AEC-1001

The 4th TSME International Conference on Mechanical Engineering
16-18 October 2013, Pattaya, Chonburi

An Innovative Approach of Diesel Particulate Matter Reduction Using Dielectric Barrier Discharge Non-Thermal Plasma

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Abstract

The major long term challenge for the diesel engine is the substantial reduction of NO_x and particulate matter (PM) emissions. Diesel particulate matter (DPM) has been concerned to human health. In additions, the new emission standards that will be enforced in the next few years will be more stringent. The several approaches for both engine control and exhaust gas aftertreatment technology such as high fuel injection pressure, multiple fuel injection, diesel particulate filter (DPF) and non-thermal plasma are required in order to the control of diesel particulate matter emission. The non-thermal plasma (NTP) technology has been established as a favourable method and enhance for control and treatment of diesel particulate matter emissions. The aim of this work was to design a dielectric barrier discharge (DBD) NTP system to treat DPM treatment system. In order to investigate the effects of using DBD NTP on engine-out DPM and the effects of space velocity on DPM reduction. Thermogravimetric analyser was also monitored to determine DPM compositions and its oxidation characteristics. The input power of DBD NTP was between 1.31 W and 2.46 W. The study was used to treat partial exhaust gas from single cylinder diesel engine on test rig. As much as 38 percent of DPM reduction was achieved. DBD NTP was effective on VOF reduction which resulted in 25 percent reduction. Space velocity was proved to play an important role in DPM compositions. Lowering space velocity by 40 percent resulted in soot reduction by 3.61 percent. Further investigation will be needed to obtain optimised DBD NTP operating condition to gain better DPM reduction.

***Keywords**:* Dielectric barrier discharge, Non-thermal plasma, Diesel particulate matter, Volatile organic fraction

1. Introduction

Diesel engines have been used as the main source of mechanical energy in many on-board and off-board applications due to its advantages in thermal efficiency and engine-out emissions in comparison to gasoline engines [1]. Although, diesel engine is the major contributor of producing nitrogen oxides (NO_x) and diesel particulate matter (DPM) which are considered harmful to human health. DPM could be the cause of respiratory irritation and even lung cancer [1]. The amount of NO_x and DPM stringent limited to low level according to upcoming emission legislations. The various methods employed to treat diesel engine-out emission, especially NO_x and DPM, for instance; engine control and exhaust gas aftertreatment. Diesel particulate filter (DPF) is mainly used to trap DPM. As diesel engines operate at very lean equivalent ratio that leads to low exhaust temperature which DPF unable to oxidise soot accumulated in DPF [2]. The longer trapping leads to soot blocking in the DPF chamber, hence, increase fuel consumption. Several methods employed to raise DPF temperature e.g. fuel injection into DPF, late fuel injection in exhaust stroke via engine management. These incorporated the increase in HC emission and also cost fuel penalty.

Non-thermal plasma (NTP) technology has been introduced in diesel emission applications [1,2] as NTP has potential to accelerate chemical process of specific substance due to its nature of selectivity [3]. In oxygen-rich environment as in diesel exhaust, NTP will enhance ozone (O_3) and NO_2 production which could be utilised the soot oxidation in DPF [4-8]. However, NTP might oxidise DPM directly utilising the electrical conductive nature of DPM [9]. Although, it should be noted that direct oxidation using NTP will be efficient if there is optimised resident time for DPM oxidation [10]. In addition, the sufficient residence time of DPM in oxidising zone can achieve by using DPF to restrict exhaust flow rate [9].

Dielectric barrier discharge (DBD) has been mentioned as a potential candidate for DPM direct oxidation as DBD configuration enhances radical species selectivity and inhibits spark discharge [3,11]. DBD configuration also requires low energy due to only heat radical molecules are required, not the entire gas. DBD was proved to have ability to alter physical and chemical characteristic of DPM [10]. Another aspect of DPM reduction apart from effect of oxidation is the effect of DPM collection on DBD electrode [12,13]. High potential electric causes electromagnetic field which DPM attracted to electrode and being collected. As low as 9kV of electrical was reported in this work [12].

