Performance evaluation of non-thermal plasma on particulate matter, ozone and CO_2 correlation for diesel exhaust emission reduction

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Abstract

This study is seeking to investigate the effect of non-thermal plasma technology in the abatement of particulate matter (PM) from the actual diesel exhaust. Ozone (O_3) strongly promotes PM oxidation, the main product of which is carbon dioxide (CO_2). PM oxidation into the less harmful product (CO_2) is the main objective whiles the correlation between PM, O_3 and CO_2 is considered. A dielectric barrier discharge reactor has been designed with pulsed power technology to produce plasma inside the diesel exhaust. To characterise the system under varied

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conditions, a range of applied voltages from 11 kV_{PP} to 21kV_{PP} at repetition rates of 2.5, 5, 7.5 and 10 kHz, have been experimentally investigated. The results show that by increasing the applied voltage and repetition rate, higher discharge power and CO_2 dissociation can be achieved. The PM removal efficiency of more than 50% has been obtained during the experiments and high concentrations of ozone on the order of a few hundreds of ppm have been observed at high discharge powers. Furthermore, O_3, CO_2 and PM concentrations at different plasma states have been analysed for time dependence. Based on this analysis, an inverse relationship between ozone concentration and PM removal has been found and the role of ozone in PM removal in plasma treatment of diesel exhaust has been highlighted.

Keywords: Non-thermal plasma; Dielectric barrier discharge; Diesel particulate matter; Ozone; Carbon dioxide; Environmental Engineering.

1. Introduction

The road sector accounts for about three quarters of transport emissions and passenger cars and light trucks contribute to a considerable share of these emissions [1]. On the other hand, diesel engine applications in various heavy-duty and medium-duty vehicles are increasing compared to gasoline engines. The emissions produced by diesel engines, however, are a ubiquitous air pollutant consisting of a complex mixture of gases, vapour and particles. The negative health effects of diesel emissions have been emphasised in the literature [2, 3] and lately, diesel exhaust has been classified as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC)[4].

Carbon monoxide (CO), hydrocarbon (HC), Nitrous Oxides (NO_x) and diesel particulate matter (DPM) have been globally regulated by diesel emission standards. DPM is basically composed of elemental carbons, which results in agglomerating and also absorbing other particles to form structures of complex physical and also chemical properties [5]. Up until now, several after-treatment technologies, such as diesel oxidation catalyst (DOC) [6], diesel particulate filter (DPF) [7], selective catalyst reduction (SCR) [8] and fuel borne catalyst (FBC) [9]have been employed to reduce diesel exhaust emissions. However, there are some drawbacks in using conventional after-treatment systems. For example, SCR catalysts require high temperatures (around 300°C) for activation and there is the possibility of ammonia leakage, catalyst poisoning and catalyst discharge under high temperature conditions [10]. DPFs also produce an additional pressure drop inside the exhaust gas, due to the PM deposition. This deposition can cause filter choking and filter regeneration is required at about 600°C. These effects cause more fuel consumption, which is not appropriate for low emission production and fuel economy. Furthermore, DPFs are inefficient in trapping small nanoparticles under 100 nm [11].

Considering the increasing environmental concerns and stringent emission standards, there is an imperative to develop new strategies for emission reduction[12]. Non-thermal plasma (NTP) technology has shown notable potential for emission control in various applications [3, 13, 14]. Plasma is the fourth state of matter that can be considered as an ionised gas. In the plasma state, sufficient energy is provided to free electrons from atoms or molecules and to allow species, ions and electrons, to coexist. Based on the relative temperature of the gas, plasmas can be classified into thermal and non-thermal plasma (NTP) [15]. In non-thermal plasma, the kinetic energy (temperature) of charged particles and kinetic energy (temperature) of background gas are

similar[16]. In the NTP application for exhaust emission reduction, the input electrical energy is transferred to the electrons which generates free radicals through collisions of electrons and promotes the desired chemical changes in the exhaust gas. While the applied electric energy in NTP reactors will be consumed for the purpose of breaking the bonds in the parent molecules, there is no sensible heating of the gas, and discharged energy is not lost either in heating up the gas or to the surroundings [17].

A variety of research studies, concerning different aspects of NTP application for NO_x removal, have been documented in the literature[3, 18]. NTP NO_x reduction generally can be divided in two groups: NO_x removal reactions that result in NO_x reduction to N_2 and NO to NO_2 conversion reactions which is more dominant [3]. In comparison with the large amount of research conducted on the influence of plasma on NO_x removal, much less has been dedicated to the effect of plasma on PM removal. Okubo et al. employed indirect or remote NTP for DPF regeneration [19, 20]. In this method, plasma is not introduced into the exhaust gas directly. Instead, plasma was introduced into the air and the NTP-treated air was injected into the exhaust gas, which causes the NO oxidation to NO_2. This induced $NO_2$with other produced activated oxygen species by plasma oxidise deposited carbon soot on the DPF surface effectively. Furthermore, the simultaneous PM, HC and NO_x removal efficiency of about 80%, 70% and 65%was reported in literature from the exhaust gas [21].

Few studies on PM removal of diesel engines have been conducted in the literature and removal mechanisms have not been studied extensively [3, 22, 23]. Furthermore, most of the research in this area was considered simulated diesel exhaust instead of actual exhaust. Many electron-impact reactions such as momentum transfer, dissociation, ionization reaction, etc. and also numerous secondary reactions induced by products of the electron-impact reactions are

possible in the plasma state[24]. This would be more complicated when plasma treatment of the diesel exhaust which is a complex mixture of thousands of gases is targeted. Therefore, the results of experiments for actual diesel exhaust may be different from what is happening in simulated exhaust. Furthermore, recently ozone has been studied as a possible solution for PM removal even in industries[12]; however, the advantage of ozone production in NTP systems for PM removal is not well established.

The objective of this paper is to investigate the effect of NTP on reduction of PM emitted by a diesel engine and oxidize it to less harmful combustion products (essentially carbon dioxide) at different discharge voltages and repetition rates. Furthermore, the mechanism of PM removal has been discussed in detail and the effect of ozone as the key parameter for PM removal has been highlighted. To examine the system in real condition which is the first step towards the applicability of NTP as an after-treatment system, the actual exhaust emission has been examined in this research.

