Reduction of NOx and PM in marine diesel engine exhaust gas using microwave plasma

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Abstract. Abatement of NOx and particulate matters (PM) of marine diesel exhaust gas using microwave (MW) non-thermal plasma is presented in this paper. NOx mainly consist of NO and less concentration of NO_2 in a typical two stoke marine diesel engine and microwave plasma generation can completely remove NO. MW was generated using two 2kW microwave sources and a saw tooth passive electrode. Passive electrode was used to generate high electric field region within microwave environment where high energetic electrons (1-3eV) are produced for the generation of non-thermal plasma (NTP). 2kW gen-set diesel exhaust gas was used to test our pilot-scale MW plasma reactor. The experimental results show that almost 100% removal of NO is possible for the exhaust gas flow rate of 60l/s. It was also shown that MW can significantly remove soot particles (PM, 10nm to 365nm) entrained in the exhaust gas of 200kW marine diesel engine with 40% engine load and gas flow rate of 130l/s. MW without generating plasma showed reduction up to 50% reduction of PM and with the plasma up to 90% reduction. The major challenge in these experiments was that igniting the desired plasma and sustaining it with passive electrodes for longer period (10s of minutes) as it required fine tuning of electrode position, which was influenced by many factors such as gas flow rate, geometry of reactor and MW power.

1. Introduction

Marine diesel engine exhaust gas contains toxic gases such as NOx($NO+NO_2$) and SO_2 and it very important to convert these gases into harmless composition to avoid the detrimental effect these gases can cause to environment (e.g.: acid rain) as well as human health (e.g.: Aggravation of asthma and Inflammation)[1]. New regulations are being also imposed by UN IMO to control the emission levels of NOx and SOx from marine exhaust [2]. While SOx emission can be limited by using fuel without sulphur, an abatement method should be adapted to remove NOx from the exhaust gas. Particulate matters (PM) are also another harmful composition found in marine diesel engine exhaust [1]. Some of the health effects caused by PM are premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function and increased respiratory symptoms [1]. Soot particles (unburnt carbon) are the major contributor to PM and needs to be removed from the exhaust before getting into the atmosphere.

In this paper, the results obtained in the experiments performed to abate NOx and PM using MW plasma is presented. Non-Thermal Plasma (NTP) is an emerging technology for abatement of NOx of gaseous emissions from diesel engine exhaust. The fundamental nature of non-thermal plasma is that the electron temperature is much higher than that of the gas temperature, including vibration and rotational temperature of the molecules. The electron energy is consumed in the ionisation, excitation and dissociation of the molecules and finally in the formation of active free radicals OH•, O•, N• and H•. These radicals oxidise NO to NO_2, which reacts with water vapour present in the exhaust gas forming aerosol HNO_3 which can be safely disposed into after adjusting its PH level using seawater. It was reported in our previous study that kinetics of NTP allows removal of NOx very effectively to almost 100% [3]. There are three methods for generating non-thermal plasma in atmospheric gas pressure; electron beam (EB) radiation, Microwave (MW) radiation and Electrical Discharge (DC, AC and pulsed field). Out of these there MW is very cost effective and had been exploited in many applications [4][5] and hence experimented in this work.

Section 2 presents the MW reactor experimental set-up and the results are presented in Section 3 along with brief discussion. Finally conclusion is drawn in Section 4.