In our study, a direct plasma treatment method was chosen using DBD scheme to treat DPM from single cylinder diesel engine. The analysis emphasised on the effects of DBD NTP and effects of SV on DPM mass loading and DPM compositions.

2. Experimental Apparatus and Procedures

2.1 Diesel engine test rig

The experiments were carried out on a Yanmar model L100V, four stroke single cylinder naturally aspiration diesel engine mounted to an eddy current dynamometer which was employed as DPM source. The partial exhaust gas was directed to an in-house built non-thermal plasma DBD reactor.

2.2 DBD NTP reactor

A DBD NTP reactor with tubular configuration of plasma reactor was chosen. A quartz tube with outside diameter of 17 mm (1.5 mm of wall thickness) and 300 mm length was employed as dielectric barrier. Stainless steel rods with outside diameter of 6 mm and 10 mm were used as inner electrodes placed center of quartz tube. This allowed the author to observe the effects of electrode gap, thus the change of space velocity on DPM reduction. The copper wire is located around outside of quartz tube acted as outer electrode. The reactor effective length was defined by the width of copper wire wrapped around along the axis of quartz tube which could be altered during experiment to change reactor space velocity. DBD NTP reactor schematic diagram is shown in Fig. 1.

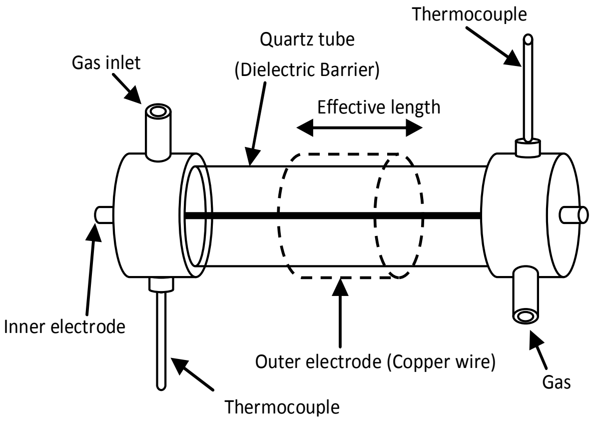

Fig. 1 DBD NTP reactor

The high potential electricity for DBD NTP reactor was produced by an in-house built HVPS. The Pulsed Frequency Modulation (PFM) technique was used to switch the transformer to produce high voltage which electric input power could be altered by changing switching frequency. DBD NTP reactor setup employed in this experiment is illustrated as shown in Fig. 2.

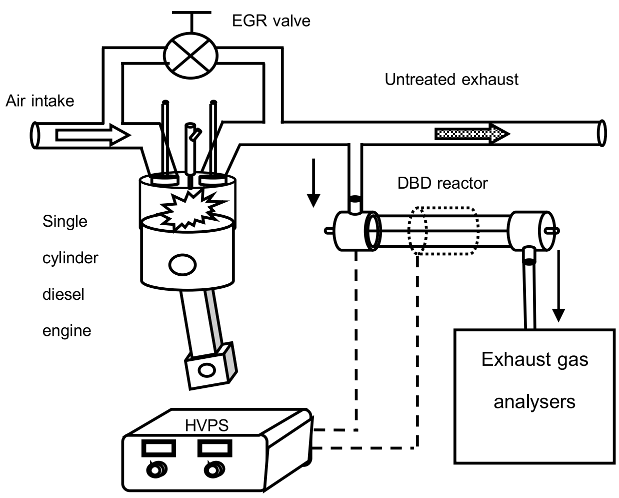

Fig. 2 Schematic diagram of DBD NTP system

2.3 Space Velocity (SV)

Space Velocity is the ratio of gas flow rate through reactor and the effective volume of the reactor as shown in Eq. 1.

$$SV = Q_{gas}/V_{reactor} \quad (h^{-1}) \qquad (1)$$

Where Q_{gas} is exhaust gas flow rate ($m^3\ h^{-1}$) and $V_{reactor}$ is reactor volume (m^3). Higher value of SV results in relative higher gas flow rate which leads to relative faster gas flow in the reactor. Hence, gas molecules in the reactor have shorter resident time within the reactor.

