Impact of High-Voltage Discharge After-Treatment Technology on Diesel Engine Particulate Matter Composition and Gaseous Emissions

Thawatchai Wongchang, Sak Sittichompoo, Kampanart Theinnoi,* Boonlue Sawatmongkhon, and Sumrerng Jugjai

ABSTRACT: Diesel particulate matter (DPM) and oxides of nitrogen (NOx) are the emissions from diesel engines (compression ignition engines) of the most concern and are currently strictly regulated. In this work, we present an alternative diesel emission control technique to assist in further emission reduction. An experiment-oriented study on diesel engine emission abatement using low-power, low-frequency, high-voltage discharge (HVD) treatment was carried out in a laboratory-scale reactor with whole diesel engine exhaust gas. A dielectric barrier discharge (DBD) reactor was used in direct contact with diesel exhaust gas at atmospheric temperature with an input energy density between 200 and 400 J/L. An investigation of the direct effect of the high-voltage discharge reactor on the diesel exhaust gas treatment was carried out to characterize both diesel particle and gaseous emissions. The proposed HVD system demonstrated up to 95% particulate matter reduction by mass or 64% reduction by number, and 63% reduction of the diesel soot particle geometrical mean diameter by HVD-generated O3 oxidation. Thermogravimetric analysis revealed the significant change in the diesel soot compositions and oxidation characteristics. HVD-treated particulate matter demonstrated a lower reactivity in comparison to untreated soot. Gas composition analysis indicated the generation of free radicals (e, O, OH, O3, and N) by the HVD system, as mainly indicated by the increase of the NO2/NO ratio and concentration of CO and O2. The pattern of CO2 reduction while CO and O2 increased indicated the dissociation of CO2 by HVD. Free radicals generated by HVD directly affected DeNO, DeNOx, NO2/NO ratio, and CO and CO2 selectivities.

INTRODUCTION

Global concern with air pollution has driven the stringent controls of the level of emitted particulate matter (PM) and oxides of nitrogen (NOx) by diesel engines, especially since the Dieselgate or Emissionsgate scandal in 2015, which led to a highly negative public opinion toward diesel engines. Several diesel emission control technologies have been developed to control harmful emissions, such as exhaust gas recirculation (EGR), lean NOx traps (LNTs), and urea selective catalyst reduction (urea-SCR) for NOx reduction; diesel oxidation catalysts (DOCs) for carbon monoxide (CO) and total hydrocarbon (THC) reductions; and diesel particulate filters (DPFs) for PM reduction. However, trade-offs due to limitations of the after-treatment system still exist and negatively affect both emission levels and engine performance, for instance, a NOx–PM trade-off by utilizing EGR; a high-pressure drop in the exhaust manifold caused by a clogged DPF, which causes increased fuel consumption and requires thermal regeneration; a fuel penalty due to regenerating LNT; and a thermal requirement to operate a catalyst-based after-treatment (e.g., DOC, LNT, and urea-SCR). The more stringent emission legislation requires a more significant emission reduction, leaving current after-treatment control systems unable to comply with the future regulations.

HVD has been investigated and proved to improve diesel exhaust emissions for gaseous (e.g., NOx, CO, and THCs) and PM emissions. Fundamentally, HVD operates using a high potential applied to electrodes between which exhaust gas can flow. Exhaust gas molecules are ionized when present near electrodes and release visible light emission,
which is referred to as plasma or known as the fourth state of matter. In HVD, a nonthermal plasma (NTP) is produced, which occurs when the kinetic energy (or temperature) of electrons is significantly higher than the kinetic energy of gaseous molecules (in this case, exhaust gas). Electrical energy is transferred to electrons in the NTP system, which leads to the formation of free radical species such as N, O, H, O2, and OH. Subsequently, O3, NO2, NO, HNO3, and several intermediate species are formed, as shown in reactions R1−R20 in the Appendix.

The usage of NTP with exhaust gases can be categorized into direct and indirect reactions, which are determined by the plasma reactor’s chemical interactions with the exhaust gases. For instance, Okubo et al. and Madhukar and Rajanikanth conducted studies with an indirect reaction through the production of ozone from air using a dielectric barrier discharge-NTP reactor (DBD-NTP) that employs a dielectric barrier material in between electrodes to prevent spark discharge. This promotes NO to NO2 for improving DPF regeneration at lower oxidation temperatures. The proposed mechanisms of soot reduction by O, OH, O2, and NO2 through R21 to R29 are shown in the Appendix.

Recently, direct DBD-NTP research on diesel exhaust gas treatment has gained momentum due mainly to its effectiveness in generating O3 from O2 (R1 and R2 in the Appendix) and NOx from NO (R11 to R15 in the Appendix) in diesel exhaust gas for DPF regeneration, NOx/PM reduction in the combination of catalysts, and/or NOx absorbents at low temperature.

In addition, HVD is employed in particle removal applications through the effect of electrostatic precipitation (ESP), which utilizes the electric field (with and without corona discharge) to trap PM from the diesel engine. A typical ESP device employs high-voltage direct current (HVDC) with negative potential connected to the inner electrode or positive potential applied to the inner electrode. Additionally, pulsed HVD or HVAC (high-voltage alternating current) has also been utilized in ESP research. The combination of HVD with Na2SO3 or Na2SO3 + NaOH solutions has been reported to remove NOx and PM with up to 90% removal efficiency with a lower energy input in comparison to a standalone HVD treatment system. However, the application is rather limited only to stationary engine application due to the requirement of Na2SO3-based solution storage, needing periodic replenishment and replacement of the used solution, making this approach unfavorable for vehicular application. Therefore, this type of HVD system will not be discussed further in this paper.

The simultaneous reduction of diesel engine gaseous and particulate matter emissions has been investigated using DBD-NTP. The removal efficiency of both PM and THCs was enhanced with increased discharge voltage at the given discharge power. However, a range of discharge voltages (from 7 to 9 kV @ 15.5 kHz) was optimum for NOx reduction. Babaie et al. studied the correlation between PM, O3, and CO2 and demonstrated that PM reduction was strongly impacted by the amount of O3 generated by the DBD reactor from the O3 available in the diesel exhaust gas. Furthermore, the dissociation of CO2 into CO (as shown in R30 through R34 in the Appendix) was observed. The study concluded a strong correlation with the discharge voltage rather than with the discharge frequency.

The preceding works on NOx–HC–PM reduction using NTP mostly investigated using simulated gas, filtered diesel exhaust gas, or dilute diesel exhaust gas. Few studies have investigated the simultaneous effect of HVD on both gaseous and PM emissions from raw diesel exhaust gas that contains PM and water vapor and can affect the formation of free radicals. Recent studies only focused on the aspect of either PM oxidation or DPF regeneration by O3 generated by NTP, while there are limited works in the literature on the aspect of the synergy effects of direct NTP and ESP. The objective of this paper is to investigate the synergy effects of low-power, low-frequency HVD on diesel exhaust gas components (NOx, CO, and THCs) and PM characteristics using untreated raw diesel exhaust gas.