2. Experimental apparatus and method

2.1. Experimental setup

The experiments have been conducted using a modern turbo-charged 6 cylinder Cummins diesel engine. The engine has a capacity of 5.9L, a bore of 102mm, a stroke length of 120 mm, compression ratio of 17:3:1, and maximum power of 162 kW at 2500 rpm. All experiments have been conducted at a speed of 1500 rpm and at the load of 160 Nm to achieve the most uniform exhaust gas performance. For all experiments, exhaust gas from the exhaust pipe was passed

through the dilution tunnel before flowing into the DBD reactor. The role of the dilution tunnel is to reduce the temperature and concentration of exhaust gas before flowing into the measurement instruments. By manipulating the flow direction at the reactor inlet using a three way valve, the emission concentration has been measured before and after plasma treatment. Flow rate was 12 L/min and kept constant during the experiments. The schematic diagram of the experimental set-up is shown in Fig. 1.

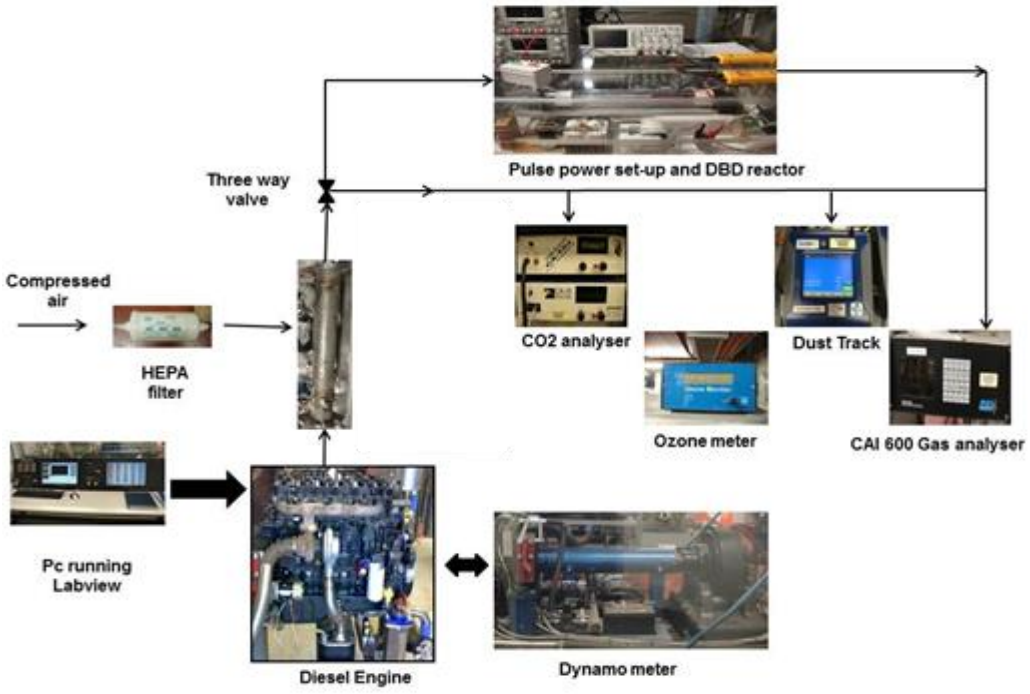


Fig. 1. Schematic diagram of the experimental setup.

2.2. Dielectric barrier discharge reactor

In all experiments, a conventional DBD reactor was used, as shown in Fig. 2. The overall dimensions of the DBD were also shown in this figure. It consists of two concentric quartz tubes with dimensions of 400 mm long and wall thickness of 1.5 mm. The outer diameters of the tubes are 20 and 25 mm, respectively. The diesel engine exhaust generated by the diesel engine was

passed through the gap between these two quartz tubes. With its predesigned geometry, the discharge gap was 1 mm. The reactor is equipped with external and internal electrodes which can be energised through a pulsed power supply. The internal electrode is a copper cylinder and the external electrode is made of copper mesh that wraps the exterior part of the outer quartz tube. The electrodes were located in the middle of the DBD reactor, the length of which was 100 mm. The quartz tubes were installed by using two Teflon caps at both ends of the DBD reactor. The diesel engine exhaust enters the reactor at the angle of 45° and then flows throughout the gap; it leaves the reactor with the same angle as well. The mean residence time of 0.13 s can be calculated for the given geometry and flow rate for the exhaust gas passing through the DBD reactor.

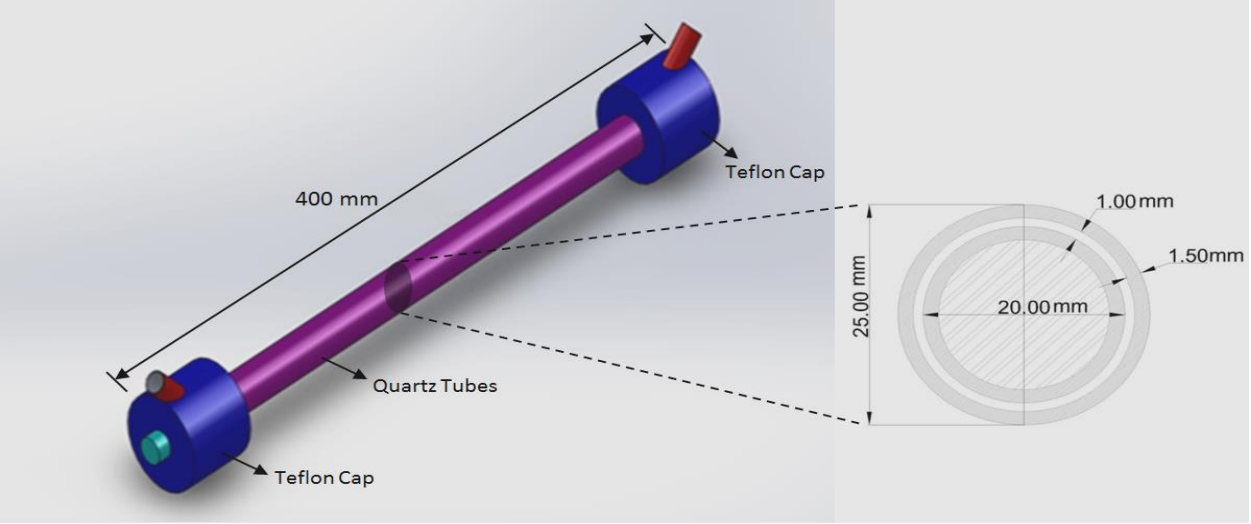


Fig. 2. Dielectric barrier discharge reactor.

2.3. Electrical and pulsed power system

Rapid release of stored energy as electrical pulses into a load, thereby resulting in the delivery of large amount of instantaneous voltage over short period of time, is known as pulsed

power. Pulsed power technology has been previously considered by different researchers in different applications [25]. Furthermore, pulsed power technology for NTP generation in pollution control application has gained a lot of advantages[3, 26, 27] and using power electronics topologies in pulsed power applications is recognised as being quite beneficial, particularly in terms of having efficient, cost effective and high power density [26, 27].