2.4 DPM analysis

Thermogravimetric Analyser (TGA) was used to observe DPM oxidising characteristic which TGA is a well known method for DPM thermal extraction analysis in previous works. [14-18] TGA is basically done by heating DPM sample up in controlled atmosphere furnace at controlled temperature. Sample weight loss as function of time or temperature for particular sample could identify sample compositions.

Table 1 TGA heating programme

Sequence	Details
1	N_2 as initial atmosphere
2	Isothermal for 40 min at 40°C
3	Heat ramp 3°C/min to 400°C
4	Isothermal for 30 min at 400°C
5	Cool down 3°C/min to 350°C
6	Switch from N_2 to O_2
7	Heat ramp 3°C/min to 600°C
8	Isothermal for 60 min at 600°C

DPM was collected using glass fiber filter which heated and undiluted exhaust gas was drawn. Filter was weighted before and after DPM loading. DPM components were analysed using Perkin Elmer Pylis1 TGA. The samples were heated in the TGA according to the TGA heating programme in table 1.

Single cylinder diesel engine was employed as DPM source. The partial exhaust gas was directed through DBD reactor where samples were collected downstream the reactor. The engine speed of 1200 and 1500 RPM and engine load of 50% and 75% represented engine steady state conditions were performed to obtain different exhaust gas and DPM concentrations. HVPS input power for all experiment conditions were adjusted constant at 27W. Test conditions illustrated in table 2.

Table 2 Engine test conditions

Engine conditions		
No.	**Speed (RPM)**	**Load**
1	1200	50%
2	1200	75%
3	1500	50%
4	1500	75%

3. Results and discussions

3.1 Effects of DBD-NTP on DPM

Fig. 3 illustrated the effect of DBD NTP on DPM loading on glass fiber filter in comparison between normal engine-out exhaust gas and NTP treated exhaust. DBD NTP showed overall DPM reduction for all engine conditions. The DPM reduction as achieved via the DBD NTP was 38 percent at engine speed of 1200 rpm 50% engine load. Using inner electrode size 6 mm of outside diameter resulted in SV 47.7 kh^{-1}. The input power of HVPS was 27W or 2.46 percent of engine output power. The results of total DPM reduction tends to match the patterns recorded from the previous publications [8-10].