INSTRUMENTATION AND EXPERIMENT SETUP

A Yanmar L100V single-cylinder direct-injection diesel engine on an eddy current dynamometer test rig was used to generate diesel exhaust gas in the experiment. The engine was run at 1500 rpm and an IMEP (indicating mean effective pressure) of 2.92 bar, corresponding to 50% of the maximum engine load. Commercial BS-diesel that contained 5% v/v biodiesel was used in this experiment. The in-cylinder pressure and rate of heat release (ROHR) were monitored by an in-cylinder transducer (Kistler 6056A) and charge amplifier (Kistler 5018A).

The exhaust gas components (CO, THCs, NOx, CO2, and O2) were monitored by a Testo 350 flue gas analyzer (Testo Ltd., Alton Hampshire, UK). Diesel particulate matter (DPM) emission was measured using a TSI 3910 SMPS (scanning mobility particle sizer) (TSI Inc., Shoreview, MN, USA) (scan up time = 45 s, scan retrace time = 15 s, 0.75 L/min inlet flow rate, 0.25 L/min sample flow rate, radial DMA (RDMA), isopropanol-based CPC, and cyclone preconditioner). The DPM components and characteristics were evaluated using a Pyris 1 TGA (thermogravimetric analysis) analyzer (PerkinElmer Inc., Waltham, MA, USA).

A tubular dielectric barrier discharge (DBD) reactor was fabricated using a quartz tube with dimensions of ø 17 × 300 mm. Two electrodes were utilized and positioned internally and externally on the quartz tube reactor. The internal electrode (ø 6 mm) made from stainless steel was placed in the center of the quartz tube. The external electrode was a copper wire wrapped around the quartz tube, whose longitudinal length defined the reactor’s effective length (Leff). High voltage (HV) was supplied by an in-house-developed high-voltage power supply (HVPS) designed to deliver low output frequency between 10 and 200 Hz. The HVPS was designed based on an automotive ignition coil with a built-in solid-state switch circuit driven by an integrated circuit based on a combination of monostable and astable multivibrator circuits. The proposed HVPS is capable of generating a high-voltage pulse in a similar approach to the experiment performed in ref 4. The calculated specific energy density (SED) of up to 400 J/L was achieved by adjustment of the HV power supply frequency. A digital storage oscilloscope (Metrix OX 7062) and high-voltage probe were employed to measure the output voltage of the high-voltage power supply that can detect a single HV pulse with Vpeak and Vaverage of 9 and 7 kV, respectively.
MEASUREMENTS

The experiments cover two parts of the investigation: (1) the direct effect of the magnitude of the high voltage supplying the reactor on the diesel particulate matter removal efficiency and (2) the effects of HVD on the diesel exhaust gas composition. The proposed experiment setup is illustrated in Figure 1. The untreated raw diesel exhaust gas composition is tabulated in Table 1.

![Figure 1. Experiment setup for the proposed HVD system.](Image)

The first part of the experiment was to evaluate the effect of applying high voltage to diesel exhaust gas using a DBD reactor on the diesel particle emission. This was carried out to assess the performance at different HVD operating conditions, as shown in Table 2. A TSI 3910 SMPS was employed to obtain the particle size distribution (PSD), total particle concentration, and geometric mean particle diameter. PM characteristics including the oxidation behavior, composition, and oxidation kinetics were determined using a ramp test on the TGA with the heating program in Table 3 utilizing a scanning rate of 3 °C/min, similar to the heating program in ref 45. The slow temperature scanning rate was chosen to ensure a sufficiently high resolution of the transition during the oxidation process of the PM sample and also to allow adequate time for the PM sample to completely oxidize, which allowed more accurate and reliable results,46 including determination of the start of the oxidation temperature onset. The TGA tests were performed on glass fibers loaded with diesel particulate matter, which were cut into 4 mm diameter discs with a specially fabricated tool. Each TGA test was conducted with the same number of discs at an approximate sample weight of 5.5 ± 0.5 mg to ensure the consistency of the tests. For PM characterizations, the P20-L50 sample was chosen based on the assumption of a high GHHSV value, which was an appropriate representative of general engine operating conditions.

The remaining part of the experiment was to study the effect of direct application of HVD on gaseous emissions. This allows a more comprehensive assessment of the relationship between diesel PM and diesel gaseous emissions. The gas hourly space velocity (GHSV) is determined by the ratio between the engine-out flow rate (Q) (in liters per minute: L/min) and the reactor’s effective volume (V) (in liters), as shown in eq 1. In this study, the GHSV was chosen in the range between 14 and 28 kh⁻¹, which was within the general operating GHSV of catalysts in emission after-treatment research. The GHSV is in inverted proportion to the gas residence time within the proposed reactor.

\[
\text{GHSV (h}^{-1}) = \frac{Q \times 60}{V}
\]  

(eq 1)

The specific energy density (SED) can be calculated from the ratio of the electrical input power of the HVPS (in watt: W) to the diesel exhaust gas flow rate (in L/min) as shown in eq 2.

\[
\text{SED(J/L)} = \frac{\text{HVPS input power}}{\text{gas flow rate}} \times 60
\]  

(eq 2)

This paper employed the SED calculated from the HVPS input power by Mohapatro et al.37 instead of using the discharge power by Song et al.,33 which represents the ‘actual’ energy required by the proposed system to operate.

The selectivity of C-containing products in % is calculated by the molar fraction of output gas species (\(y_{\text{CO}}\), \(y_{\text{CO}_2}\) and \(y_{\text{THCs}}\)) using eqs 3 and 4 for CO and CO₂ selectivities, respectively.

\[
\text{SEL}_{\text{CO}} = \frac{y_{\text{CO}}}{y_{\text{CO}} + y_{\text{CO}_2} + y_{\text{THCs}}} \times 100\%
\]  

(eq 3)

Table 1. Diesel Exhaust Gas Constituents

| species | NO (ppm) | NO₂ (ppm) | NOx (ppm) | CO (ppm) | CO₂ (%) | THC⁺ (ppm) | O₂ (%) |
|---------|---------|---------|---------|--------|--------|--------|--------|
| concentration | 389.0 | 77.2 | 466.2 | 299.0 | 3.96 | 1191.0 | 15.11 |

“Hexane (C₆H₁₄) equivalent.