2. Experimental setup with microwave plasma

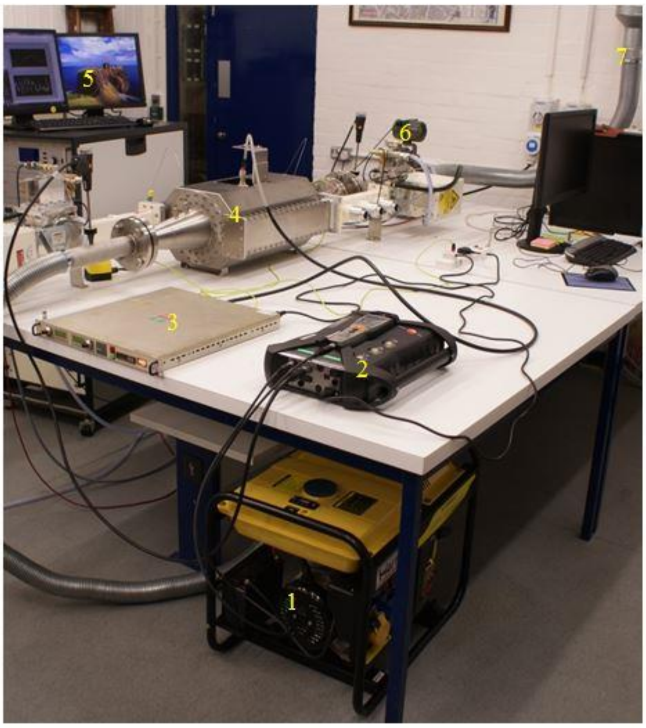


Figure1: Pilot scale Microwave plasma at Brunel University: 1- 2kW gen-set generator, 2 – Testo gas analyser at inlet/outlet of NTPR, 3 – Spelman 30 kV DC power supply, 4 – Multi-mode MW cavity, 5 – Sensors data logging system, 6 – Flow meter; 7 – Gas extraction to atmosphere

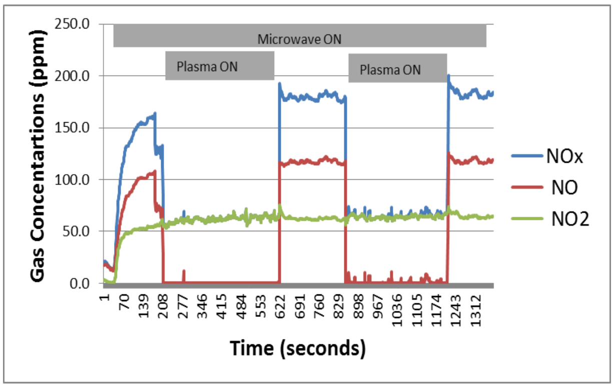
Figure 1 show the MW plasma experimental setup used in Brunel University laboratory. This set-up includes multi-mode microwave cavity, gen-set diesel generator, Testo-350 gas measurement systems (x2), 30kV high voltage supply, gas flow rate meter and data logging system. Two 2kW microwave generators operating at 2.45GHz were used to supply required microwave energy into the microwave cavity through two slotted waveguides. Full details of the cavity design can be found in [6]. The gen-set generator exhaust contains higher percentage of NO than NO_2, which is very similar to the exhaust from a typical 2-stoke diesel marine engine. Passive electrodes (needle electrode, saw tooth electrode and cross saw tooth electrodes) were used to ignite plasma in the MW reactor and it produced excellent results in the NOx abatement for moderate flow rate (60 – 70 l/s) from the gen-set generator.

3. Results and discussion

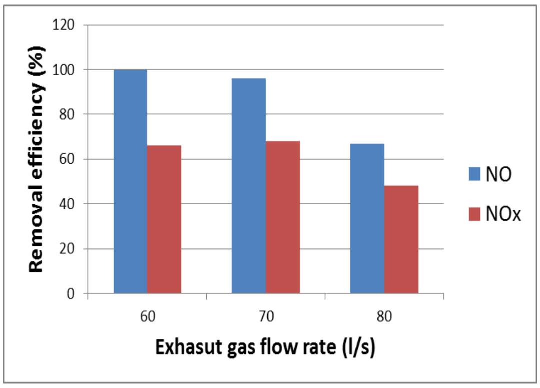
Two sets of experiments were carried out with pilot scale MW plasma. The first one was performed in the Brunel Laboratory for the exhaust from a 2kW gen-set diesel electricity generator and the second test was for the exhaust from a 200kW diesel engine in the Southampton pilot scale test site. The main purpose of the first set of experiments was to understand the performance of NOx removal whereas the second set of experiments was intended to perform for the removal of PM (soot).