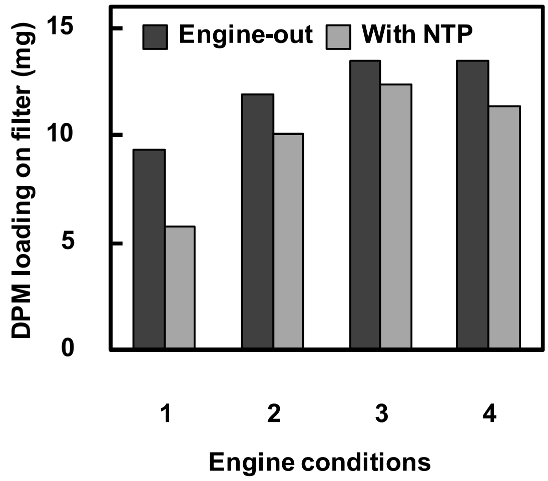

Fig. 3 Effect of DBD NTP on DPM loading

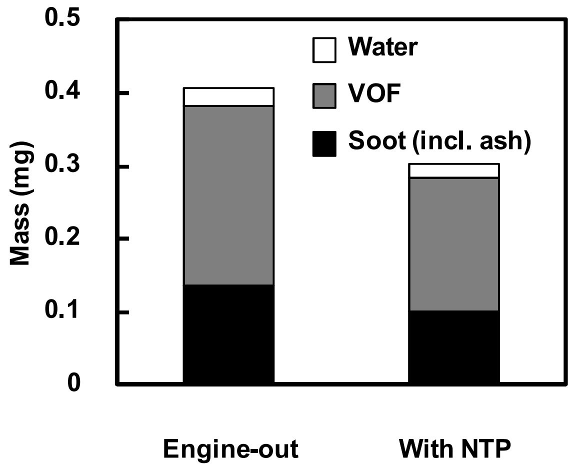

Fig. 4 Effects of NTP on DPM compositions of engine at 1500 rpm 50% engine load

Fig. 4 revealed the result of DPM composition via TGA weight loss curves. It can be seen that the treated exhaust gas collect from NTP has lower total mass of DPM than untreated engine-out exhaust gas. In addition, water, VOF and soot were simultaneously reduced via NTP especially, VOF was significantly reduced by 25percent which agreed with the result presented in previous work [19]. Meanwhile, 25.73 percent of soot reduction was found by the use of DBD NTP system.

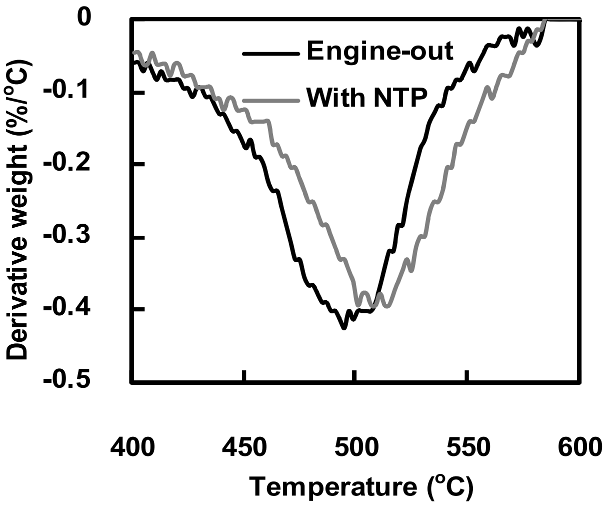

Fig. 5 Effects of NTP on soot oxidation of engine at 1500rpm 50% engine load

The start of soot oxidation and the derivative weight loss curves as shown in Fig. 5 identified the inflection points of DPM from both exhaust conditions. The derivative peak of DPM with NTP treatment was slightly lower than that of untreated DPM which confirmed less amount of soot in NTP treated DPM. It should be noted that NTP treated DPM peak slightly shifted toward higher temperature which also supported the fact that VOF in exhaust gas was reduced.

3.2 Effects of space velocity on DPM

The previous work [10] demonstrated that direct NTP treatment on DPM required sufficient residence time or contact time over NTP for completely oxidise DPM. This related to SV of our proposed DBD NTP reactor which SV could be altered by changing reactor effective volume. In this experiment, the SV was varied by changing inner electrode size which the larger electrode diameter resulted in lowering reactor effective volume and thus, increased SV. Another aspect to consider was gas velocity in reactor which affected by SV. Higher SV caused by lowering effective volume. In this case, effective length was kept constant, therefore; only cross-section area of exhaust gas path within reactor was changed. The smaller cross-section area of gas path leads to the exhaust gas move faster. In addition, this means soot particles would have less residence time within reactor. Hence, the DPM reduction activities are reduced with higher SV of reactor.

