DIRECT APPLICATION OF NON-THERMAL PLASMA TO PM REDUCTION FROM MARINE DIESEL ENGINES

Jarosław Myśków, Tadeusz Borkowski

Maritime University
Waly Chrobrego Street ½, 70-500 Szczecin, Poland
phone: +48 91 4809400, fax: 48 91 4809575
e-mail: jmyskow@am.szczecin.pl, tborkowski@am.szczecin.pl

Abstract

This paper describes the experimental method – using non-thermal plasma reactor to cleaning exhaust gases - focused on PM compound. The demonstrator NTP reactor assembly was built as the by-pass in the real exhaust gas after-treatment system, in marine diesel engine. The reactor used to experiment is called - DBD (dielectric barrier discharge) type. The main aim of investigation was to analyze exhaust gas PM compounds under steady load of the engine.

Test bench construction enables direct exhaust stream (main exhaust duct by-pass) to plasma reactor exposure with no additional components (coolers, orifices) that can change the exhaust gas properties. A new monitoring PM analyzing system, which can measure soot and SOF in low mass level, has been engaged. It consist of a diffusion charging (DC) detector with a dilution device for soot measurement, and two differential flame ionization detection (FID) method, which uses two FID detectors with separate sample lines.

Exhaust emission reduction strategy for ships, Particulate Matters - PM in exhaust gas, non-thermal plasma reactor, experimental test bed and procedure, an example of reactor power measurement, test results provided into seven stages are presented in the paper.

Keywords: *marine diesel engine, exhaust emission, particulate matter, non-thermal plasma reactor*

1. Introduction

The marine traffic drastically influences the environment – especially in coastal regions. The ships prime mover - diesel engines offer low fuel consumption, efficiency and durability. In turn, they burn low grade heavy fuel oil which is dominant fuel used by the marine commercial transportation. The Maritime Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) has approved amendments to the Marpol Annex VI regulations to reduce harmful emissions from ships. The main changes would be seen as a progressive reduction in sulphur oxide (SO_x) and PM emissions. The another approach in reduction of harmful compounds from diesel engines was done by U.S. Environmental Protection Agency - EPA, which improved emission standards of particulate matters for non-road and especially marine engines. The new standards will cut PM pollution by 90% and NO_x by 89%, respectively. The standards should be achieved by means of the combination of ultra-low sulphur diesel fuel and advanced engine cleaning systems [3].

2. Exhaust emission reduction strategy for ships

There are several options for existing ship operators that can reduce emissions and their related impacts. A variety of approaches are available to achieve emission reductions from the two primary sources of ocean-going vessels, main and auxiliary engines and secondary - auxiliary boilers. Generally, main engines are large bore, slow speed and auxiliary engines are medium or high speed, four stroke. Boilers are also responsible for emission, especially in port and shore areas.

Existing vessels can become cleaner, with respect to air quality, if the following elements will be incorporated in their operation:

1. Cleaner fuels - distillate marine fuels for both main and auxiliary engines and boilers with low sulphur. It will reduce sulphur oxides - SO_x, particulate matters - PM, and nitrogen oxides - NO_x emissions. For example, switching to distillate diesel and gas oil with the lowest available sulphur contamination is strongly recommended by Environmental Protection Agency - EPA in US - (Port of Los Angeles and Long Beach - Pacific Rim from 2005) [3, 9].
2. Vessels speed reduction, in US since 2001 some ports (mentioned above) have participated in special program - Voluntary Speed Reduction Program - VSR. Vessels shall reduce their speed to 12 knots on arrivals and departures to the ports. The speed reduction zone is monitored and recorded. The speed reduction is an operational change that all vessels can make to reduce NO_x and PM emissions, and it doesn't require any vessel modification. Presently the restricted area is 20 nautical miles from shore line, and the next step will be 40 nautical miles [3, 9].
3. Injector nozzle slide valves, these are a new more efficient design of fuel assembly that reduce NO_x and PM emission by means of minimizing sac volume effect. This concept was introduced in 2002 and nowadays most of the main engines are delivered with this kind of injectors. In many cases old engine can be retrofitted.
4. Low emission mode, some main propulsion engines, can operate in different mode of operation, depending on voyage conditions. In port vicinity they can develop a low NO_x emissions mode that gives higher fuel consumption.
5. Main and auxiliary engine exhaust emission after-treatment solution. These exhaust emission technologies are currently under development and testing and focus on NO_x, SO_x and PM reducing. Land based equipment such as: selective catalytic reduction - SCR, water scrubbers, dry low NO_x combustion, humid air injection, water fuel emulsion, direct water injection, exhaust gas recirculation - EGR system, electronic engine control, low temperature plasma with catalyst can be used.

