina catalyst system, without the addition of any reductant, it was shown that this process exhibited an enhancement in de-NOₓ efficiency. The plasma reactor (75 J L⁻¹) was operated at room temperature, while the catalyst reactor was operated at 300 °C. 57% de-NOₓ removal was achieved using two-stage system, compared with the 20% and 22% with separate catalyst or plasma processes, respectively. The improvement in the de-NOₓ efficiency was more pronounced when the plasma reactor was operated at 150 °C. The NOₓ removal efficiency using the plasma-only process was ~5% while increased to ~50% using the two-stage process. The plasma was believed to convert NO to NO₂ efficiently, given the lean condition of the exhaust and also convert hydrocarbons to aldehydes, which reacted above 250 °C over activated alumina, forming N₂ and resulting in an increase in NOₓ removal efficiency [10,13]. To achieve higher conversions, a four-stage process (plasma-catalyst-plasma-catalyst) was also examined and at constant energy density, the four-stage process showed an even better performance, compared with the two-stage process, in terms of NOₓ removal [10]. However, the four-stage process makes the design of aftertreatment system complicated. The temperature variation in the catalyst reactor, while
operating the plasma reactor (52 J L⁻¹) at room temperature, was also reported. An increase in the temperature of the catalyst reactor from 25 to 250 °C led to a gradual decrease in the de-NOx results from ~55% to ~40%, respectively, which was thought to be due to a decrease in the adsorption of the activated alumina, and then, increased to 57% at 300 °C. The activated alumina was believed to not be catalytically active below ~300 °C and acted as an adsorbent at low temperatures [10].

Combining low and high temperature-active catalytic materials has been shown to enhance the temperature range during post plasma-SCR of NOx [14]. Ba/zeolite Y and Ag/Ɣ-Al₂O₃ catalysts were combined in different configurations e.g. dual bed, mixed bed or separately, and examined in the post plasma-SCR of a simulated exhaust gas feed between 100-500 °C under steady-state and transient operation. Steady-state experiments were performed at 200, 350 and 500 °C with both the plasma and SCR reactors held at the same temperature, while transient experiments were performed by heating and cooling the plasma and SCR reactors with each heating or cooling defined as one thermal cycle. The latter process was conducted at 10 °C min⁻¹ between 100-500 °C after holding for 12 min at the minimum or maximum temperature, respectively. This thermal cycling was continued until the last two consecutive cycles overlapped. The best configuration to reduce NOx levels in the exhaust was found for the Ba/zeolite Y catalyst placed before the Ag/Ɣ-Al₂O₃ catalyst. The higher activity of this configuration was attributed to the formation of formaldehyde over the Ba/zeolite Y catalyst which then acted as a reductant over the Ag/Ɣ-Al₂O₃ catalyst. On adding propene as a reductant at a C₃:NOx = 12, resulted in steady-state NOx conversion above 80% at 200 °C and 95% at 500 °C while the average NOx conversion under transient operation between 100 °C and 500 °C was around 70%. In the latter case, the drop in NOx conversion was thought to be due to the desorption of NOx at temperatures below 200 °C and the low activity of the Ag/Ɣ-Al₂O₃ catalyst at these temperatures [14].

Cho et al. [15] reported a post-plasma SCR system applied to the exhaust of a 4.9L, 6 cylinder Isuzu diesel engine dynamometer system specifically at low temperatures. In this system, oxygenated hydrocarbons were generated by reforming the diesel fuel through an air plasma reactor. The plasma-induced air and highly active oxygenated hydrocarbons were added to a sidestream of the exhaust of
the Isuzu diesel engine prior to the SCR system. The plasma air containing O₃, a stronger oxidizing agent compared to O₂, was believed to convert the NO to NO₂ and partially oxidize hydrocarbons which then increase the NOₓ conversion in the SCR reactor. The experiments were performed under steady-state FTP simulated conditions that provided an actual vehicle certification test, despite of the exclusion of cold start and transient operation conditions (the exhaust temperature varied from 150 to 500 °C). Dual-bed catalysts such as Ba/zeolite Y-Cu/zeolite Y and Ba/zeolite Y-Ag/Al₂O₃ were tested as SCR catalysts with the Ba/zeolite Y-Cu/zeolite Y catalysts, showing the best performances (~60% mode-averaged NOₓ conversion). This was attributed to the higher oxidation activity of the Cu catalysts compared to the Ag ones due to inhibition of the latter by heavy HCs present in the exhaust at temperatures < 300 °C [15].

Peng et al. [16] observed a synergistic effect between the catalyst and the plasma in the NOₓ removal over a perovskite catalyst (La₀.₈K₀.₂Cu₀.₅Mn₀.₉5O₃). A mixture of NO, O₂ and C₃H₆ was passed through a plasma DBD reactor filled with Ɣ-Al₂O₃ powder before passing over a catalyst bed mixed with soot, with the latter being heated from 100 to 500 °C. The results showed a maximum NOₓ removal rate of 44% with plasma-alone, compared with 72% with the plasma-catalyst system when using 0.27% C₃H₆ in the feed. Lee et al. [17] also reported an improvement in the catalyst activity during C₃H₆-SCR, when using a plasma DBD reactor to pre-treat the feed containing 1660/23 ppm NO/NO₂, 1800 ppm C₃H₆ (hydrocarbon (C₁-based)/NOₓ ratio = 3.2), 10% O₂, He or N₂ balance at < 400°C in a PPC system. Using this system, the NOₓ to N₂ conversion was 40 – 50% with a Ag/Al₂O₃ catalyst at 300-500 °C, revealing a better performance compared to Ɣ-Al₂O₃ as the catalyst. The results with N₂ balance and He balance were found to be identical when the NO/NO₂ ratio remained constant after the DBD reactor, although this led to a significant difference in the energy densities used (10 J L⁻¹ when using a He as balance compared with 36 J L⁻¹ with the N₂). The plasma was believed to oxidize a portion of NO in the feed to NO₂ under lean-burn conditions which facilitated the NOₓ conversion to N₂ under HC-SCR conditions. The presence of hydrocarbons in the feed was believed to promote NO oxidation and form nitrogen-contained organic compounds that further reacted on the catalyst to form N₂ and CO₂.
The mechanism of NO\textsubscript{x} removal using a post plasma-SCR system has been examined by considering the long-lived chemical products generated in the plasma [18]. The SCR reaction alone over a Ag/Al\textsubscript{2}O\textsubscript{3} catalyst (using a feed mixture of 435 ppm NO, 10 ppm NO\textsubscript{2}, 6000 ppm C\textsubscript{2}H\textsubscript{4}, 8% O\textsubscript{2} and balance N\textsubscript{2}) indicated that temperatures higher than 300 °C were needed to activate the catalyst and obtain high NO\textsubscript{x} conversions. For example, the thermal NO\textsubscript{x} removal efficiency at 240 °C was only 6.7%. Treatment of the feed with plasma before the SCR reaction at 240 °C resulted in an increase in the NO\textsubscript{x} removal efficiency to 90.1%, revealing the synergistic effect in the post plasma-SCR system. Analysis of the products obtained after the plasma treatment (703 J L\textsuperscript{-1}) showed that all NO was converted. A portion was converted to NO\textsubscript{2} and, due to the presence of hydrocarbons, some was also converted to nitrogen-contained organic compounds such as methyl nitrate (CH\textsubscript{3}NO\textsubscript{2}), nitro methyl (CH\textsubscript{3}CN) and ethyl nitrate (C\textsubscript{2}H\textsubscript{5}ONO\textsubscript{2}), as postulated by Nie et al. [18]. Post plasma product analysis also revealed the presence of other organic compounds such as formaldehyde (HCHO), acetaldehyde (CH\textsubscript{3}CHO) and acetylene (C\textsubscript{2}H\textsubscript{2}).