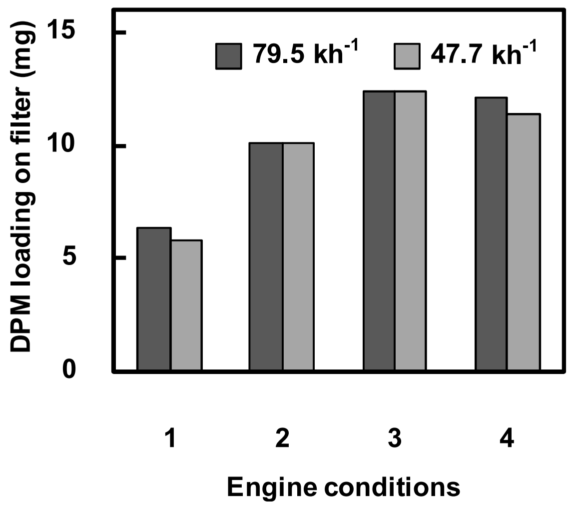

Fig. 6 Effect of SV on DPM loading

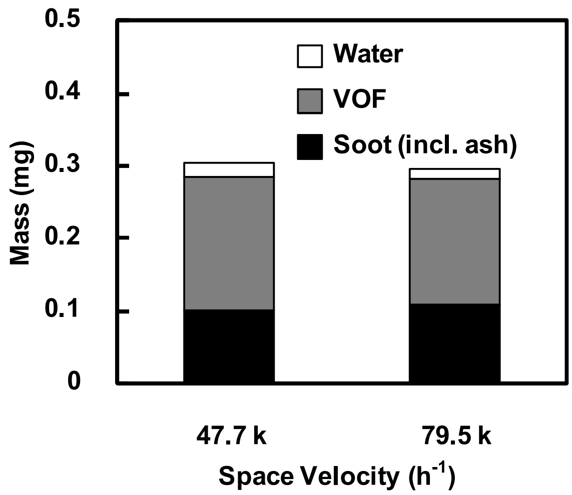

Fig. 7 Effects of SV on DPM composition of engine at 1500rpm 50% engine load

Fig. 6 demonstrated the effect of DPM loading due to changing in SV of DBD NTP reactor. The higher SV (79.5 kh^{-1}) has no significant effects on DPM loading and DPM compositions compared to lower SV (47.7 kh^{-1}) as shown in Fig. 7.

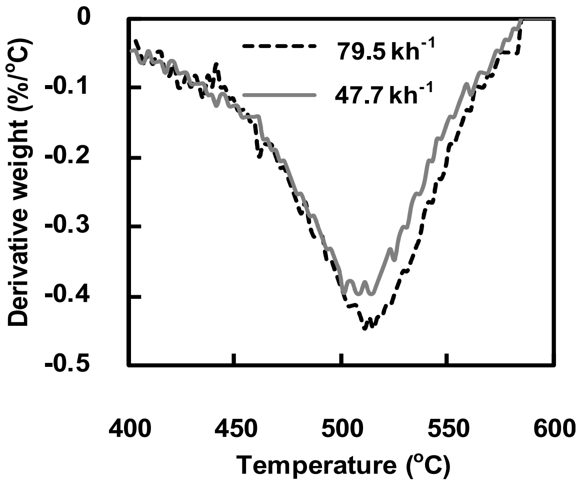

Fig. 8 Effects of SV on soot oxidation of engine at 1500rpm 50% engine load

The increase of SV was expected to increase the soot concentration (33.33% to 36.94 %) and decrease in VOF (60.72% to 58.30%). This was confirmed by the different in soot derivative weight loss peaks. The DBD NTP reactor operated with low SV remained with less soot content and slightly lower temperature at its inflection point. Fig. 8 illustrated derivative weight loss of DPM from treated exhaust gas where higher SV (DBD NTP with 10 mm inner electrode rod demonstrated slight shifted toward higher temperature as less VOF content indicated. This showed consistency with the previous results discussed in the previous section.

4. Conclusion

NTP was able to achieve DPM reduction at relatively low input power in this experiment. NTP was effective on simultaneous VOF and carbon soot reduction compared to DPM compositions of untreated exhaust gas. Increasing space velocity of NTP reactor resulted in slightly increase in carbon soot element due to insufficient resident time in NTP reactor to properly complete soot oxidation. Further investigations will be needed for optimisations of DPM reduction.

5. Acknowledgements

This work was supported by Grant TRG5680088 from the Thailand Research Fund (TRF) and King Mongkut's University of Technology North Bangkok (KMUTNB).

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Nomenclature

DBD	Dielectric Barrier Discharge
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
EGR	Exhaust Gas Recirculation
HC	Hydrocarbon
HVPS	High Voltage Power Supply
NO_x	Nitrogen oxides (NO, NO_2)
NTP	Non-Thermal Plasma
SV	Space Velocity
TGA	Thermogravimetric Analyser
VOF	Volatile Organic Fraction