For all experiments in this research, a bipolar pulsed power supply is employed to sustain NTP and prevent arcing. The employed topology is based on a push pull inverter [22, 28, 29]. Due to the capacitive behaviour of the DBD load, it is possible to put the push-pull inverter in resonant mode and generate semi-sinusoidal waveforms at the output. Fig. 3.A depicts a typical measured voltage waveform (V_0) with a peak-to-peak value of 21 kV_{PP} at repetition rate (f_r) of 2.5 kHz. The detail of the pulsed power supply hardware set-up was fully explained in [28, 29].

In order to extract and analyse important electrical properties such as power consumption of the DBD reactor, the V-Q Lissajous method as a standard process for diagnostics of DBD systems has been used [29, 30]. To measure Q, an auxiliary capacitor is placed in series with the DBD. Thus, by measuring the voltage across the auxiliary capacitor and multiplying its value by capacitance, it is possible to calculate Q. It should be noted that value of the auxiliary capacitor should be large enough so as not to affect the DBD capacitance. The area of V-Q curve (Fig. 3-B) at different operating points is a measure of the energy consumption per pulse of the DBD reactor. By multiplying the calculated areas with the employed repetition rate, the power consumption of the DBD reactor can be determined. The relevant equations are as follow:

$$W = \int Q dV \tag{1}$$

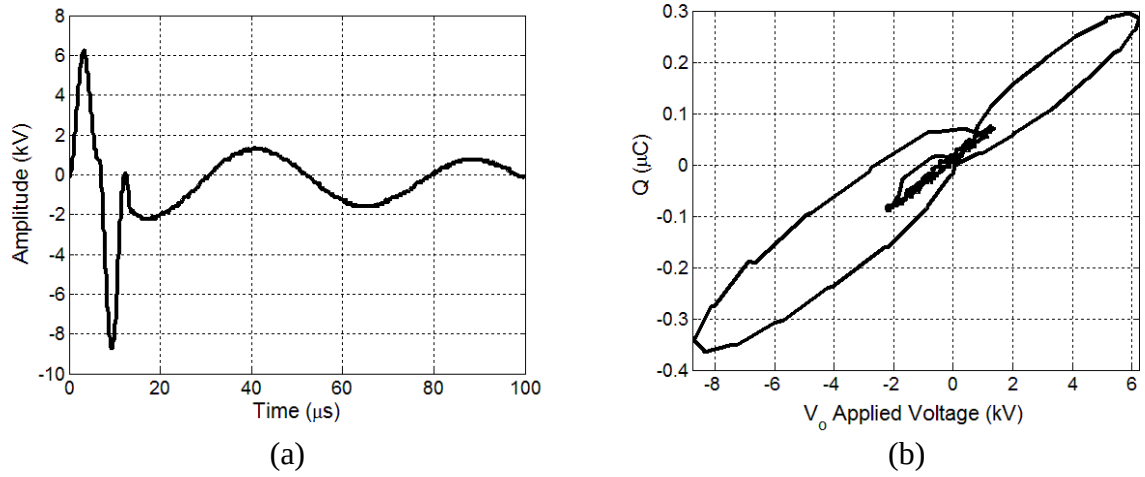
$$C = \frac{dQ}{dV} \tag{2}$$

Substituting the capacitance equation into an energy equation ($dV = \frac{dQ}{C}$):

$$W = \int \frac{Q}{C} dQ = \frac{Q^2}{2C} = \frac{1}{2} CV^2 \tag{3}$$

DBD power consumption is calculated as:

$$P_{average} = W \times f = \frac{1}{2} CV^2 f \tag{4}$$



(a) (b)

Fig. 3. Typical measurement at 21 kV_{PP} and 2.5 kHz a) applied voltage waveform and b) V-Q plot with the area of 17.15 Watts.

3. Results and Discussion

When plasma is introduced inside the exhaust gas, oxidation processes will be started and NO_x, unburned hydrocarbons, and particulate matter can be oxidised[22]. In addition, due to the effectiveness of NTP on the removal of a variety of species inside the exhaust, the concentration variation of a special component may affect the other species differently during the experiments. In this paper, different contour plots have been presented to evaluate the effect of NTP on discharge power, ozone production, CO_2 and PM concentrations. PM and CO_2 concentrations

were normalized based on their initial concentrations while plasma is turned off. All these parameters have been plotted against voltage and repetition rate using a minimum-to-maximum mesh grid, with interpolation for every single unit of repetition rate and voltage using MATLAB version 2013a. In the following sections, the contour plots of discharge power, ozone, CO_2 and PM at different voltages and repetition rates are discussed separately, and then the interrelation between them under different plasma operating conditions has been studied.

3.1. Discharge power evaluation

Discharge power is one of the main challenges of NTP applications since the emission removal efficiency in plasma state depends on the amount of energy density. Specific energy density (SED) is a common term for emission removal applications which has been defined as discharge power divided by the mass flow rate [3].On the other hand, discharge power itself is a function of frequency and applied voltage. Therefore, the analysis of the DBD reactor electrical characteristics has been considered at a range of voltage levels and operating repetition rates in this research. Output voltage (V_0) and repetition rate (f_r) were designated as controlling parameters to determine the transferred power. The high voltage pulses were applied to the reactor at six different voltage levels including 11, 13, 15, 17, 19 and 21 kV_{PP} and four different repetition rates of 2.5, 5, 7.5 and 10 kHz. The 24 operating points are selected, based on a combination of varied operating repetition rates and voltages, to evaluate the behaviour of the DBD reactor at various power levels.

Fig. 4shows a contour plot of the discharge power at different repetition rates and voltages calculated from Eq. 4. The values of discharge power for the area in yellow are very low. Due to

the insufficient level of the applied voltage, the effect of plasma has not been observed in this area. Hence, varying the applied voltage and repetition rate does not affect the discharge powerin this area[21].The slope of the discharge power contour plots is about 45° and increases with the applied voltage levels, correspondingly. This means that the discharge power has been influenced by the applied voltage more than the repetition rate, especially by approaching the higher voltage levels. This finding can be confirmed from Eq. 4since the discharge power is related to the applied voltage squared.