Table 2. HVD Operating Conditions

| test condition denoted | electrical input power (W) | reactor effective length (mm) | exhaust gas flow rate (L/min) | specific energy density (SED) (J/L) | gas hourly space velocity (GHSV) (kh⁻¹) |
|------------------------|---------------------------|-----------------------------|-------------------------------|-----------------------------------|--------------------------------------|
| engine-out             | 0                         | N/A                         | 3.0                           | N/A                               | N/A“                                |
| P10-L100               | 10                        | 100                         | 3.0                           | 200                               | 14.323                               |
| P20-L50                | 20                        | 50                          | 3.0                           | 400                               | 28.647                               |
| P20-L100               | 20                        | 100                         | 3.0                           | 400                               | 14.323                               |

“Not applicable.

Table 3. TGA Heating Program

| step | start of step temperature (°C) | end of step temperature (°C) | action in furnace | duration (min) | purge gas |
|------|-------------------------------|-------------------------------|-------------------|---------------|-----------|
| 1    | 40                            | 40                            | isothermal        | 40            | N₂        |
| 2    | 40                            | 400                           | heating up at 3 °C/min | 60            | N₂        |
| 3    | 400                           | 400                           | isothermal        | 30            | N₂        |
| 4    | 400                           | 350                           | cooling down at 3 °C/min | 60            | N₂        |
| 5    | 350                           | 600                           | heating up at 3 °C/min | 60            | O₂        |
| 6    | 600                           | 600                           | isothermal        | 60            | O₂        |
\[ SEL_{CO_2} = \frac{\gamma_{CO_2}}{\gamma_{CO} + \gamma_{CO_2} + \gamma_{THC}} \times 100 \] (4)

**RESULTS AND DISCUSSION**

**Effect of HVD on Diesel Particulate Matter Size.** Figure 2 demonstrates the visual conditions of the DPM samples collected on the glass fiber filter at medium engine load in comparison with the engine-out condition and PM treated by HVD applied at 200 J/L. The images illustrate the effectiveness of HVD toward PM removal through a visual assessment (lighter in color). Significantly less PM loaded was observed despite having the same duration and flow rates of the loading process for both conditions. However, the PM could not be removed completely and was limited to a certain concentration of PM in the reactor due to the short residence time of the PM within the reactor that led to partially oxidized PM collecting on the glass fiber filter. The reduced PM concentration was due mainly to the oxidation by radical species produced from O₂-rich diesel exhaust gas, which happened in a two-step process, as explained by Yao et al.\(^{18}\) (i) the electrostatic precipitation of DPM in the exhaust gas\(^{13}\) on to the electrodes and (ii) the oxidation of the precipitated DPM. Electrostatic precipitation played an important role in PM reduction, as black solid particles deposited onto the inside electrode and the quartz tube wall were evident, as reported in previous research.\(^{26,27,29}\) Coulomb's force or Coulomb electric field force\(^{16}\) was mainly concluded to account for the soot particles collecting on the internal electrode and reactor wall (the quartz tube inside the wall). In addition, Coulomb's force was thought to act together with the gradient force affecting soot particles in the nonuniform electric field\(^{16}\) and attracted further soot particles. It can be seen that there was a significant concentration of soot deposited on the quartz tube wall at the upstream of the effective DBD region or “reaction zone” (where the wrapped copper wire acted as the outside electrode) and a noticeably lower soot concentration at the downstream. The observed distributed gradient concentration of soot deposited on the reactor wall suggested that the soot particles were effectively charged within the electric field created by the HVD and attracted to the quartz tube wall where the copper wire was located. Additionally, the soot deposit gradient could be affected by the presence of O₂ and other free radicals generated by HVD, which partially oxidized the soot and left fewer soot particles on the quartz tube wall. It was thought that less O₂ was produced at the inlet of the reaction zone due to the insufficient residence time of the exhaust gas molecules to interact with the charged particles produced by HVD, therefore resulting in a higher density of soot deposition at the inlet of the reaction zone in comparison to the outlet. However, the higher O₂ concentration toward the outlet of the reaction zone resulted in partial oxidation, which reduced the soot density observed on the quartz tube. This similar phenomenon of a high concentration of soot deposit near the leading edge of the electrode was also visually observed as reported in ref 26.

The particle size distribution (PSD), total particle concentrations, and geometric mean diameter for both the number and mass of engine-out and HVD-treated conditions are illustrated in Figure 3A–D. Overall, the majority of the particles, in number and mass, for both raw exhaust and treated exhaust are mostly in the accumulation mode or classified as ultrafine particles and nanoparticles, as generally seen in diesel particulate matter studies.\(^{45,48–50}\) As a noticeably unique characteristic of DPM, the peak of the particle number concentration (at 115.5 nm) is located nearly identically to the peak of the particle mass concentration (at 154 nm). This is due mainly to the agglomerated carbonaceous and absorbed material forming large particles in accumulation mode, where most of the total particles mass exists. The results shown include several comparisons including (a) the effect of the space velocity and electrode effective length (P20-L50 vs P20-L100) and (b) the effect of the specific energy density (P10-L100 vs P20-L100). Overall, the PSD profiles indicate the significant effectiveness of HVD treatment on PM reduction, able to achieve a reduction of up to approximately 65% of the total particle concentration by number or approximately 95% reduction by mass (approx. 84% reduction at 48.7 nm and 52% reduction at 115.5 nm). This therefore leads to a decrease in the geometrical mean diameter of up to 63.50% due to the fact that the PM removal is mainly within the accumulation mode, while the nanoparticle removal is less effective on both a number basis and a mass basis, as shown in Figure 3E, F. This was further supported by the shifting of the PSD peaks toward ultrafine particles (<100 nm) and nanoparticles (<50 nm). This was explained by the partial diesel soot oxidation on the DPM’s surface, DPM mainly consisting of VOC, which has a higher tendency to be oxidized by free radicals in comparison to carbon in the soot, and resulted in a decreased particle diameter.\(^{41,43}\) Ji et al.\(^{30}\) reported the alteration of the DPM microstructure from a large aggregate and longer chain structure into a smaller aggregate and shorter chain, which is consistent with the results shown in Figure 3.

The electrodes’ effective length proved to be highly effective in removing PM regardless of the input power (comparing P10-L100 and P20-L100), which initially agreed with the thermogravimetric analysis results (discussed in the next section). A noticeable further PM mass reduction could be observed when the reactor’s effective length was increased. This is mainly because of the substantial decrease in effective GHSV, as a result of which the residence time of the diesel exhaust gas in the reactor lengthened drastically, allowing more time for the PM to complete the oxidation process by radical species. The longer residence time also allows more soot particles to successfully precipitate onto the collecting electrode,\(^{51}\) and hence, greater PM removal was achieved. Meanwhile, an
Improvement of the PM removal rate was also seen with the increase of input power (from 10 to 20 W), which was observed in the total particle emission and mean particle size. This is because of the nonproportional relationship between the discharge power and the amount of oxidized PM, as described in ref 27, where increasing the input power would enhance the oxidation efficiency to a certain point and the oxidation efficiency would then plateau despite the increased power.