Gas phase plasma treatments can lead to many reaction intermediates. A proposed reaction mechanism during gas phase plasma of NO/NO\textsubscript{2}/C\textsubscript{2}H\textsubscript{4}/O\textsubscript{2}/N\textsubscript{2} feed system based on product analysis and previous studies is summarised in Table 1 [18]. It is believed that radicals predominantly participated in the reaction during gas phase plasma [17]. The gas phase plasma in the presence of hydrocarbons under the lean conditions is effective in oxidizing the NO to NO\textsubscript{2}. For example, considering the aforementioned feed system, oxidative species via reactions R11-R16, including CH\textsubscript{3}O\textsubscript{2}, C\textsubscript{2}H\textsubscript{5}O\textsubscript{2}, O\textsubscript{3} and HO\textsubscript{2} can oxidize NO to NO\textsubscript{2} via reactions R18-R21. NO\textsubscript{x} removal in this feed system can then occur through different routes. The dissociation energy of O\textsubscript{2} (R1; 5.1 eV) is much smaller than N\textsubscript{2} (R2; 9.8 eV) [17] and this leads to the formation of more O radicals and thus, oxidative species rather than N radicals under the lean conditions of the exhaust. The low concentration of N radicals accounts for small NO\textsubscript{x} conversion to N\textsubscript{2} and N\textsubscript{2}O in excess oxygen via reactions R34 and R35. The NO\textsubscript{x} removal via OH radicals to form HNO\textsubscript{2} and HNO\textsubscript{3} (reactions R36 and R37) are also considered negligible due to the absence of H\textsubscript{2}O in the feed and consequent small
concentrations of OH radicals although this mechanism cannot be ignored in the real automotive exhaust gas feed due to high H$_2$O concentrations. It is likely that the NO$_x$ removal predominantly occurs via the formation of nitrogen-contain organic chemicals such as CH$_3$ONO$_2$, C$_2$H$_5$ONO$_2$ and CH$_3$NO$_3$ in this system [11,18]. O radicals at high concentration in the plasma decompose C$_2$H$_4$ via reactions R3-R6 and form oxygented byproducts such as CO, CO$_2$, HCHO and C$_2$H$_3$. After the two-stage plasma-SCR process, all the organic compounds formed during the plasma treatment are removed and NO$_x$ removal efficiency increases. The aldehydes, NO$_2$ and nitrogen-contianing organic hydrocarbons formed in the gas phase plasma are more active in the SCR over Ag/Al$_2$O$_3$ catalyst than, for example, C$_2$H$_4$ and their formation thus increases the NO$_x$ conversion to N$_2$ [18].

Table 1. Proposed reaction mechanism during gas phase plasma treatment of NO/NO$_2$/C$_2$H$_4$/O$_2$/N$_2$ system. Adapted from [18].