NOx Removal

A number of test were performed at different operating condition of exhaust of the gen-set diesel generator (temperature, flow rate and load) and each of the test required fine tuning of MW power and position of cross saw tooth in the reactor to ignite and maintain the plasma. The typical results are shown in figure 2. As shown in figure 2(a), when MW plasma is ignited, the concentration NO went down to almost zero and hence the concentration of NOx reduced significantly while there was no reduction happened to NO. This results were obtained when exhausts gas temperature was between 40-700C and exhaust flow rate was 60l/s. Removal efficiency for this test was 100% of NO and 65% of NOx for the microwave power of 1kW (i.e.: 2x 500W). When the flow rate was increased for same supplied MW power, the removal efficiency dropped in proportion. The removal efficiencies for three flow rates are shown in the figure 2(b). As can be seen in this figure NO (and NOx) removal efficiency has decreased for the increased gas flow rate, as it would require more plasma energy to treat higher gas flow rate. It was also noted from another set of tests that for relatively higher gas temperature (> 1000C), the concentration of NO was increased while gas passed through MW plasma. This resulted in negative removal efficiency of NO and NOX (<-100%) and it was due to oxidation of N radicals into NO. Therefore the temperature of the exhaust gas is very important in the NO abatement process.



(a)

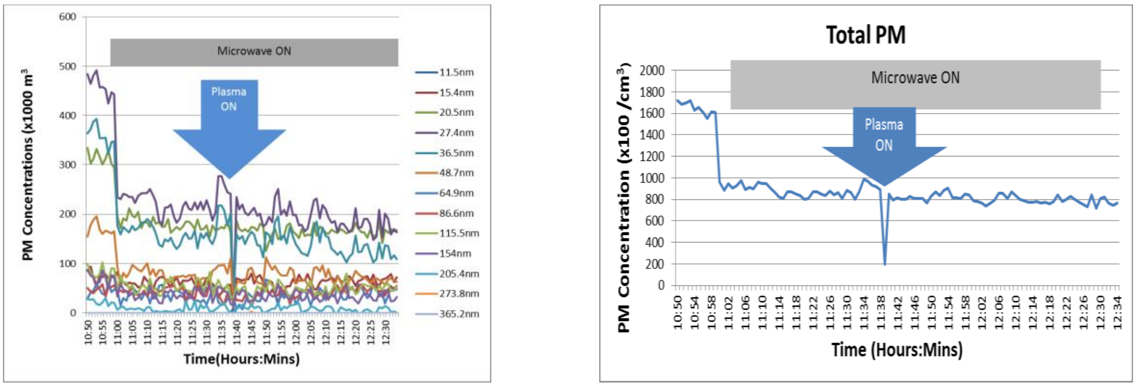


(b)

Figure 2: Results for NOx removal (a) NOx concentrations when plasma is ignited (b) NOx removal efficiency vs exhaust flow rate for the gas temperature between 40-70 ^{0}c

PM Removal

A number of experiments were carried out to investigate the PM removal capacity of MW plasma at the Southampton pilot scale test site. Exhaust from 200kW diesel engine at 40% engine load was passed through MW plasma and measurements at the outlet were taken using TSI PM Analyser. Two scenarios of PM removal with MW were experimented, with and without plasma. These results are shown in figure 3. Figure 3(a) shows particle of various size form 11.5nm to 365.2nm. As can be seen in this figure, when microwave is ON the concentrations of particles has dropped significantly, mainly the small sized particles. When plasma stuck (at around 11:38am) for a very short period, the removal of particles was very high. Figure 3(b) shows the removal of total particles for Microwave ON and plasma ON. It is estimated that form number of repeated PM removal tests that removal efficiency with microwave without plasma was 50% and as high as 90% when MW plasma was generated. The precipitation of the particles is due to the distribution of electric field within the reactor generated by the MW. When the plasma is formed the ionisation of the gas molecules enhanced the electric field as a consequence the particles removal efficiency increased significantly.



(a) (b)

Figure 3: PM removal using MW plasma (a) various sizes of PM (b) Total PM

3. Conclusions

Removal NOx from the exhaust was shown experimentally using microwave plasma for the exhaust flow rate up to 60l/s and for the exhaust temperature between 40-70oC. It was also shown that removal of PM (soot particles) can also be performed using MW plasma very effectively. The challenges still remaining are ignition and maintaining of non-thermal MW plasma for larger volume of multi-mode MW cavity reactor.

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