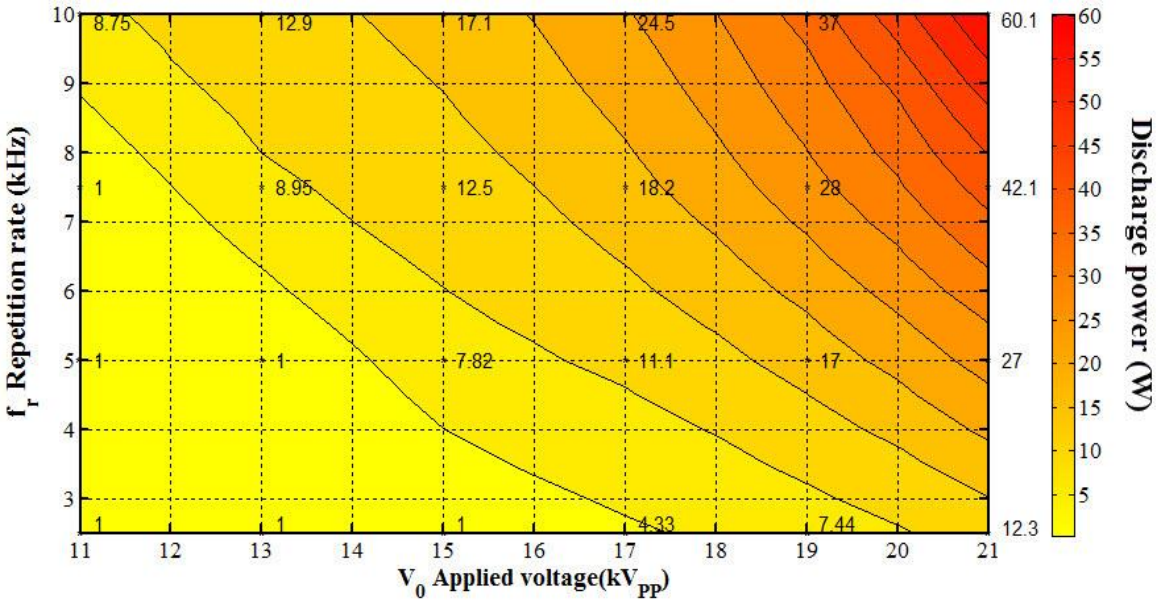


Fig. 4. Discharge power at different applied voltages and repetition rates.

Furthermore, dependency of consumed power to applied voltage and repetition rate is shown in Fig. 5. This figure displays the variation of specific energy density (SED) as a function of applied voltage for different repetition rates. SED is considered as an important criterion in NTP energy evaluation. As can be seen, SED increases continuously by increase of applied voltage at each repetition rate and maximum SED of 300 J/L is achieved during the experiments.

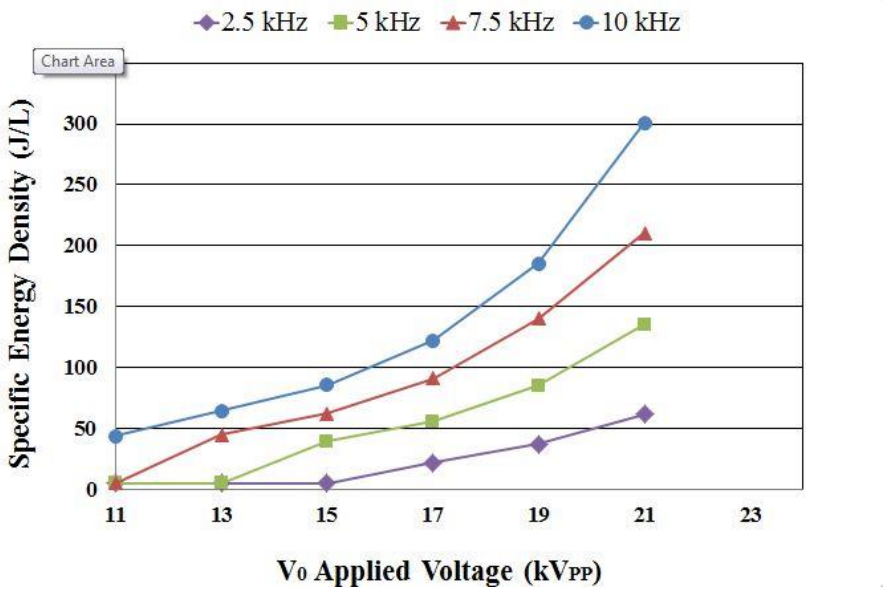


Fig. 5. Effect of applied voltage and frequency on specific energy density.

3.2. Effect of NTP on Ozone concentration

Ozone is produced in many devices, such as electronic air cleaners, laser printers and copiers, which rely on atmospheric discharges [31]. Ozone can participate in many reactions in plasma treated gas. The main reaction for ozone production in the plasma state is the reaction of the O radical with oxygen, based on the following reaction [32]:

$$O_2 + O + M \rightarrow O_3 + M \tag{5}$$

where M is a third-body collision partner.

In addition, ozone will be consumed through different reactions in plasma state. For example, the ozone will be consumed by the following reactions for NO_x reduction in plasma exhaust treatment[13, 32]:

$$N + O_3 \rightarrow NO + O_2 \tag{6}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (7)$$

$$NO_2 + O_3 \rightarrow NO_3 + O_2 \quad (8)$$

$$2NO_2 + O_3 \rightarrow N_2O_5 + O_2 \quad (9)$$

Note that the atomic nitrogen (N) can be produced due to the dissociation of nitrogen and/or NO molecules by high energy electrons in plasma state [3] and NO_3, which is an unstable compound, usually turns into NO and NO_2 in the environment [33].

Therefore, ozone will be produced over some conditions and consumed in other conditions during plasma treatment. Fig. 6 displays the contour plot of ozone concentration as a function of applied voltage and repetition rate. As displayed in this figure, by increasing the applied voltage, ozone concentration has been increased after formation of plasma inside the exhaust. If the applied voltage increases, a higher electric field is generated and then more O radicals are formed inside the exhaust gas. The concentration of ozone is also increasing, by increasing the pulse repetition rate during the experiments[34]. This trend can be observed at all voltages and repetition rates except for 21 kV_{PP} and 10 kHz. At this state, due to the high amount of discharge power (60.1 W), more nitrogen atoms would be generated inside the exhaust gas. So the destruction of ozone at this high level of discharge power would be the consequence of ozone consumption through Eq. 6-9 by N radicals [34]. Moreover, oxygen saturation inside the reactor at this high discharge power level can be reached, which results in reduction of ozone concentration.

Another interesting finding is that for the low applied voltages, ozone concentration is almost constant and it is not changed by increase of the repetition rate. It shows the weakness of plasma at those operating conditions and also a higher dependency of plasma to the voltage level rather than to the repetition rate. Furthermore, since the plasma is weak at this voltage range, low

rate of O radical can be produced and therefore the ozone production and reduction rate is almost the same.