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>e + O$_2$ → e + O + O</td>
<td>R1</td>
</tr>
<tr>
<td>e + N$_2$ → e + N + N</td>
<td>R2</td>
</tr>
<tr>
<td>C$_2$H$_4$ + O → CH$_2$COH + H</td>
<td>R3</td>
</tr>
<tr>
<td>C$_2$H$_4$ + O → CH$_3$ + HCO</td>
<td>R4</td>
</tr>
<tr>
<td>C$_2$H$_4$ + O → HCHO + CH$_2$</td>
<td>R5</td>
</tr>
<tr>
<td>C$_2$H$_4$ + O → C$_2$H$_2$ + OH</td>
<td>R6</td>
</tr>
<tr>
<td>C$_2$H$_4$ + H → C$_2$H$_3$</td>
<td>R7</td>
</tr>
<tr>
<td>C$_2$H$_4$ + HO$_2$ → CH$_3$CHO + OH</td>
<td>R8</td>
</tr>
<tr>
<td>C$_2$H$_4$ + OH → C$_2$H$_2$ + H$_2$O</td>
<td>R9</td>
</tr>
<tr>
<td>C$_2$H$_4$ + OH → HCHO + CH$_3$</td>
<td>R10</td>
</tr>
<tr>
<td>CH$_3$ + O$_2$ → CH$_2$O</td>
<td>R11</td>
</tr>
<tr>
<td>O$_2$ + C$_2$H$_4$ → C$_2$H$_2$O$_2$</td>
<td>R12</td>
</tr>
<tr>
<td>H + O$_2$ + M → HO$_2$ + M</td>
<td>R13</td>
</tr>
<tr>
<td>O + O + M → O$_2$ + M</td>
<td>R14</td>
</tr>
<tr>
<td>HCO + O$_2$ → CO + HO$_2$</td>
<td>R15</td>
</tr>
<tr>
<td>CH$_2$COH + O$_2$ → H$_2$C=C=O + HO$_2$</td>
<td>R16</td>
</tr>
<tr>
<td>H$_2$C=C=O + H → CO + CH$_3$</td>
<td>R17</td>
</tr>
<tr>
<td>CH$_3$O$_2$ + NO → CH$_3$O + NO$_2$</td>
<td>R18</td>
</tr>
<tr>
<td>O$_2$ + NO → O$_3$ + NO$_2$</td>
<td>R19</td>
</tr>
<tr>
<td>HO$_2$ + NO → OH + NO$_2$</td>
<td>R20</td>
</tr>
<tr>
<td>C$_2$H$_4$O$_2$ + NO → C$_2$H$_2$O + NO$_2$</td>
<td>R21</td>
</tr>
<tr>
<td>CH$_2$OH + O$_2$ → HCHO + CO + OH</td>
<td>R22</td>
</tr>
<tr>
<td>OH + CH$_3$ → HCHO + H</td>
<td>R23</td>
</tr>
<tr>
<td>HCO + HCO → HCHO + CO</td>
<td>R24</td>
</tr>
<tr>
<td>CH$_3$ + O → HCHO + H</td>
<td>R25</td>
</tr>
<tr>
<td>CH$_3$ + O → HCHO + H</td>
<td>R26</td>
</tr>
<tr>
<td>CH$_3$O + CH$_3$ → HCHO + CH$_3$</td>
<td>R27</td>
</tr>
<tr>
<td>C$_2$H$_5$ + O → C$_2$H$_2$ + OH</td>
<td>R28</td>
</tr>
<tr>
<td>C$_2$H$_5$ + OH → CH$_3$CHO</td>
<td>R29</td>
</tr>
<tr>
<td>CH$_3$O + NO$_2$ → CH$_3$ONO$_2$</td>
<td>R30</td>
</tr>
</tbody>
</table>
Varying the energy density affects the product distribution during plasma treatment, leading to an enhancement in the synergistic effect of the plasma and SCR in NOx removal. An increase in the energy density up to 210 J L⁻¹ increased the concentration of NO₂ while decreasing the NO and NOx (NO + NO₂) (as shown in Figure 2), revealing that a majority of NO in the feed is converted to NO₂ and a minor amount is converted to nitrogen-containing organic hydrocarbons. The NO₂ remained constant on increasing the energy density from 210 to 484 J L⁻¹ but NO constantly decreased. This reflected that the decrease in NO at these energy densities was due to a conversion to nitrogen-containing organic hydrocarbons since total NOx also decreased. Further increase in the energy density above 484 J L⁻¹ not only decreased the NO but also NO₂, which meant that, at high energy densities, part of the NO₂ was also converted to nitrogen-containing organic hydrocarbons via reactions R30-R32. This behavior was in agreement with the proposed mechanism in Table 1 for NOx removal in the presence of hydrocarbons. NO₂ acts as an intermediate to form nitrogen-containing organic hydrocarbons from NO and high energy densities favor their formation. These species are active in the SCR [18,19]. The two-stage plasma SCR experiments using He balance instead of N₂ balance at different energy densities demonstrated that the amount of nitrogen-containing organic compounds produced following the plasma treatment was related to the N₂ and N₂O formed in the subsequent SCR process although the selectivity to N₂ remained constant at 82% [19].
Mechanistic studies of thermal C3H6-SCR of NO over Ag/Al2O3 with the assistance of a NTP using in-situ diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) revealed two subsequent steps in the hydrocarbon-SCR reaction: (a) nitration to generate isocyanate (-NCO) species, (b) reduction of the adsorbed NOx species to N2 using isocyanate, e.g. -NCO + -NO3- → N2 + CO2, in agreement with [18], showing that the nitrogen-containing species can improve the de-NOx efficiency. Although NO oxidation and formation of nitrates on the catalyst surface were found to be kinetically irrelevant for the SCR reaction, the abundance of electron-rich organic species was key for the nitration process and improvement of the NOx reduction. The Ag/Al2O3 catalyst was not very effective to oxidize propene (C3H6) and form electron-rich organic oxygenates at low temperatures (<400 °C). However, the NTP could promote the nitration step by formation of electron-rich organic oxygenates and nitrogen-contained organic species in O-predominant and N-predominant environments, respectively. The nitration step may have occurred through the reaction between

Figure 2. NO, NO2, NOx concentrations after plasma treatment as a function of energy density.
Adapted from [18].
adsorbed nitrates and electron-rich organic oxygenates and also oxidation or decomposition of nitrogen-contained organic species [20].

A two-stage plasma-catalyst system placing the plasma downstream of catalytic bed has also been examined. Such hybrid system was reported to remove up to 30% of NOx and almost all particulate matters (PMs) and CO from the exhaust of a light duty IDI diesel engine (2500 cc) during a dynamometer test bed and chassis dynamometer with CVS-75. A Pt-based oxidation catalyst placed in the engine exhaust was shown to oxidize almost all CO and ~50% of NO to NO2 depending on the catalyst temperature and NO concentrations, while the plasma reactor located in the downstream of the catalyst bed, reduced NO2 using carbonaceous particles deposited in the corona discharge reactor. The DC corona discharge is believed to have promoted the deposition of PMs and soots by electrostatic force in the plasma reactor [21].

HC-SCR was investigated by Niu et al. [22] over a Co-HZSM-5 catalyst with C2H2, C2H4 or CH4 as reductants. NO conversion of 93% was obtained when using 500 ppm NO, 500 ppm C2H2, 15% O2 in N2 at 300 °C and 138 J L⁻¹ energy density. A volcano curve was obtained with further increase in temperature, as shown in Figure 3. The reaction was also carried out over quartz pellets, showing <5% conversion, while the catalyst without discharge gave 80% conversion. A stronger promotion of the in plasma catalytic system compared with the thermally activated catalyst was obtained at lower reaction temperatures, with an over a 2-fold increase found below 200 °C (20% to 50%) and no NOx removal in the plasma gas phase. However, some N2O formation was observed under plasma conditions. Furthermore, the hydrocarbon conversion to COx increased from ~10% to >80% when using the in plasma catalytic system, with CO2/CO ratio just over 1. A similar promotion effect was obtained with C2H4 as reductant; however, a drop in NOx conversion occurred at higher temperatures for the in plasma catalysis which is attributed to an increase in the rate of NOx formation with temperature. However, the increase in CO2/CO ratio from 6.6 to 11.7 for the plasma system compared with the thermal process may be an indication of the strong competition between the SCR activity and the full oxidation reaction of the hydrocarbon. For CH4-SCR, the conversion increased
only slightly from 25%-30% with the increase in temperature, while the catalyst alone showed no conversion up to 300 °C, and a maximum of 15% at 400 °C. No CH₄ conversion was observed below 300 °C and the addition of the catalyst in the discharge zone did not show a significant improvement in the NOₓ conversion below 200 °C. Therefore the NOₓ conversion at low temperature was proposed to be due to gas phase plasma decomposition rather than selective catalytic reduction by methane. This was further confirmed by varying the oxygen concentration in the feed with a maximum of 50% NOₓ removal with CH₄ observed at 250 °C and 144 J L⁻¹ in the absence of oxygen and further decreased with an increase in oxygen.