**Thermogravimetric Analysis of Diesel Particulate Matter.** The diesel PM composition, including water, VOC, and EC, as depicted in Figure 4A for all test conditions for the...
purpose of comparison with the engine-out condition. The results presented are in the components' mass for a simplified comparison of the soot mass reduction between each condition by utilizing the same number of DPM loaded filters in the TGA to ensure a fair comparison between conditions. The use of this methodology provides a rapid overview measurement of the PM emitted into the atmosphere for each condition. A significant reduction of PM using HVD was also seen by comparing the total DPM mass loaded on the filters. Overall, a reduction of the total DPM mass of between 47 and 58% could be observed, which was mainly achieved by EC and H₂O reductions of between 49 and 59% and 68 and 80%, respectively. Meanwhile, the decreased VOC mass indicated a less significant contribution to the total DPM mass reduction in the range between 16 and 49%. These results confirm that the DPM reduction mechanism with the utilization of the HVD system is through the interaction between highly reactive species (mainly O, OH, O₃, and NO₂) and DPM (referred to as "suspended DPM") that was treated and slipped out from the HVD reactor. Direct interaction between the soot particles and autoselective discharge was reported to cause soot cake locally at high temperature (>1000 K) for a short duration (<10 ms), which promoted local DPM oxidation.

The DPM components' mass fractions illustrated in Figure 4B indicate a relatively similar EC fraction (between 18 and 21%) for both the engine-out and HVD-treated conditions. A drastic increase of the VOC fraction (from 41% for engine-out to between 50 and 67% for HVD-treated) and a reduced H₂O fraction (engine-out, 37% reduced to between 13 and 28%) could be observed with HVD-treated DPM samples in general. These findings suggested that the DPM was dehydrated by two possible processes: (1) energized DPM by means of autoselective thermally caused H₂O evaporation and (2) the interaction between charged electrons and H₂O through reactions R5–R7. The results in Figure 4 indicate the direct relationship between the HVD input power and H₂O concentration, the explanation for which could be that increasing SED led to the increase in the part of the input energy being converted into heat. Due to the relatively low temperature required for H₂O to vaporize, a more significant reduction of H₂O from DPM could be seen in comparison to the reduction of VOC.

The analysis of DPM oxidation characteristics of the DPM samples (engine-out and HVD treated at P20-L50) is illustrated in Figure 5. The normalized values of the soot mass from the thermogravimetric (TG) analysis illustrated the insignificant changes of the DPM component fractions (despite the significant change in terms of the absolute component mass) influenced by the HVD treatment. However, the mass oxidation profiles (Figure 5A) indicated a shifting toward a higher temperature, which suggested less DPM reactivity. With the limited available quantity of highly reactive free radicals generated and the gas resident time within the reactor (governed by GHSV), this time-varying soot oxidation phenomenon was experimentally confirmed by using indirect soot oxidation with NTP-induced O₃, and it was reported that the VOC/EC ratio was higher for diesel soot under treatment.
at a relatively short duration (<5 min) and VOC was the first to be oxidized by HVD-generated radical species (mainly O3). In our study, the decreased oxidation reactivity of the EC was thought to be due to the synergy effects of (1) the extremely short exposure duration between free radicals and DPM that left the DPM sample with a high VOC/EC ratio and (2) the change of EC nanostructure by direct contact with HVD. Additionally, the derivative thermogravimetric (DTG) analysis (Figure 5B) reveals that the maximum mass loss rate temperature (MMLRT) was shortened and shifted to a higher-temperature region for DPM samples after HVD treatment. This phenomenon was explained by ref 41 as being due to the fact that the free radicals produced by HVD (e.g., e−, O, OH, and O3) partially oxidized the DPM and resulted, to a greater degree, in the graphitization of the EC. The ignition temperature onset of EC (at the EC mass loss of 5%) was also evidently shifted toward a higher temperature, from 416.7 to 426.3 °C, which further confirmed that partial oxidation by HVD-generated free radicals reduced the DPM reactivity when exposed to O3 for a short duration.39

The MMLRT of the HVD-treated DPM samples demonstrated a noticeable shift toward higher temperature, from 510.9 to 520.6 °C. The significantly lower mass loss rate (dm/dT) suggests that free radicals generated by HVD and direct contact of the HVD with the EC altered the EC nanostructure to a more orderly organization or a higher degree of graphitization to form more graphene layers,38,39,43 which resulted in lower soot reactivity.

Furthermore, activation energy (Ea) analyses were carried out to evaluate the oxidation kinetics of the DPM samples, where the lower Ea results in less energy being required to overcome the energy threshold to begin the oxidation process of the elemental carbon. The estimation of Ea was performed based on the TG curve during the nonisothermal process using the Arrhenius equation. The scatter plots of Ln(−dm/dt) against 1/T of DPM samples from raw and HVD-treated exhaust are shown in Figure 5C, in which linear straight-line fitting was performed with correlation coefficients (R2) above 0.9 to ensure the reliability of the results. The slope of the fitted straight line corresponded to the activation energy, as mentioned in the literature,40−42 and was expressed as slope = −Ea/R. Figure 5D illustrates the Ea of DPM samples from before and after HVD treatment, showing that HVD treatment leads to a significant increase of Ea. The Ea of the DPM samples demonstrates agreement with the TG and DTG data regarding the shift of the soot oxidation temperature onset and MMLRT, from which it can be concluded that DPM after HVD exposure was less reactive to oxidation, in agreement with the Ea results. In contrast, the results from other studies38,42 demonstrated the opposite trend (higher DPM reactivity), which was due to the difference in the duration of DPM exposure to free radicals generated by HVD from both indirect (O3 generated from bottled O2) and direct (free radicals from O2-rich exhaust gas) treatments. One study39 reported that exposing DPM to O2-rich gas for up to 5 min caused the MMLRT to shift toward a higher temperature (compared to untreated DPM samples) and the relative intensity ratio from Raman analysis was reduced, which indicated a higher degree of graphitization, thus lowering the DPM oxidation reactivity. The longer contact duration (>5 min, up to 20 min) between the DPM and synthesized O3 demonstrated the opposite trend, where the MMLRT shifted back toward a lower temperature (more reactive) despite a higher degree of graphitization. The reason for this is that, with sufficient time for contact between DPM and O2-rich gas, this leads to the breaking down of long-chain DPM into shorter chains of microcrystalline particles, which was confirmed by the TEM results, increasing the specific surface area (SSA) of the particles and improving the oxidation reactivity.39 In our case, the direct diesel exhaust treatment by HVD had a shorter residence time (higher GSHV), meaning a limited contact duration between the DPM and free radicals generated by HVD, thus causing the DPM’s incomplete oxidation to alter the DPM composition and structure within a shorter duration.