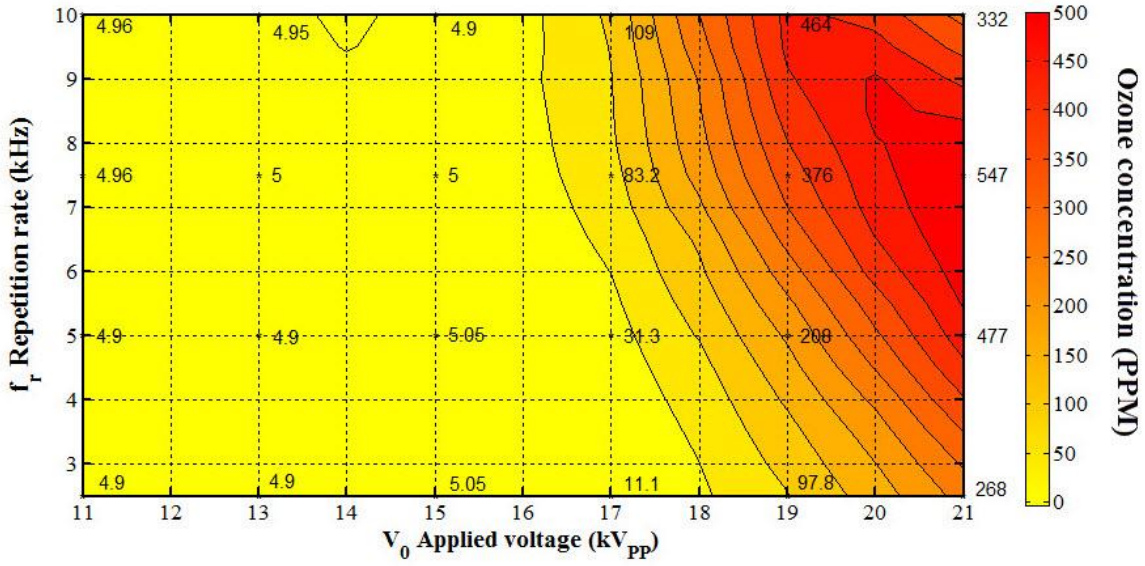


Fig. 6. Effect of repetition rate and applied voltage on ozone concentration.

3.3. Effect of NTP on PM concentration

Carbonaceous PM or soot in plasma treated gas can be incinerated by NO_2, O_3 and activated oxygen components according to the following reactions [35]:

$$C + 2NO_2 \rightarrow CO_2 + 2NO \quad (10)$$

$$C + NO_2 \rightarrow CO + NO \quad (11)$$

$$2C + NO_2 \rightarrow 2CO + \frac{1}{2}N_2 \quad (12)$$

$$2C + 2NO_2 \rightarrow 2CO_2 + N_2 \quad (13)$$

$$2C + 2O_3 \rightarrow 2CO_2 + O_2 \quad (14)$$

$$C + O_3 \rightarrow CO + O_2 \quad (15)$$

The first two reactions occur at oxygen rich conditions and the last two in oxygen lean conditions. Note that NO_2exists in the exhaust gas and it will be increased under plasma conditions. NO_2 can be formed from the oxidation of NO in oxygen rich conditions and is also due to NO reaction with O_3 and other radicals of O and OH under plasma conditions. On the other hand, NO_2 and O_3will be consumed for PM incineration reactions as presented by Eqs.10-15.

Fig. 7 is the contour plot of normalised PM concentration as a function of applied voltages and repetition rates. PM concentration at reactor inlet prior to start the experiments was 0.499 mg/m^3. Generally it is found that by increasing the voltage level and repetition rate, PM concentration is decreased. As shown, the optimum value for PM concentration occurs at a voltage level of 19 kV_{PP} and repetition rate of 10 kHz. At higher repetition rates, such as 7.5 and 10 kHz, the minimum value of PM concentration has been found at 19 kV_{PP}, which is just less than the maximum applied voltage. The reason for the PM removal decrease at high repetition rates, after approaching the optimum value of applied voltage, will be explained in more detail in Section 3.5. Briefly, at lower repetition rates (2.5 and 5 kHz) the normalised PM has been decreased continuously by increasing the applied voltage. Therefore, the optimum value of PM removal may occur at even higher voltage levels for the two aforementioned repetition rates. It can also be observed that at high voltages, normalised PM is always decreased by increasing the pulse repetition rate.

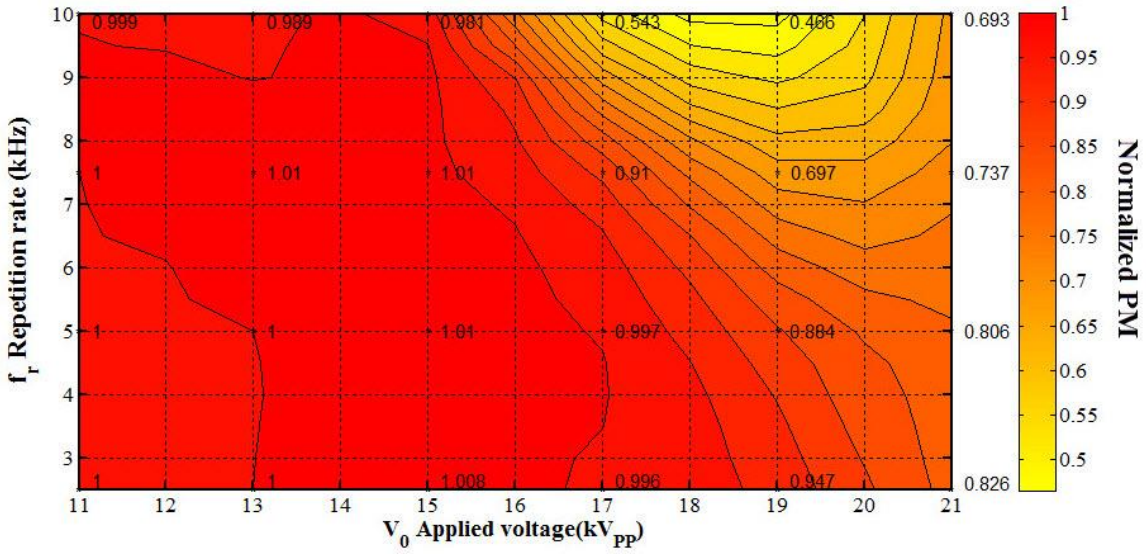


Fig. 7. Effect of repetition rate and applied voltage on normalized PM.

3.4. Effect of NTP on CO_2 concentration

As discussed in previous section, PM was removed by plasma effectively in different operating conditions while the oxidation process can result in production of less harmful product i.e. CO_2. The initial value of CO_2 concentration is about 0.421% at the beginning of the experiments. Fig. 8 shows a contour plot of normalised CO_2concentration as a function of applied voltage and repetition rate. From this figure, by increase of the pulse repetition rate and applied voltage the concentration of CO_2in exhaust is reduced. This reduction is due to the higher electric field and higher discharge power, which can be obtained by an increase of the applied voltage and repetition rate. At higher discharge powers, electrons will gain more energy to start the electrons' impact reactions and the electrical field can be powerful enough to excite the carbon dioxide molecules. Therefore, the probability of producing free electrons and ions is higher and dissociation of CO_2 molecules after applying plasma is more likely to occur through

the different electron impact reactions. While the particles can be oxidized to CO_2 in plasma state, the electron impact reactions will decompose the produced Carbone dioxide molecules.