Efficient SCR of NOₓ was also reported for a 12% CuO/15% TiO₂/γ-Al₂O₃ catalyst in a He plasma with 2% NO, 4% CH₄ and 5% O₂. A maximum of 61.4% NOₓ conversion and ~ 90% CH₄ conversion
at 450 °C, was obtained with little N₂O formation and good selectivity towards N₂ [23]. Partial oxidation of CH₄ was also observed under these reaction conditions and the CO formation was observed to increase with a decrease in temperature from ~30% at 450 °C to almost 80% at 100 °C. Once again, removal of oxygen from the system led to an increase in the NOₓ conversion to 100% through plasma dissociation since only a small CH₄ conversion (~10%) was observed under these conditions. In comparison, in the absence of the discharge the catalytic activity for NOₓ removal was only 17% and ~27% with addition of O₂. The power supply was operated in a DC mode and the power consumption was 30 W. Therein, a small decrease in the specific surface area of the catalyst after reaction was reported as well as an increase in the Cu⁺ and Cu⁰ concentration after plasma discharge. It was postulated that the plasma assisted reaction could enhance the production of Cu⁺ and Cu⁰ and, therefore, the CH₄ and NO conversion since Cu⁺ is thought to be the active species at low temperature and Cu⁰ at high temperature. The reduction in oxidation state of the Cu was attributed to the formation of CO during the discharge.

Perovskite-type catalysts have also been studied in the plasma-assisted SCR of NOₓ. Hueso et al. [5] examined the effects of the plasma-catalyst system for CH₄-SCR at low temperatures using a La₈₋ₓSrₓCoO₃₋₄ perovskite. The utilisation of a surfatron device connected to a microwave power supply at a power of 75 W and gas pressure of 4 Torr. Optical emission spectroscopy (OES) was used to characterise the plasma species and to obtain information on the changes occurring on the surface of the catalyst exposed to the discharge. X-ray photoelectron spectroscopy was undertaken following in-situ plasma experiments performed in a prep-chamber. In order to understand if the role of the catalyst is purely to favour the combination of the active species formed in plasma on its surface or if it actively participates in the reaction, a commercial SiO₂ powder with a high surface area (270 m² g⁻¹) was used for comparison. Under the investigated conditions, (3600 ppm CH₄, 3000 ppm NO, 3 x 10⁵ ppm O₂ in Ar or N₂ as balance gas) a decomposition yield of 97-99% for CH₄ and 88% or 68% for NO in Ar or N₂, respectively, were observed for the plasma-only reactions. N₂, O₂, H₂O and CO were the main products and less than 10% CO₂ formation was observed. The synergetic effect of the plasma and catalyst was identified for a simplified mixture containing only CH₄ and O₂. The results
showed a dramatic increase in the CO$_2$ selectivity, with a temperature dependant conversion-efficiency, showing a maximum of ~ 90% both in an Ar or N$_2$ plasma at 190 °C. This behavior was only observed when La$_{0.5}$Sr$_{0.5}$CoO$_{3-d}$ was used as catalyst, and it was postulated that the perovskite directly participated in the oxidation of CO to CO$_2$. A simpler role of providing surface reaction sites at which active plasma species (CO*, OH*, CH*, H*, O* for Ar plasma or N$_2$*, CN*, NO* for N$_2$ plasma) react with each other, as would be the case when using SiO$_2$ was discarded.

The synergetic effect was explained through the formation of new active sites or oxygen on the surface of the catalyst which was due to the direct contact of the Reactive Oxygen Species (ROS) produced by plasma (O*, OH*) with the catalyst. The study also showed that NO addition to the feed did not have a significant impact on the CO$_2$ selectivity. The NO removal efficiency decreased when the catalyst was placed in the discharge zone, in particular with N$_2$ as balance gas. The results were attributed to the NO formation by the interaction between the excited NO* and other N-containing species formed by the plasma and the oxide ions of the catalyst surface, giving rise to the –NO$_x$ and –NO$_2$ species that were identified in the XPS spectra.

The interaction of the ROS produced by the plasma with the surface of the catalyst is very important as it can have a beneficial effect in removing species that can, otherwise, easily accumulate on the catalysts at low temperature reaction conditions leading to deactivation of the catalysts. One such example can be found in the work of Stere et al. who studied the selective catalytic reduction of NO$_x$ with octane or toluene over a 2% Ag/Al$_2$O$_3$ using a DBD reactor and an in situ DRIFTS-MS system [24,25]. The results shown in Table 2 demonstrated that the SCR activity was strongly enhanced by the presence of the catalyst in the discharge area (Figure 4) for a mixture containing 720 ppm NO, 4340 ppm C1, 4.3% O$_2$, 7.2% H$_2$O and 7.2% CO$_2$ with a balance of helium. Up to 50% NO$_x$ reduction was observed for the hybrid plasma catalyst system at ambient temperature conditions with the catalyst in the discharge area, while without the catalyst, a decrease in conversion to 11.5% was obtained when octane was used as a reductant and to 4% with toluene. A decrease in the reduction of NO$_x$ with the reaction temperature (250 °C) for the octane-SCR
highlighted the competitive reactions occurring in this process, *i.e.* the partial oxidation of the hydrocarbon (leading to N\textsubscript{2} production by NO reduction) and the complete oxidation of the octane (thus, reduced NO\textsubscript{x} conversion), and the need to fine tune the reaction parameters. At low temperatures the partial oxidation was favoured leading to NO\textsubscript{x} conversion whereas at higher temperatures, the octane was completely combusted and limited the NO\textsubscript{x} conversion. Interestingly, it was reported that, when using toluene, an increase in temperature led to an increase in NO\textsubscript{x} conversion. This was attributed to the fact that toluene is less easily oxidised compared with octane and, therefore, partial oxidation occur over a wider temperature windows. Another benefit of the IPC system was a decrease in the rate of deactivation compared with the thermal system while maintaining good N\textsubscript{2} selectivity and low N\textsubscript{2}O formation.
Table 2. NOx and Hydrocarbon Conversion (Conv) and Selectivity to N2, N2O, CO, and CO2 during the Toluene-SCR of 15NO in the Presence of the NTP Using the Blank Reactor, the Reactor in the Presence of the Thermocouple, and the Reactor in the Presence of the Thermocouple and 2% Ag/Al2O3 Catalyst at Ambient Temperature. Adapted from [24].