**Effects of HVD on Diesel Exhaust Gas Composition.**

Figure 6A illustrates NO and NO2 before and after HVD treatments, indicating an overall NOx reduction (DeNOx) with HVD treatment in the range between 9.07 and 10.32%. This was mainly from NO reduction (DeNO) within the window of 12.08 and 16.20%. Consequently, NO2 was increased between 6.09 and 19.30%, as illustrated in the NO2/NO ratio plotted in Figure 6B. This reaffirms that the formation of NO2 was from the reaction between NO and the free radicals generated by HVD through possible direct reaction pathways R11 to R14, which formed NO2 from NO using O, O3, OH, HO2, and NO3. It was thought that the presence of water in the exhaust gas contributed to the formation of O, OH, and H through reactions R5−R7, resulting in the reduction of water as confirmed by the DPM composition. On the other hand, indirect reaction pathways for

**Figure 6.** NO and NO2 concentrations (A) and NO2/NO ratio (B).
NO₂ formation (R15 to R20) required OH to form HO₂ and HNO₃, which took further intermediate steps to produce NO₂. It could be seen that DeNO (12.1 to 22.9%) was noticeably greater than DeNOx (9.1 to 10.7%) with HVD treatment, which proved the formation of NO₂ from NO with the reaction of free radicals. In addition, the lower DeNOx implied that DeNOx might also proceed through another pathway that reduced the NO concentration, such as the formation of acidic nitrogen components (e.g., HNO₃) through R16 and R18 and/or the formation of higher oxides of nitrogen (N₂O₅, N₂O₆). Furthermore, due to the oxidizing condition of diesel exhaust gas (with >15% v/v of O₂), the reduction of NO into N₂ via R10 is less favorable. According to the results in Figure 6 at a fixed exhaust gas flow rate, increasing the input power of HVPS and the reactor’s effective length demonstrated an overall increase of DeNO, DeNOx, and NO₂ formation as the result of a higher specific energy density (SED) from 200 to 400 J/L, and a substantial increase in the exhaust gas residence time within the reactor. Overall, the change of input power from 10 to 20 W (or increased SED) demonstrated a more significant effect on NO₂ formation than the change of the reactor’s effective length due to the increase of the high-voltage discharge pulse repetition rate (frequency) promoting the collision of the electrons, and therefore produced a greater concentration of O₃. In addition, increasing the reactor’s effective length improved O₃ production by enhancing the contact time between the O₂-rich exhaust gas and corona discharge. As shown in Figure 7, O₃ was detected at very low concentrations of 0.02, 0.05, and 0.05 ppm for operating conditions P20-L50, P20-L100, and P100-L100, respectively. The measured O₃ concentrations correspond to the O₃ generation efficiencies of 0.282, 1.410, and 0.705 mg O₃/kWh, respectively. Meanwhile, about twice as much O₃ concentration was obtained by applying HVD to ambient air (depicted as “Atmospheric”). The low O₃ concentration detected in the reformed exhaust gas was thought to be due to suppression by the presence of water in the exhaust gas, which reduced the number of excited electrons and lowered the O₂ concentration available to form O₃, as well as by competing reaction pathways that utilized O₃ (e.g., NO₂ formation and diesel soot oxidation). A direct correlation of the O₂ concentration with the NO₂ concentration as shown in Figure 8A suggests that O₂ was formed as the result of possible reactions between NO and O₃ (R11R11), NO₂ and O₃ (R15R15), OH and O₃ (R17R17), and unstable NO₃ converted into NO₂ and O₂ (R20R20) and therefore confirmed that O₃ was formed by HVD. Dissociation of CO₂ into CO, O, or O₂ via reactions R30−R34 (where CO₂* and N₂* are the energized forms of CO₂ and N₂, respectively) also potentially contributed to the increase of O₂ and the decrease of CO₂ as reported in ref17. According to the change of the volumetric concentration of CO₂ and O₂, it could be seen that the magnitude of the increase of the O₂ concentration was slightly greater than that of the reduction of the CO₂ concentration, which is consistent with the additional O₂ formation with NOx as discussed above.

A noticeable increase of the CO concentration can be observed in Figure 8B for exhaust gas treated by HVD, which corresponds to the decrease of the CO₂ concentration via dissociation. This results in the change of selectivity of both CO and CO₂ illustrated in Figure 9A,B. However, considering that the theoretical 1:1 ratio of CO formation to CO₂ is caused by dissociation, the results exhibited a substantial difference in magnitude between the increase of the CO concentration (in ppm-v/v) in comparison to the reduction of the CO₂ concentration (in %-v/v). The formation of CO₃ via CO₂ + O₃ and CO₂ + O was the plausible reaction pathway for corona discharge that utilized CO₂ as a reactant given the availability of O₃ and O and the average electric field (17.5 kV/cm). In this study, the relatively high GHSV value led to a short duration of the gas/particle residence time within the HVD reactor, which resulted in the DPM undergoing partial oxidation, as mentioned in refs 41, 43 regarding the oxidation behavior of suspended DPM treated by the NTP reactor.
Hence, an increase of CO selectivity was observed, while the CO₂ selectivity decreased as a result. The increase of THC by the application of HVD was also observed for any given HVD operating condition, which was due mainly to the interaction between excited electrons, O radicals, and VOCs, which caused the breakdown of large THC molecules into smaller THCs in a greater number, hence the higher THC concentration. There was an insignificant difference of the THC concentrations between different HVD operating conditions, indicating the low sensitivity of THC formation toward HVD conditions. In this study, due to limitations of the instrument used for THC measurement (in equivalent value of C₆H₁₄), it can only be speculated that large THC molecules, such as toluene (C₇H₈), benzene (C₆H₆), butane (C₄H₁₀), or dodecane (C₁₂H₂₆), dissociated into smaller and detectable THCs, as mentioned in previous studies.

**Implication of HVD for the Existing Emission Control System.** HVD demonstrates satisfactory PM removal through the oxidation of radicals and electrostatic precipitation trapping. The proposed system has a potential to act as an auxiliary filter in EGR application, as studied by Gill et al., who investigated the filtered EGR approach for PM reduction without a NOx–PM trade-off using a DPF as the exhaust gas filter for a diesel engine fueled with ULSD (ultra-low-sulfur diesel) and oxygenated RME (rapeseed methyl ester). HVD could be used as a standalone exhaust filtering system, replacing DPF, or as a supporting system to enhance the DPF trapping efficiency and enable continuous DPF regeneration, which is expected to further improve the emission reductions for meeting future emission legislation.