The common reaction mechanisms for decomposing the CO_2 molecules in plasma state are given by Eq. 16-20. Electron impact reactions and different active oxygen species can be involved in CO_2 concentration reduction through the following equations[15]:

$$CO_2 + O \rightarrow CO + O_2 \tag{16}$$

$$CO_2 + O_2 \rightarrow CO + O_3 \tag{17}$$

$$e + CO_2 \rightarrow CO + O + e \tag{18}$$

$$e + CO_2^{*} \rightarrow CO + O \tag{19}$$

$$2CO_2 + 2N_2^{*} \rightarrow 2CO + O_2 + 2N_2 \tag{20}$$

where CO_2^{*} and N_2^{*} are the excited forms of CO_2 molecule and N_2molecule, respectively and the produced CO from varied reactions is in different levels of energy [15]

Another observation from Fig. 8 is the special shape of the contour plots. CO_2 contours are close to vertical, especially at high voltages and low repetition rates. This implies that at high voltage levels, the variation of repetition rate (f_r) does not affect the concentration of CO_2 significantly and the applied voltage has a greater impact on CO_2 decomposition of diesel exhaust.

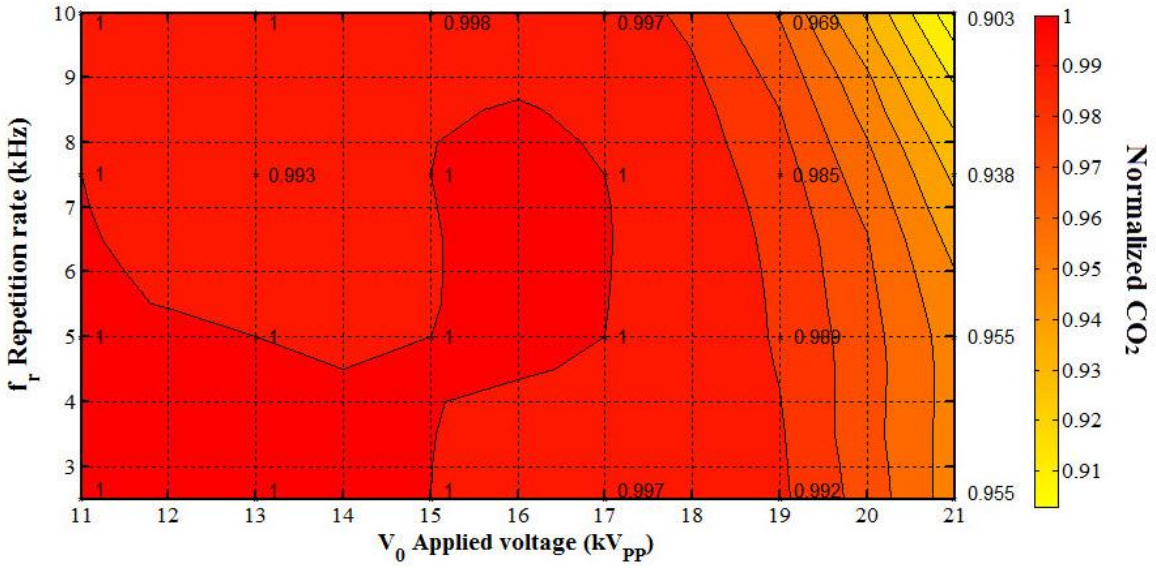


Fig. 8. Effect of repetition rate and applied voltage on normalized CO_2.

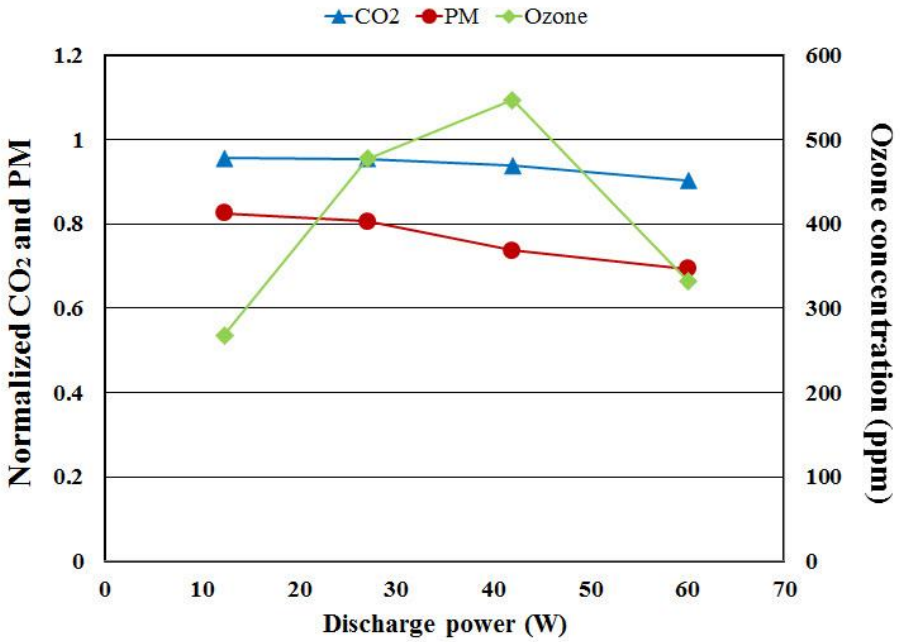
3.5. Interrelationship of ozone, CO_2 and PM concentration

As already discussed, the highest performance of NTP can be achieved at higher voltage levels and repetition rates. Fig. 9-a and Fig. 9-b show the variation of ozone, CO_2 and PM as a function of discharge power at 21 kV_{PP} for different repetition rates, and at 10 kHz for different voltage levels, respectively. In both figures, CO_2 dissociation is occurred slightly, with the increase of applied voltage and repetition rate. Moreover, by increasing the repetition rate at 21 kV_{PP} the concentration of ozone increases except at 10 kHz (Fig. 9-a), and with increasing the applied voltage ozone concentration increases except at 21 kV_{PP} (Fig. 9-b). As displayed in Fig. 9-a, PM concentration decreases continuously for all the studied repetition rates. However, at 10 kHz the PM concentration increases slightly at 21 kV_{PP} after a continuous decrease (see Fig. 9-b).