<table>
<thead>
<tr>
<th>Experiment</th>
<th>NOx</th>
<th>C7H8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total NOx Conv (%)</td>
<td>N2 (%)</td>
</tr>
<tr>
<td>Empty reactor</td>
<td>4.0</td>
<td>Trace</td>
</tr>
<tr>
<td>Blank reactor + thermocouple</td>
<td>24.5</td>
<td>75.9</td>
</tr>
<tr>
<td>2% Ag/Al2O3 in the presence of a thermocouple</td>
<td>42.4</td>
<td>96.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>NOx</th>
<th>C7H8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total NOx Conv (%)</td>
<td>N2 (%)</td>
</tr>
<tr>
<td>Empty reactor</td>
<td>11.5</td>
<td>Trace</td>
</tr>
<tr>
<td>Blank reactor + thermocouple</td>
<td>34.8</td>
<td>75.9</td>
</tr>
<tr>
<td>2% Ag/Al2O3 in the presence of a thermocouple</td>
<td>51.7</td>
<td>77.9</td>
</tr>
</tbody>
</table>
The remarkable enhancement in conversion and N\textsubscript{2} selectivity was further investigated using a combined DRIFTS hybrid plasma system. The \textit{in-situ} mechanistic study was performed using a state of the art cell (Figure 5) \cite{25} designed to allow the interaction of the plasma stream with the surface of the catalyst bed, on which infrared spectra were simultaneously collected.

Figure 4. Schematic (A) and photograph (B) of the plasma reactor used during the HC-SCR activity test. Reprinted with permission from \cite{24}. Copyright 2014 American Chemical Society.
The in-situ IR measurements provided invaluable information on the adsorbed species in the presence of plasma leading to more insights on the mechanisms of the reaction for the plasma-assisted SCR with octane and toluene. It was postulated that the NTP might play an important role in cleaning the surface of the catalyst, since the deactivation of the plasma-SCR reaction was not as prevalent as in the case of thermally activated process. Furthermore, the formation and disappearance of IR bands associated to isocyanate and cyanide species $\text{–NCO}^/\text{–CN}$, gave valuable information on the reaction mechanism for the plasma assisted-SCR. It is believed that under the investigated conditions, the octane-SCR reaction proceeded through a similar reaction mechanism to the thermal case, with the isocyanate species observed at 2260 cm$^{-1}$ being a key intermediate in the NO$_x$ removal mechanism, formed via R-NO$_2$ compounds as well as from the conversion of cyanide species [26]. Interestingly, for the toluene it was suggested that both the R-ONO and the R-NO$_2$ routes might be occurring or
only the R-ONO route, given that no –NCO was detected, while the band at 2165 cm⁻¹, attributed to cyanides, increased under plasma reaction.

Figure 6. Changes in surface species observed during the (A) n-octane-SCR and (B) toluene-SCR of NOx over 2 wt % Ag/Al₂O₃ with and without plasma. Feed composition: 720 ppm of NO, 540 ppm of n-C₈H₁₈ or 620 ppm of C₈H₁₈ equivalent of 4340 ppm as Cl, 4.3% of O₂, and He balance. The total flow rate was 100 cm³ min⁻¹. Reprinted with permission from [25]. Copyright 2014 American Chemical Society.
In summary, the plasma-catalyst system was shown to have a synergistic effect on HC-SCR process and increased the NOx removal efficiency. The promotion effect of plasma-catalyst system is more pronounced at low temperatures (< 300°C), where the catalyst-alone is not active. Formation of oxygenated species such as aldehydes and nitrogen-contained organic compounds and conversion NO to NO2 during plasma are reported as the reasons for higher de-NOx efficiency in plasma-catalyst system.

3. NH3-SCR using NTP

The NH3-SCR system is a mature de-NOx technology which has been widely used to remove NOx from stationary flue gases since 1980s and has been extended to automotive application more recently. Several investigations have demonstrated that NOx conversion rate increases at low temperatures (< 250°C) with an increase in NO2/NO ratio especially if an equimolar ratio of NO and NO2 in the exhaust is achieved [11,27] i.e. the reaction (2) has a higher rate at low temperatures, compared to reaction (1).

\[
\begin{align*}
4\text{NO} + 4\text{NH}_3 + \text{O}_2 &\rightarrow 4\text{N}_2 + 6\text{H}_2\text{O} \quad (1) \\
2\text{NO} + 2\text{NO}_2 + 4\text{NH}_3 &\rightarrow 4\text{N}_2 + 6\text{H}_2\text{O} \quad (2)
\end{align*}
\]

In keeping with this approach pre-oxidation of NO to NO2 using NTP generated by a DBD reactor upstream of a NH3-SCR reactor was reported to improve the de-NOx efficiency in the 100 - 250 °C range [27]. The results of treating the filtered exhaust of a 4.4 kW diesel generator, containing NO, NO2, hydrocarbons, CO, aldehydes and O2, with a two-stage plasma-NH3-SCR reactor using a V2O5/TiO2 monolithic catalyst is shown in Figure 7. The NO and NO2 concentration profiles obtained after the plasma reactor evidence the conversion of NO to NO2 with increased energy density, an concurrent increase in NOx removal efficiency obtained after two-stage plasma-NH3-SCR at 100 °C. At about 60 J L⁻¹, which corresponds to almost equal NO and NO2 concentrations, the NOx removal efficiency is relatively high and with further increases in the energy density, the NOx removal efficiency stabilizes [11].
Wang et al. [28] examined the efficiency of plasma-assisted catalytic system for NO removal using a 4 wt.%Cu 4 wt.%Ce/ZSM-5 catalyst in the presence of 500 ppm NO, 500 ppm NH₃, 6% O₂ in N₂ and a 60000 h⁻¹ GHSV. Therein, up to 90.7% and 80.1% NO and NOₓ, respectively, removal efficiencies were achieved at 180 °C and an energy density of 367 J L⁻¹. In the absence of a catalyst, the removal efficiencies were 34% and 12% for NO and NO₂, respectively. It was postulated that the oxidation of NO was facilitated by the increased oxygen migration between Cu and Ce and Cu ions could be incorporated into the vacant sites on the CeOₓ surface to form oxygen vacancies, which increased the amount of adsorbed oxygen species on the surface of the catalyst. The increased catalytic reduction of NO at ambient temperature was attributed to the low thermal stability of the acid sites of the 4 wt.%Cu 4 wt.%Ce catalyst.

The addition of propene to the feed and an increase in input voltage enhanced the de-NOₓ efficiency of the plasma-NH₃-SCR system. However, these changes also generated a significant amount of by-
products such as CO, N₂O, HCHO, CH₃CHO at the outlet of SCR reactor [27]. Previous work reported a synergistic effect in NOₓ removal efficiency using a hybrid plasma-catalyst system using a NH₄⁺ modified zeolites as the SCR catalyst in a DBD reactor in the presence of high oxygen concentrations at 100 °C. As found for the HC-SCR reaction, it is believed that plasma converts some NO to NO₂ which ultimately leads to an increase of the NOₓ removal efficiency [29].