**CONCLUSIONS**

An experimental investigation on diesel engine emissions control using low-power, low-frequency, high-voltage discharge (HVD) treatment was carried out in a laboratory-scale dielectric barrier discharge (DBD) reactor in a direct treatment configuration with raw diesel engine exhaust gas from the steady-state condition. Investigations of the simultaneous effect of HVD treatment on both diesel particle and gaseous emissions were carried out.

The proposed HVD system demonstrated a significant reduction of PM in terms of mass, number, and diesel soot geometric particle diameter by HVD-generated free radicals. The synergistic effect of PM oxidation by radical species and electrostatic precipitation on PM reduction could be observed in this study. Thermogravimetric (TG) analysis revealed a significant change in the H₂O, VOC, and EC fractions and oxidation characteristics. The HVD-treated PM exhibited a higher apparent activation energy (Eₐ), as a result lowering the oxidation reactivity in comparison to the untreated PM. Meanwhile, the gas composition analysis indicated the generation of free radicals (e, O, OH, O₃, and N) by the HVD system indirectly via observation of the behaviors of the DeNO, DeNOₓ, NO₂/NO ratio, THC concentration, and CO and CO₂ selectivities. The competition reactions for radical species, especially O, OH, and O₃, between NOx, CO, and solid carbonaceous soot led to distinctive characteristics of treated diesel emissions.

This experimental investigation demonstrated the behavior and characteristics of real diesel gaseous and particle emissions affected by the HVD system as a potential candidate for an additive or auxiliary system to complement the existing emission control systems. With the main attention on particulate matter emission nowadays, the understanding of diesel particulate matter oxidation behaviors could be further studied using DSC, TEM, and Raman, which will enable more insight on diesel soot morphology and benefit effective diesel particle emission controls.

**APPENDIX**

List of reaction pathways

\[
e + O_2 \rightarrow O^+ + O^+ + e \quad (R1)
\]

\[
e + O_2 \rightarrow O + O^+ + 2e \quad (R2)
\]

\[
e + N_2 \rightarrow N + N^+ + 2e \quad (R3)
\]

\[
e + N_2 \rightarrow 2 N \quad (R4)
\]

\[
e + H_2O \rightarrow e + O + OH \quad (R5)
\]

\[
e + H_2O \rightarrow e + H^* + OH^* \quad (R6)
\]

\[
e + H_2O \rightarrow OH + H^+ + 2e \quad (R7)
\]

\[
e + CO_2 \rightarrow e + O + CO \quad (R8)
\]

\[
O + O_2 \rightarrow O_3 \quad (R9)
\]

\[
N + NO \rightarrow N_2 + O \quad (R10)
\]
NO + O → NO₂ (R12)
NO + O → NO₂ (R12)
NO₂ + O → NO₃ + O₂ (R14)
NO₂ + O₁₅ → NO₂ + O₂ (R15)
NO + O → NO₂ (R12)
NO + HO₂ → OH + NO₂ (R13)
NO + NO₃ → 2NO₂ (R14)
NO₂ + O → NO₃ + O₂ (R15)
NO + HO₂ → HNO₃ (R16)
O₂ + OH → HO₂ + O₂ (R17)
NO₂ + OH → HNO₃ (R18)
HNO₃ + OH → NO₃ + H₂O

**Authors**

Thawatchai Wongchang — Department of Mechanical and Automotive Engineering Technology, Faculty of Engineering and Technology, King Mongkut’s University of Technology North Bangkok (CTAE), Science and Technology Research Institute, King Mongkut’s University of Technology North Bangkok (CTAE), Science and Technology Research Institute, King Mongkut’s University of Technology North Bangkok, Bangkok 10800, Thailand; Corresponding Author. E-mail: sumrerng@kmutnb.ac.th, ktn@kmutnb.ac.th

Sak Sittichompoo — College of Industrial Technology and Research Centre for Combustion and Alternative Energy (CTAE), Science and Technology Research Institute, King Mongkut’s University of Technology North Bangkok, Bangkok 10800, Thailand

**Corresponding Author**

Kampanart Theinnoi — College of Industrial Technology and Research Centre for Combustion and Alternative Energy (CTAE), Science and Technology Research Institute, King Mongkut’s University of Technology North Bangkok, Bangkok 10800, Thailand; orcid.org/0000-0003-0575-324X; Email: kampanart.t@cit.kmutnb.ac.th, ktn@kmutnb.ac.th

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors would like to express their thanks for the support of the Thailand Research Fund (TRF) and King Mongkut’s University of Technology North Bangkok (KMUTNB) under research grant TRG 5680088.

**REFERENCES**

1. Amelang, S.; Wehrmann, B. “Dieselgate” - a timeline of the car emissions fraud scandal in Germany https://www.cleanenergywire.org/factsheets/dieselgate-timeline-car-emissions-fraud-scandal-germany (accessed Aug 3, 2020).
2. Okubo, M.; Kuwahara, T.; Kannaka, Y.; Kuroki, T.; Yoshida, K. Improvement of NOx Reduction Efficiency in Diesel Emission Using Nonthermal Plasma - Exhaust Gas Recirculation Combined Aftertreatment. In Conference Record of the IEEE Industry Applications Society Annual Meeting (IAS), IEEE: 2010, DOI: 10.1109/IAS.2010.5615918.
3. Yoshida, K.; Kuwahara, T.; Kuroki, T.; Okubo, M. Diesel NOx Aftertreatment by Combined Process Using Temperature Swing Adsorption, NOx Reduction by Nonthermal Plasma, and NOx Recirculation: Improvement of the Recirculation Process. J. Hazard. Mater. 2012, 231-232, 18-25.
4. Mohapatro, S.; Rajanikanth, B. S. Portable HVAC and Pulsed Plasma Sources for Control of NOx in Diesel Engine Exhaust. IEEE Trans. Dielectr. Electr. Insul. 2011, 18, 1821-1828.
5. Vinh, T. Q.; Watanabe, S.; Furuhata, T.; Ari, M. Fundamental Study of NOx Removal from Diesel Exhaust Gas by Dielectric Barrier Discharge Reactor. J. Mech. Sci. Technol. 2012, 26, 1921-1928.
6. Sarah, A. G.; Rajanikanth, B. S. NOX Reduction from Biodiesel Exhaust by Plasma Induced Ozone Injection Supported by Lignite Waste Adsorption. IEEE Trans. Dielectr. Electr. Insul. 2016, 23, 1-9.
7. Mohapatro, S.; Allamsetty, S. NOx Abatement from Filtered Diesel Engine Exhaust Using Battery-Powered High-Voltage Pulse Power Supply. High Voltage 2017, 2, 69-77.
8. Mohapatro, S.; Sharma, N. K.; Madhukar, A. Abatement of NOx Using Compact High Voltage Pulse Power Supply: Towards Retrofitting to Automobile Vehicle. IEEE Trans. Dielectr. Electr. Insul. 2017, 24, 2738-2745.
9. Madhukar, A.; Rajanikanth, B. S. Augmenting NOx Reduction in Diesel Exhaust by Combined Plasma/Ozone Injection Technique: A Laboratory Investigation. High Voltage 2018, 3, 60-66.
10. Kirkpatrick, M. J.; Odic, E.; Leininger, J. P.; Blanchard, G.; Rousseau, S.; Glipa, X. Plasma Assisted Heterogeneous Catalytic Oxidation of Carbon Monoxide and Unburned Hydrocarbons: Laboratory-Scale Investigations. Appl. Catal. B 2011, 106, 160-166.
11. Thonglek, V.; Kiatsiriroat, T. Agglomeration of Sub-Micron Particles by a Non-Thermal Plasma Electrostatic Precipitator. J. Electrost. 2014, 72, 33-38.
(12) Sekine, Y.; Koyama, H.; Matsukata, M.; Kikuchi, E. Plasma-Assisted Oxidation of Carbon Particle by Lattice Oxygen on/in Oxide Catalyst. Fuel 2013, 103, 2–6.