3. Particulate Matters - PM in exhaust gas

Air pollution caused by diesel engines and boilers – especially particulate matters and nitrogen oxides emission is one of the biggest problem. In the near future the emission of diesel particulate matters will become additionally, an important factor affecting engine development.

As results of hydrocarbon fuel combustion, harmful compounds are released to atmosphere. Exhaust gases include solid particles originating from:

1. incompletely combusted fuel and lubricating oil,
2. fuel ashes,
3. residual materials from combustion chamber and exhaust duct.

Heavy and distillate diesel fuel oil are major contributor to creating particulate matter (PM). Incompletely combusted particles of fuel sediment as residual materials tend to coat internal surfaces of the exhaust duct. The majority of them is conveyed to atmosphere in stream exhaust gas. Some fuel hydrocarbon chains are disintegrated in high temperatures, releasing hydrogen, but not being completely oxidized. The remaining of the matter forms soot, mainly containing carbon. Diesel engine particulate matter often contains a small amount of various compounds which may contribute to undesirable health effects.

Basically, particulate matter represents a complex mixture of organic and inorganic substances. Formal PM structure distinguishes different size of particle:

1. PM_{10} – coarse, with diameter less 10μm,
2. $PM_{2,5}$ – fine, with diameter less than 2.5μm,
3. $PM_{0,1}$ – ultra fine, with diameter less than 100nm,
4. $PM_{0,05}$ – nano, with diameter less than 50 nm.

Figure 1 shows typical PM composition, and the Fig. 2 shows the schematic diagram of diesel particulate matter and gas phase compounds.

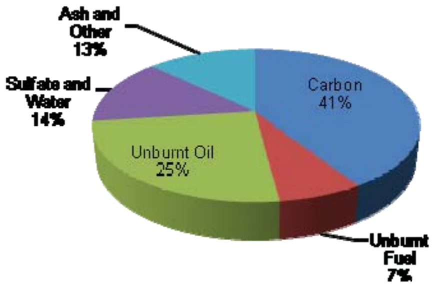

Fig. 1. Typical particle composition

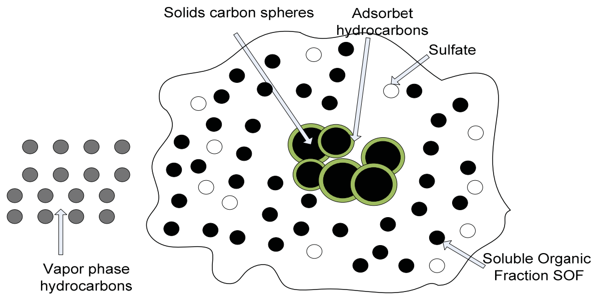

Fig. 2. Schematic diagram of PM

The well known adverse environmental and health effects of PM have resulted in common approach of emission restriction and therefore the concentration in the exhaust will be regulated soon, and some steps to remove these harmful compounds should be taken.

4. Non-thermal plasma reactor

Nowadays, continuous research is being conducted on limiting the emission of harmful substances released to atmosphere. There are numerous methods of emission suppression. Mainly they can be divided into three groups of methods:

- connected with preliminary fuel treatment,
- leading to construction changes,
- connected with exhaust gases treatment.

To the methods associated with exhaust gas treatment belongs non-thermal plasma – NTP. This kind of the gas treatment has good advantages: there is no need any intrusions into the engine construction and has no interaction to the engine performances.