4. NOₓ storage-reduction catalysis (NSR) using NTP

NOₓ storage-reduction technology (or lean NOₓ trap (LNT)), first introduced by Toyota, is used commercially to remove the NOₓ emissions from the exhaust of light-duty diesel vehicles. This technology works using fuel-lean and fuel-rich cyclic conditions wherein the fuel-lean condition (excess O₂) leads to the NSR catalyst adsorbing NOₓ. Thereafter, during the fuel-rich condition (excess reductant) the adsorbed NOₓ reduces to N₂. The NSR catalyst requires sites for adsorption of NOₓ and also sites for the reduction of NOₓ. Pt/BaO/Al₂O₃ is the most common catalyst for NSR catalysis and has a good performance at temperature above 300°C. Due to low exhaust gas temperatures (180 - 350°C) of light-duty diesel vehicles, low temperature NSR catalysts are required [30]. Therefore, as an attempt to address the low temperature NOₓ removal efficiency non-thermal plasma-catalyst system had been tested.

A number of research studies developed a DBD reactor and applied NTP to the rich phase of the NSR process (IPC system) using different catalysts including a perovskite catalyst (LaMn₀.₉Fe₀.₁O₃) [30] and M/BaO/Al₂O₃ formulations with M = Mn, Fe, Co, Ni, Cu, Pt [31,32]. In comparison to a Pt/BaO/Al₂O₃ catalyst, the Pt-free catalysts exhibited higher NOₓ storage capacity, in the fuel-lean feed containing NO, O₂ and an Ar balance at low temperatures (30 – 300 °C) but also significantly lower activity in NOₓ removal step under fuel-rich conditions containing H₂ and an Ar balance. The low activity of these catalysts in the NOₓ reduction step was significantly improved by the use of the NTP, attributed to the facile H₂ activation during NTP (Table 3). For example, high NOₓ conversions (up to 90%) between 150-350 °C using Co/Ba/Al₂O₃ was reported [32]. The effect of CO
versus H\textsubscript{2} as the reductant during plasma-NSR over Pt/Ba/Al\textsubscript{2}O\textsubscript{3}, Pd/Ba/Al\textsubscript{2}O\textsubscript{3} and Pd/Co/Ba/Al\textsubscript{2}O\textsubscript{3} was also investigated. The addition of CO reduced the NO\textsubscript{x} conversion significantly at low temperatures over both Pt/Ba/Al\textsubscript{2}O\textsubscript{3} and Pd/Ba/Al\textsubscript{2}O\textsubscript{3}. In contrast, the Pd/Co/Ba/Al\textsubscript{2}O\textsubscript{3} was shown to have a better activity in the presence of CO in the plasma-NSR process with NO\textsubscript{x} conversions close to 99\% at 150-350 °C [33]. These studies did not investigate the effect having small amount of O\textsubscript{2} in the rich phase or the use of N\textsubscript{2} as balance gas instead of Ar balance, which was known to significantly change the results during NTP.

Table 3. NO\textsubscript{x} storage capacity measured at lean conditions (500 ppm NO, 8\% O\textsubscript{2} and Ar balance; GHSV = 14,400 mL g\textsubscript{cat}\textsuperscript{-1} h\textsuperscript{-1}; time = 50 min); NO\textsubscript{x} conversion during storage and reduction experiment (lean phase: 500 ppm NO, 8\% O\textsubscript{2} and Ar balance, time = 10 min; rich phase: 2\% H\textsubscript{2} and Ar balance, time = 2 min); NO\textsubscript{x} conversion during plasma-assisted storage and reduction experiment (lean phase: 500 ppm NO, 8\% O\textsubscript{2} and Ar balance, time = 10 min; rich phase: power = 1.8 w, 2\% H\textsubscript{2} and Ar balance, time = 2 min) over different catalysts as a function of temperature. Adapted from [31].

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>NO\textsubscript{x} storage capacity (µmol g\textsuperscript{-1})</th>
<th>NO\textsubscript{x} conversion (%)</th>
<th>NSR</th>
<th>NTP-NSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>200 350</td>
<td>200 350</td>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td>Pt/Ba/Al\textsubscript{2}O\textsubscript{3}</td>
<td>175 248</td>
<td>38 89</td>
<td>71</td>
<td>98</td>
</tr>
<tr>
<td>Co/Ba/Al\textsubscript{2}O\textsubscript{3}</td>
<td>260 265</td>
<td>16 10</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Ni/Ba/Al\textsubscript{2}O\textsubscript{3}</td>
<td>210 265</td>
<td>8 47</td>
<td>97</td>
<td>90</td>
</tr>
<tr>
<td>Mn/Ba/Al\textsubscript{2}O\textsubscript{3}</td>
<td>264 265</td>
<td>20 26</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Cu/Ba/Al\textsubscript{2}O\textsubscript{3}</td>
<td>205 265</td>
<td>4 26</td>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>Fe/Ba/Al\textsubscript{2}O\textsubscript{3}</td>
<td>120 170</td>
<td>5 28</td>
<td>78</td>
<td>100</td>
</tr>
</tbody>
</table>
Wang et al. [34,35] similarly combined NTP with NO\textsubscript{x} storage and reduction or decomposition over a H-ZSM-5 (Si/Al = 22) catalyst (IPC system). In this study, the NO\textsubscript{x} containing feed was adsorbed on the catalyst for a long time at room temperature before the stored NO\textsubscript{x} was reduced to N\textsubscript{2}, N\textsubscript{2}O. The reduction was performed under oxygen lean conditions (e.g. 5% O\textsubscript{2} and 95% N\textsubscript{2}) using NTP and a reductant (CH\textsubscript{4} and NH\textsubscript{3}) at room temperature for a short period of time. The NO\textsubscript{x} desorption and conversion to N\textsubscript{2} were correlated with the energy density of the plasma and the concentration of the reductant (maximum NO\textsubscript{x} conversion to N\textsubscript{2} was 95%). N\textsubscript{2}O was found to be the main by-product during this process and its decomposition to N\textsubscript{2} and O\textsubscript{2} was facilitated by an increase in the plasma energy density. Both CH\textsubscript{4} and NH\textsubscript{3} as reducing agents were shown to be very effective in controlling the NO\textsubscript{x}. In addition to the NSR process, NO decomposition in plasma under oxygen lean condition has been shown to occur in the absence of a reductant through:

\[
N + NO \rightarrow N_2 + O
\]  

However, the extent to which this reaction occurred was limited due to the lower dissociation energy of O\textsubscript{2} compared to N\textsubscript{2}. In the presence of NH\textsubscript{3}, NH\textsubscript{3} based free radical species were formed which reduced NO to N\textsubscript{2} through:

\[
NH + NO \rightarrow N_2 + OH
\]  
\[
NH_2 + NO \rightarrow N_2 + H_2O
\]

increased the NO\textsubscript{x} removal efficiency due to activation of NH\textsubscript{3} being easier compared with N\textsubscript{2} [34]. CH\textsubscript{4} is believed to not only act as a reducing agent but also limit the reverse reaction, i.e. formation of NO\textsubscript{x}, by consuming oxygen. An increase in CH\textsubscript{4}/O\textsubscript{2} ratio resulted in an increase in NO\textsubscript{x} conversion up to 95% and CH\textsubscript{4} was found to be completely converted to CO\textsubscript{2} during the plasma-NSR process [35].