(13) Thonglek, N.; Dechthummarong, C.; Kiatsiriroat, T. Soot Treatment by Using High Voltage Pulse Energized Electrostatic Precipitator. Energy Procedia 2011, 9, 292–298.

(14) Yao, S.; Shen, X.; Zhang, X.; Han, J.; Wu, Z.; Tang, X.; Lu, H.; Jiang, B. Sustainable Removal of Particulate Matter from Diesel Engine Exhaust at Low Temperature Using a Plasma-Catalytic Method. Chem. Eng. J. 2017, 327, 343–350.

(15) Babaie, M.; Davari, P.; Zare, F.; Rahman, M. M.; Rahimzadeh, H.; Ristovski, Z.; Brown, R. Effect of Pulsed Power on Particle Matter in Diesel Engine Exhaust Using a DBD Plasma Reactor. IEEE Trans. Plasma Sci. 2013, 41, 2349–2358.

(16) Keidar, M.; Bellis, I. Plasma Engineering: Applications from Aerospace to Bio and Nanotechnology, 2nd ed.; Academic Press, 2013; DOI: 10.1016/B978-0-12-813702-4.00001-6.

(17) Babaie, M.; Davari, P.; Talebizadeh, P.; Zare, F.; Rahimzadeh, H.; Ristovski, Z.; Brown, R. Performance Evaluation of Non-Thermal Plasma on Particulate Matter, Ozone and CO2 Correlation for Diesel Exhaust Emission Reduction. Chem. Eng. J. 2015, 276, 240–248.

(18) Wang, P.; Gu, W.; Lei, L.; Cai, Y.; Li, Z. Micro-Structural and Componennts Evolution Mechanism of Particular Matter from Diesel Engines with Non-Thermal Plasma Technology. Appl. Therm. Eng. 2015, 85, 1–10.

(19) Chae, J. O. Non-Thermal Plasma for Diesel Exhaust Treatment. J. Electrostat. 2003, 57, 251–262.

(20) Okubo, M.; Kuroki, T.; Kawasak, S.; Yoshida, K.; Yamamoto, T. Continuous Regeneration of Ceramics Particulate Filter in Stationary Diesel Engine Using Nonthermal Plasma-Induced Ozone Injection. IEEE Trans. Ind. Appl. 2009, 45, 1568–1574.

(21) Okubo, M.; Arita, N.; Kuroki, T.; Yoshida, K.; Yamamoto, T. Total Diesel Emission Control Technology Using Ozone Injection and Plasma Desorption. Plasma Chem. Plasma Process. 2008, 173–187.

(22) Yao, S. Plasma Reactors for Diesel Particulate Matter Removal. Recent Pat. Chem. Eng. 2009, 2, 67–75.

(23) Shi, Y.; Cai, Y.; Fan, R.; Cui, Y.; Chen, Y.; Ji, L. Characterization of Soot inside a Diesel Particulate Filter during a Nonthermal Plasma Promoted Regeneration Step. Appl. Therm. Eng. 2019, 150, 612–619.

(24) Dong, B.; Li, Q.; Gan, Q.; Zhao, X. Removal of Simulated NOx from Motor Vehicle Exhaust by High-Voltage Pulsed Discharge Coupled with LaMn1-XFe2O3 Exhaust Catalyst. J. Environ. Chem. Eng. 2020, 8, 103554.

(25) Okubo, M. Development of Super-Clean Diesel Engine and Combusotor Using Nonthermal Plasma Hybrid Aftertreatment. In Journal of Physics. Conference Series (Online); IOP Publishing, 2015; Vol. 646.

(26) Katatani, A.; Hosono, H.; Murata, H.; Yahata, H.; Mizuno, A. Electrostatic Precipitator without Using Corona Discharge—State of Collected Particles on Pole-Plates. Int. J. Plasma Environ. Sci. Technol. 2016, 10, 35–40.

(27) Hayashi, S.; Sakiyama, D.; Takashima, K.; Mizuno, A. Collection of Diesel Exhaust Particles Using Electrostatic Charging Prior to DPF and Regeneration of DPF Using Sliding Discharge. Int. J. Plasma Environ. Sci. Technol. 2012, 6, 160–165.

(28) Kuroki, T.; Ishidade, M.; Okubo, M.; Yamamoto, T. Charge-to-Mass Ratio and Dendrite Structure of Diesel Particulate Matter Charged by Corona Discharge. Carbon 2010, 48, 184–190.

(29) Kawakami, H.; Sakurai, T.; Ekawa, Y.; Yamamoto, T.; Zukaner, A. Performance Characteristics between Horizontally and Vertically Oriented Electrodes EHD ESP for Collection of Low-Resistive Diesel Particulates. J. Electrostat. 2013, 71, 1117–1123.

(30) Kuroki, T.; Takahashi, M.; Okubo, M.; Yamamoto, T.; Member, S. Single-Stage Plasma – Chemical Process for Particulates, NOx, and SOx. IEEE Trans. Ind. Appl. 2002, 38, 1204–1209.

(31) Jolibois, J.; Takashima, K.; Mizuno, A. Application of a Non-Thermal Surface Plasma Discharge in Wet Condition for Gas Exhaust Treatment: NOx Removal. J. Electrost. 2012, 70, 300–308.