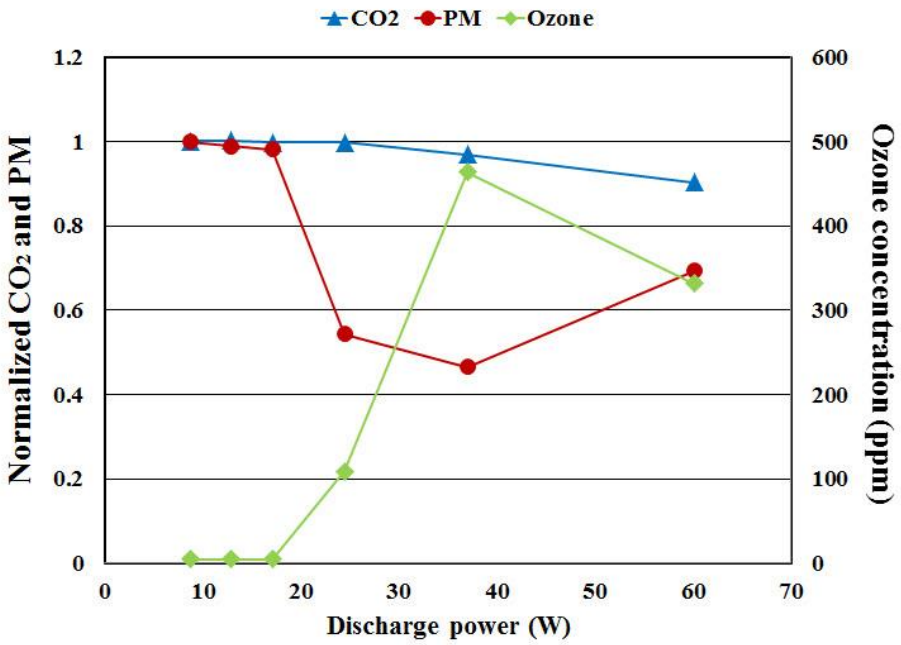
While PM oxidation to less harmful products such as CO_2 is favourable, the PM concentration reduction is accompanied by reduction of CO_2 concentration in Fig. 9. By

considering diesel PM as elemental Carbone, the main possible reaction mechanisms for PM removal are defined through Eq. 10-15. As can be seen in these reactions, there are different reaction pathways for PM oxidation to CO_2 and CO. However, the reduction in CO_2 concentration shows that even if PM oxidizes to CO_2, the produced CO_2 will be dissociate in plasma state possibly through Eq. 16-20 and produce more CO. One should also take into account that the particle concentrations are of the order of mg/m^3 as compared to CO_2 concentrations that are of the order of 10 g/m^3. Even if all of the carbon from the particles is oxidised that would be a very small contribution to the total CO_2 concentration.

To provide better understanding of plasma behaviour, time dependent diagrams of CO_2, PM and ozone concentration have been plotted at different voltage levels and repetition rates. As depicted in Fig.10-12, at each operating condition the exhaust gas was passed through the plasma reactor for a period of 180 seconds and all results have been plotted. The advantage of analysing the measured results is to understand the correlation between ozone, $CO_2$and PM under plasma conditions.



(a)



(b)

Fig. 9. The variation of ozone, CO_2 and PM as a function of discharge power a) at 21 kV_{PP} for different pulse frequencies and b) at 10 kHz frequency for different applied voltages.

As shown in Fig. 10, regardless of applied repetition rate, normalised CO_2concentration generally decreases with an increase of voltage level. However, at low repetition rates and voltage levels, plasma has not made any sensible changes in CO_2 concentration. As clearly shown, when the voltage level reaches 19 kV_{PP}, plasma starts to dissociate CO_2 molecules for all repetition rates. However, the dissociation increases by increasing the repetition rate. CO_2does not show significant variation during the test period (180 s) in all operating conditions except at 21 kV_{PP} where the maximum CO_2 dissociationis obtained. At 21 kV_{PP}, a continuous decrease of CO_2 concentration during the experiment can be observed for all repetition rates due to the high

amount of discharge power. Therefore, it can be concluded that the threshold discharge power for CO_2 dissociation in diesel exhaust is higher than the plasma formation threshold.

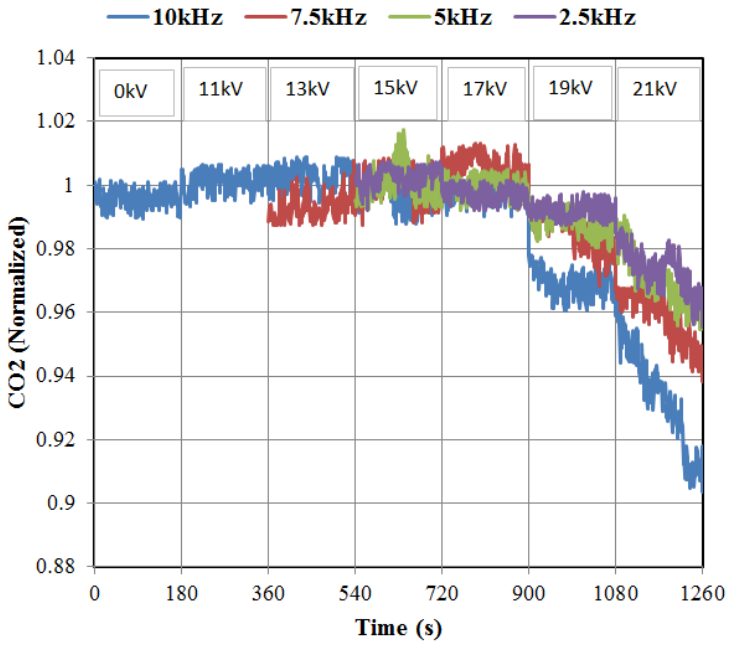


Fig. 10. Normalized CO_2 as a function of time at different applied voltages and different frequencies.

To study PM concentration variation at varied operating conditions, the obtained measurements have been illustrated in Fig. 11. PM concentration decreases slightly before a voltage of 17 kV_{PP} especially as the repetition rate increases. From this point on (17 kV_{PP}), PM concentration starts to decrease significantly while for each repetition rate, this reduction starts at a different voltage level. Generally, for all ranges of voltage level, the obtained PM removal at 7.5 kHz and 10 kHz is higher compared to two other repetition rates. It is interesting that the maximum drop is at 17 kV_{PP} with repetition rate of 10 kHz, while the minimum PM concentration occurs at the same repetition rate with 19 kV_{PP}. Furthermore, for the voltage levels of 19 kV_{PP} and 21 kV_{PP} at the repetition rate of 10 kHz, and also for the voltage of 21 kV_{PP} at

repetition rate of 7.5 kHz, PM concentration is increasing over the time period of the experiment. This interesting finding will be explained in conjunction with the ozone data from Fig. 12.