The addition of 2% H\textsubscript{2}O and 2% CO\textsubscript{2} to the feed in the plasma-NSR process over Co/Ba/Al\textsubscript{2}O\textsubscript{3} catalyst was found to significantly inhibit the NO\textsubscript{x} reduction efficiency and remove the benefits of NTP. This effect was attributed to a decrease in the NO\textsubscript{x} storage capacity of the Co/Ba/Al\textsubscript{2}O\textsubscript{3} catalyst in the presence of H\textsubscript{2}O and CO\textsubscript{2}. The addition of Pd to the Co/Ba/Al\textsubscript{2}O\textsubscript{3} catalyst mitigated the inhibition effect of H\textsubscript{2}O and CO\textsubscript{2} in the plasma-NSR system and increased the stability of that catalyst both with and without the presence of H\textsubscript{2}O and CO\textsubscript{2} [32]. Similar results were obtained on the
addition of 2% H2O to the feed during plasma-facilitated NOx storage and decomposition or reduction using CH4 over a H-ZSM-5 catalyst. Therein, the NOx conversion and selectivity to N2 were decreased; however, H2O did not have any effect on the process using NH3 as the reductant [34,36]. H2O was shown to compete with NOx during storage step, promote formation of N2O in the reduction step and thus, decrease NOx reduction efficiency [36].

In another approach NTP was applied to the lean step of the NSR process (storage step). Li et al. [37] reported an enhancement in NOx storage capacity of a Pt/Ba/Al2O3 catalyst at 100 - 300°C when using a plasma-catalyst system compared with the thermally activated process. In this case, the plasma increased the NO to NO2 oxidation rate via O-radicals formed by collision of electrons with O2 in the gas phase. NOx storage capacity could be further increased by having the catalyst in plasma discharge zone rather than the plasma followed by the catalyst bed. The catalyst in the plasma discharge zone not only adsorbed the NO2 formed by plasma but also adsorbed the NO from the gas-phase which then reacted with adsorbed oxygen radicals and forms more NO2 which then contributed to higher NOx storage capacity [37].

5. NO oxidation using NTP-catalyst system

As noted for the NSR catalysis, whilst NO is the dominant species in the exhaust, it adsorbs weakly on the catalyst surface and thus, it is common to first convert NO to NO2 which can improve the catalytic activity in the NOx reduction process at low temperatures (although some research studies have questioned the role of NO oxidation in NOx removal especially in the presence of hydrocarbons) [18,19,38]. In applications associated to the stationary sources e.g. waste gas streams, it is proposed to extend the oxidation of NO further to N2O5, which can be easily removed by various air pollution control systems such as wet or semi-dry scrubbers. There is a patented process called low-temperature NOx (LoTOx system), in which ozone injects to the exhaust stream to convert NO to NO2 and further to N2O5 [39–42]. This process was shown to remove 90% of NOx emissions [39]. Jogi et al. [43] investigated NO oxidation using a hybrid plasma-catalytic reactor (IPC system; fed by a mixture of
NO, O₂ and N₂) and an ozone injector (air plasma or O₂ pure plasma) followed by a fixed-bed catalytic reactor (PPC system; fed by ozone, NO and N₂) at 10-500 J L⁻¹ using Fe₂O₃ and TiO₂ as catalysts. The hybrid plasma-catalytic reactor was not efficient for NO removal e.g. the 450 ppm inlet NO concentration decreased by 40-50 ppm in the outlet when increasing the plasma energy density up to ~230 J L⁻¹ and only NO₂ was observed as product. In contrast, the ozone injection reactor was able to oxidize all NO to NO₂ at 10-12 J L⁻¹ and further to N₂O₅ by an increase in plasma energy density, correlated to the O₃ concentration. The catalyst presence in the ozone injection reactor contributed not only to O₃ destruction, so that the outlet O₃ concentration significantly decreased, but also to further NO oxidation to N₂O₅ [43].

The effect of catalyst placement in the discharge zone during NO oxidation in the hybrid plasma-catalytic reactor was also tested. Both configurations (catalyst placed at the outlet or along the full-length of the discharge zone) led to an improvement in the NO to NO₂ oxidation, compared with in the absence of the catalyst or when the catalyst was placed at the inlet of discharge zone. Without the catalyst, NO was oxidized to NO₂ in the discharge zone and on increasing the NO₂ concentration in the bed, the reverse reaction occurred until the reaction reached equilibrium. If the catalyst was placed in the inlet of discharge zone, the NO₂ formed via the catalyst was converted back to NO by the end of the reactor where no catalyst was present [44].

The ozone injection reactor (with TiO₂ as the catalyst) was further studied at different catalyst temperatures, flow rates and inlet NO concentrations [42]. NO to NO₂ oxidation was correlated with the inlet O₃ concentration. When inlet O₃ concentration reached the NO concentration at inlet condition, all NO was oxidized to NO₂. Further increases in the inlet O₃ concentration led to further oxidation of the NO₂ to N₂O₅ (Figure 8).
The TiO$_2$ catalyst did not have any detectable effect on the reaction at low temperatures but improved the conversion of NO$_2$ to N$_2$O$_5$ at high temperatures. The NO$_2$ to N$_2$O$_5$ reaction is believed to be limited by the formation of NO$_3$ which can be enhanced by the catalyst. For example, NO$_2$ can adsorb on the catalyst surface and form NO$_3$ species (NO$_{2(g)}$ + O.* $\rightarrow$ NO$_3$.*) using surface oxygen species supplied by O$_3$ decomposition (O$_{3(g)}$ + * $\rightarrow$ O$_{2(g)}$ + O.*). Thereafter, these species react with another NO$_2$ to form N$_2$O$_5$. The stoichiometric ratio of [O$_3$]/[NO] to convert all NO to N$_2$O$_5$ is 1.5. One way to improve the efficiency of ozone injection reactor from an industrial point of view would be to operate at stoichiometry where the lowest amount of O$_3$ is consumed. Jogi et al. [42] reported that this ratio can be reduced by the effect of several operating parameters (Figure 9). For example, an increase in the inlet [NO], an increase in temperature, a decrease in flow rate or the presence of catalyst all led to a decrease in the [O$_3$]/[NO] ratio.
6. Conclusions and recommendations

The combination of NTP and catalysis has been examined in various reactor configurations to enhance the performance of the current de-NO\textsubscript{x} technologies such as SCR and NSR applicable to the exhaust gas streams of stationary or mobile sources under lean conditions. Technically, the plasma-catalyst system has been shown to have a synergistic effect on the de-NO\textsubscript{x} efficiency. The plasma-catalyst system is mostly applied at low temperatures (< 300°C) where current thermally activated technologies are not efficient.