(32) Kuroki, T.; Nishii, S.; Kuwahara, T.; Okubo, M. Nanoparticle Removal and Exhaust Gas Cleaning Using Gas-Liquid Interfacial Nonthermal Plasma. J. Electrost. 2017, 87, 86–92.

(33) Song, C.-L.; Bin, F.; Tao, Z.-M.; Li, F.-C.; Huang, Q.-F. Simultaneous Removals of NOx; CO and PM from Diesel Exhaust Emissions by Dielectric Barrier Discharges. J. Hazard. Mater. 2009, 166, 523–530.

(34) Sato, S.; Hensel, K.; Hayashi, H.; Takashima, K.; Mizuno, A. Honeycomb Discharge for Diesel Exhaust Cleaning. J. Electrostat. 2009, 67, 77–83.

(35) Talebizadeh, P.; Babaie, M.; Brown, R.; Rahimzadeh, H.; Ristovski, Z.; Ara, M. The Role of Non-Thermal Plasma Technique in NOx Treatment: A Review. Renewable Sustainable Energy Rev. 2014, 40, 886–901.

(36) Sato, S.; Mizuno, A. NOx Removal of Simulated Diesel Exhaust with Honeycomb Discharge. Int. J. Plasma Environ. Sci. Technol. 2010, 4, 18–23.

(37) Mohapatro, S.; Rajanikanth, B. S. Study of Pulsed Plasma in a Crossed Flow Dielectric Barrier Discharge Reactor for Improvement of NOx Removal in Raw Diesel Engine Exhaust. Plasma Sci. Technol. 2011, 13, 82–87.

(38) Fan, R.; Cai, Y.; Shi, Y.; Cui, Y. Effect of the Reaction Temperature on the Removal of Diesel Particulate Matter by Ozone Injection. Plasma Chem. Plasma Process. 2019, 39, 143–163.

(39) Ji, L.; Cai, Y.; Shi, Y.; Fan, R.; Wang, W.; Chen, Y. Effects of Nonthermal Plasma on Microstructure and Oxidation Characteristics of Particulate Matter. Environ. Sci. Technol. 2020, 54, 2510–2519.

(40) Pu, X.; Cai, Y.; Shi, Y.; Wang, J.; Gu, L.; Tian, J.; Li, W. Diesel Particulate Filter (DPF) Regeneration Using Non-Thermal Plasma Induced by Dielectric Barrier Discharge. J. Energy Inst. 2018, 91, 655–668.

(41) Gao, J.; Ma, C.; Xing, S.; Sun, L. Oxidation Behaviours of Particulate Matter Emitted by a Diesel Engine Equipped with a NTP Device. Appl. Therm. Eng. 2011, 179, 593–602.

(42) Ma, C.; Gao, J.; Zhong, L.; Xing, S. Experimental Investigation of the Oxidation Behaviour and Thermal Kinetics of Diesel Particulate Matter with Non-Thermal Plasma. Appl. Therm. Eng. 2016, 99, 1110–1118.

(43) Gao, J.; Ma, C.; Xing, S.; Sun, L.; Huang, L. Nanostructure Analysis of Particulate Matter Emitted from a Diesel Engine Equipped with a NTP Reactor. Fuel 2017, 192, 35–44.

(44) Texas-Instrument. NASS5, NES55, SASS5, SASS5 Datasheet. 2014, pp. 9–12.

(45) Gill, S. S.; Tsalolik, A.; Herreros, J. M.; York, A. P. E. Diesel Emissions Improvements through the Use of BioDiesel or Oxygenated Blending Components. Fuel 2012, 95, 578–586.

(46) Wang, C.; Xu, H.; Herreros, J. M.; Lattimore, T.; Shuai, S. Fuel Effect on Particulate Matter Composition and Soot Oxidation in a Direct-Injection Spark Ignition (DISI) Engine. Energy Fuels 2014, 28, 2003–2012.

(47) Kittelson, D. B. Engines and Nanoparticles: A Review. J. Aerosol Sci. 1998, 29, 575–588.

(48) Aitaj, T.; Pintér, M.; Utry, N.; Kiss-Albert, G.; Gulyás, G.; Pusztai, P.; Puskás, R.; Bereczky, A.; Szabados, G.; Szabó, G.; Könya, Z.; Bozóki, Z. Characterisation of Diesel Particulate Emission from Engines Using Commercial Diesel and Biofuels. Atmos. Environ. 2016, 134, 109–120.

(49) Fayad, M. A.; Tsalolik, A.; Fernández-Rodríguez, D.; Herreros, J. M.; Martos, F. J.; Lapuerta, M. Manipulating Modern Diesel Engine Particulate Emission Characteristics through Butanol Fuel Blending and Fuel Injection Strategies for Efficient Diesel Oxidation Catalysts. Appl. Energy 2017, 190, 490–500.

(50) Tsalolik, A.; Hernandez, J. J.; Megaritis, A.; Crampton, M. Dual Fuel Diesel Engine Operation Using H2 Effect on Particulate Emissions. Energy Fuels 2005, 19, 418–425.
(51) Parker, K. Electrical Operation of Electrostatic Precipitators, 1st ed.; Institute of Engineering and Technology (IET), 2003.
(52) Williams, A.; Garner, C.; Harry, J. Low Power Auto Selective Regeneration of Monolithic Wall Flow Diesel Particulate Filters. SAE Technical Paper, 2009, No. 2009–01–1927, DOI: 10.4271/2009-01-1927Wil.
(53) Bo, Z.; Yan, J.; Li, X.; Chi, Y.; Cen, K. Nitrogen Dioxide Formation in the Gliding Arc Discharge-Assisted Decomposition of Volatile Organic Compounds. J. Hazard. Mater. 2009, 166, 1210–1216.
(54) Fridman, A. Plasma Chemistry; Cambridge university press, 2008, DOI: 10.1017/CBO9780511546075.
(55) Ewing, R. G.; Waltman, M. J. Production and Utilization of CO3− Produced by a Corona Discharge in Air for Atmospheric Pressure Chemical Ionization. Int. J. Mass Spectrom. 2010, 296, 53−58.
(56) Gill, S. S.; Turner, D.; Tsolakis, A.; York, A. P. E. Understanding the Role of Filtered EGR on PM Emissions. SAE Technical Paper 2011, No. 2011–01–2080, 100–107, DOI: 10.4271/2011-01-2080.
(57) Gill, S. S.; Turner, D.; Tsolakis, A.; York, A. P. E. Controlling Soot Formation with Filtered EGR for Diesel and Biodiesel Fuelled Engines. Environ. Sci. Technol. 2012, 46, 4215–4222.