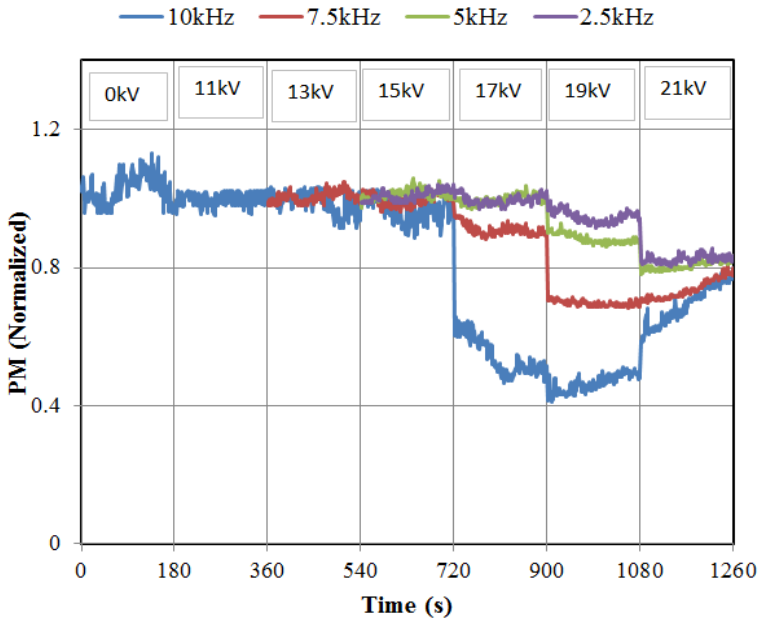


Fig. 11. Normalized PM as a function of time at different applied voltages and different frequencies.

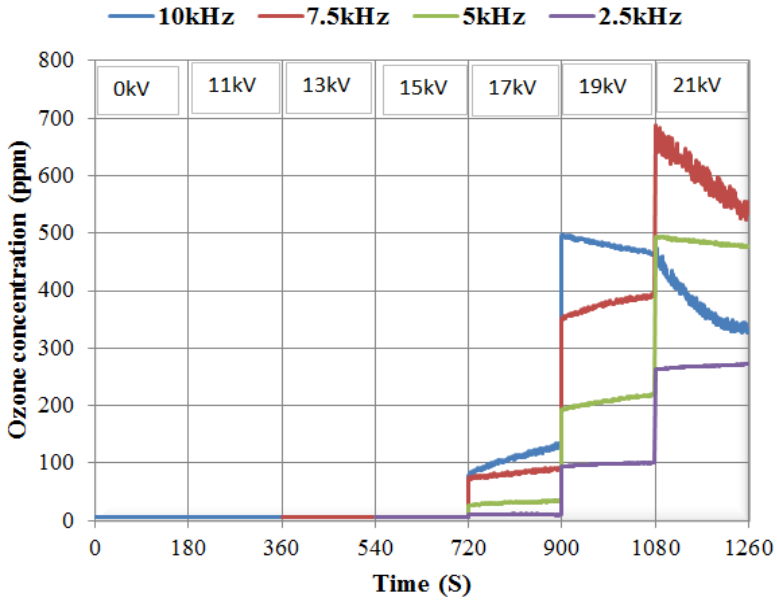


Fig. 12. Ozone concentration as a function of time at different applied voltages and different frequencies.

Fig. 12 illustrates the concentration of ozone over the time period of experiments. Ozone concentration is very low at a voltage level of 17 kV_{PP}, regardless of the applied repetition rates, which implies no ozone production by NTP at these levels. When the applied voltage approaches 17 $kV_{PP,}$ ozone concentration increases significantly for all repetition rates. The ozone concentration at 17 kV_{PP} is almost constant over the period of study for 2.5 and 5 kHz. However, it increases slightly at 7.5 kHz and more significantly at 10 kHz. For 19 kV_{PP}, ozone concentration increases at 2.5, 5 and 7.5 kHz with different gradients over the period of study. On the other hand, in the same period of time, ozone concentration has been decreased continuously at 19 kV_{PP} and 10 kHz. This trend is in contrast with the PM concentrating trend obtained from Fig. 11 at the same operating points. Thus, decreasing the ozone concentration, a lesser amount of PM can be removed by the DBD plasma reactor at this state. The same trade-off can be observed between ozone and PM at 21 kV_{PP} for repetition rates of 7.5 and 10 kHz as well. Furthermore, as can be observed in Fig. 10, CO_2 concentration at 21kV_{PP} and 10 kHz will be constant and even increase to some extent at the end ofthe time period of the experiment. This can be due to the reduction of ozone and also PM oxidation at this state. Therefore, ozone is found to be a key parameter for PM removal from diesel exhaust gas, which should be considered in all plasma emission treatment applications.

4. Conclusion

In this paper, the NTP technique has been employed for emission reduction of actual diesel exhaust. NTP has been introduced inside the diesel exhaust by using a DBD reactor.

Measurements have been conducted before and after introducing plasma inside the reactor to illustrate the effect of NTP on diesel emissions. The effect of NTP on PM, CO_2 and ozone has been considered experimentally and the interrelationship between them has been clarified. Discharge power has been calculated at each operating point by means of the V-Q Lissajous method. Discharge power and SED have been found to increase continuously by increase of the applied voltage and repetition rate, and the maximum values of 60.1 W and 300 J/L have been obtained at 21kV_{PP} and 10 kHz for discharge power and SED, respectively. NTP was found to be effective for PM removal while a considerable amount of ozone has been produced during the experiments.

The PM removal of more than 50% concentration has been achieved during the experiments. Discharge power, emission reduction and ozone production have been influenced by variation of applied voltage more than the repetition rate. The correlation study of emissions showed the key role of ozone in PM reduction. PM concentration was decreased continuously by increasing the voltage level at all repetition rates over the time period of study, except for the voltage level of 21 kV_{PP} at 10 kHz and 7.5 kHz, due to the reduction in ozone concentration. Furthermore, an opposite trend has been observed in the concentration of ozone and PM. For all operating conditions when ozone is increasing at the beginning of experiments, PM concentration has been decreased continuously. However, at 19 kV_{PP} and 10 kHz, 21 kV_{PP} and 10 kHz, and 21 kV_{PP} and 7.5 kHz, reduction of ozone production by plasma over the time resulted in PM concentration being increased due to the PM oxidation reduction. The effect of NTP in emission reduction applications is more pronounced in time dependant analysis and it is strongly recommended for use in future research instead of using the simple averaging method.

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