Predominantly, NTP has been combined with SCR in a two-stage system configuration, where a flow of feed is first passed through the NTP and, thereafter, the outlet gases are reacted over a fixed bed
catalytic reactor. In general, the NTP leads to the formation of oxygenated species such as aldehydes, nitrogen-containing organic species and NO is converted to NO₂, which improve the reduction efficiency to N₂ during the HC-SCR reaction. An increase in plasma energy density was correlated to having higher de-NOₓ efficiency. Furthermore, NTP has been used as a pretreatment to convert the NO to NO₂ before NH₃-SCR reactor, which is believed to improve the NOₓ reduction efficiency at low temperatures.

The NTP has been applied to the NSR using different concepts. In one case, it is applied to the lean phase of the NSR and expected to improve the adsorption capacity of the catalyst by conversion of NO to NO₂. Alternatively, a catalyst with high adsorption capacity is chosen and the NTP is applied to the rich phase to improve the reduction activity of the catalyst at low temperature. Both were shown to be successful, although for most of the catalysts studied, inhibition by addition of H₂O and CO₂ to the feed was observed.

Finally, NO oxidation has been studied to improve the NOₓ removal processes using plasma-catalyst system in different reactor configurations relevant to both mobile and stationary sources’ applications. Although an increase in plasma energy density generates more O₃ which converts NO to NO₂ and finally to N₂O₅, the catalyst is shown to destruct the O₃ residuals and contribute to the efficiency of N₂O₅, which is attributed to the facile of formation of NO₃ species on the catalyst surface.

While not so many studies have been focusing so far on the in-plasma configuration, placing the catalyst in the discharge zone could open new routes towards efficient NOₓ removal but there are still significant challenges to overcome as finding the suitable materials, reactor design and operation conditions, including gas composition and discharge type [45,46] can be the game changing parameters.

Despite of the many investigation reported on NOₓ removal using plasma-catalyst system and claim of synergistic effect, there is no report of demonstration of this system on a vehicle. However, a pilot
scale aftertreatment system that was a combination of NTP and adsorption has been designed and successfully met the most recent International Maritime Organization NOx emissions standards by removing 94% of NOx in the exhaust of a marine diesel engine [47,48]. This system operated on adsorption and desorption cycles where plasma was on during desorption cycle only and required ~4% of output engine power.

Despite commercial applications of NTP in the wastewater treatments, air pollution control or food and beverage industries [49,50], one of the challenges in commercial use of plasma-based systems in emission control is energy requirements to drive NTP if used continuously. In the investigations covered by the present review, the energy density required to decrease emissions in the exhaust ranged from 10 to almost 2000 J L⁻¹. This corresponds to less than 1 BHP per liter of the engine intermediate load for the lower range while the higher end corresponds to several tens of BHP per liter which is unlikely to be acceptable. It is therefore clear that the energy requirement of such plasma-based systems will need to be at the heart of their development to be viable future solutions. Some proposed ways to reduce energy requirements associated with the NTP-catalyst systems are the development of novel catalysts, optimizing the power supply and operation mode and also design of reactors suitable for each particular application. The energy requirement can be managed if the NTP is not used continuously. As described earlier, a NTP-based aftertreatment system for marine diesel was successfully optimized using cyclic operation where plasma was only on in desorption cycles and for a short time.

Catalysts designed for NTP operation also present an opportunity to improve the energy load. These should be optimised to enhance the synergy of combining the catalyst with the NTP discharge zone. Therefore, the dielectric constant, pore size, acidity of the materials become important parameters to consider for these applications, as already discussed by various groups [46,51–55]. Although there is an enhancement in the de-NOx efficiency observed when using a plasma-catalyst system, high energy densities are required to activate the catalysts in the plasma at low temperatures. Mechanistic studies using thermal characterization methods to understand the surface changes, kinetics and reaction
elemetry steps occurring on the catalyst surface can be helpful towards designing novel catalysts. For example, plasma treatment was shown to affect the acidity of zeolite catalysts [55]. Liu et al. [56] observed an increase in Lewis and Brönsted acidity of Pd/HZSM-5 catalyst when pre-treated in glow discharge plasma, followed by air-calcination, leading to an increase in Pd dispersion and thus, an enhancement in catalytic activity and stability during methane oxidation. Acid zeolite or ion exchanged zeolite catalysts are currently the preferred choice for the SCR reaction. Kwak et al. [57] reported an increase in NO\textsubscript{x} conversion by an increase in the acid sites of H\textsuperscript{+} modified NaY zeolites during plasma-assisted SCR of a simulated diesel engine exhaust gas mixture. Considering the plasma effect on catalyst acidity of zeolites, this creates an opportunity to develop new improved catalyst for NO\textsubscript{x} removal using plasma-assisted catalyst systems.

The other possible way to reduce energy requirements is to design a plasma-catalyst reactor with higher energy efficiencies that should be also compatible with the exhaust system. Most of studies in the literature used DBD reactor with two reactor configurations (IPC and PPC) for NO\textsubscript{x} removal as extensively studied in this paper. There are limited studies combined other types of plasma reactors such as gliding arc, radio frequency, microwave discharge and corona discharge with catalyst for NO\textsubscript{x} removal. Indarto et al. [58], investigating the decomposition of CO\textsubscript{2} using gliding arc reactor, claimed that the gliding arc reactor had better energy efficiency compared to DBD, corona discharge and radio frequency plasma systems. Kim et al. reported NO\textsubscript{x} reduction over γ-Al\textsubscript{2}O\textsubscript{3}, mechanically mixing γ-Al\textsubscript{2}O\textsubscript{3} with TiO\textsubscript{2} and BaTiO\textsubscript{3} and Co-ZSM-5 catalysts using a combined pulse corona discharge with catalyst system in both IPC and PPC reactor configurations. The highest de-NO\textsubscript{x} efficiency was obtained using the IPC system with γ-Al\textsubscript{2}O\textsubscript{3} as the catalyst and addition of a reductant (e.g. methanol). The energy densities reported are in the range of 10-160 J L\textsuperscript{-1}, similar to the energy densities of DBD reactors.
References


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