Non-thermal plasma is currently a promising field of research considering its application in exhaust gases purification process [6, 8]. Generally, plasma is called a fourth state of matter. This is a partially ionized gas mixture and contains electrons, ions, neutral atoms, molecules, reactive free radicals and photons. In the described experiment, a non-thermal reactor with cylindrical electrodes with barrier discharge was used – DBD. The advantage of the barrier discharge is low pressure and temperature under non-equilibrium conditions. In the contrary the disadvantage is a rather small distance between electrodes (a few mm) and therefore - small active volume of reactor. An individual element of the reactor is formed by high voltage plate (stainless steel) and a low voltage electrode – a rod, (stainless steel as well). A dielectric barrier is a quartz glass pipe. Exhaust gases flow inside and outside the pipe, through the area of discharge, between the electrodes. A detailed description of the reactor was published in the earlier paper [7]. The phenomenon of discharge occurs when the voltage exceeds the insulating effect of the quartz tube. Power electronic supply is a novel, series parallel resonance circuit topology - SPRC with zero current switching - ZCS properties. AC reactor supply voltage measured in peak-to-peak values in the range between 12.3-13.3 kV and was used for experiments. To obtain the dissipated power of the plasma energy a Lissajous-figure method has been used – an example is shown on Fig. 3 [5, 10].

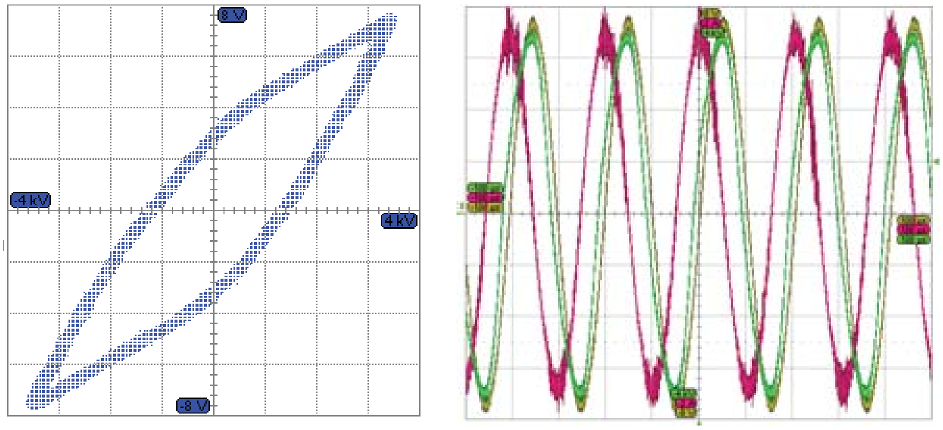

Fig. 3. An example of reactor power measurement - Lissajous-figure (left) and characteristic voltage and, current in the reactor and voltage on the measuring capacitor (right)

The assumed reaction mechanism leading to the removal of PM and SOF can be done as follows [1, 2, 6]:

- soluble organic fraction SOF:

$$SOF + NO \rightarrow NO_2 + \text{(neutral products)}, \tag{1}$$

- -particulate matters PM:

$$C_x + OH \rightarrow C_{x-1} + CO + 1/2H_2, \tag{2}$$

$$C_x + 2OH \rightarrow C_{x-1} + CO_2 + H_2, \tag{3}$$

$$C_x + O \rightarrow C_{x-1} + CO, \tag{4}$$

$$C_x + 2O \rightarrow C_{x-1} + CO_2, \tag{5}$$

$$C_x + 2NO_2 \rightarrow C_{x-1} + CO_2 + 2NO, \tag{6}$$

$$C_x + NO_2 \rightarrow C_{x-1} + CO + NO. \tag{7}$$

Particulate matters - PM and SOF fraction could be removed in discharge zone of DBD reactor.

5. Experimental test bed and procedure

Non-thermal plasma reactor module was built in an exhaust gas by-pass system - a part of exhaust system from marine diesel engine which specification data shown below:

type	Sulzer 6AL20/24 (4 stroke, turbocharged),
nominal power	P_{nom}=324 Kw,
nominal revolution	n_{nom}=720 obr/min,
specific fuel consumption	218.3 g/kWh,
cylinder diameter	200 mm,
piston bore	240 mm.

The experimental engine and non-thermal plasma reactor test-cycles were conducted on marine laboratory test-stand and all engine performances were continuously and simultaneously recorded together with exhaust gas components concentration, by means of central data acquisition and monitoring system presented in Fig. 4.

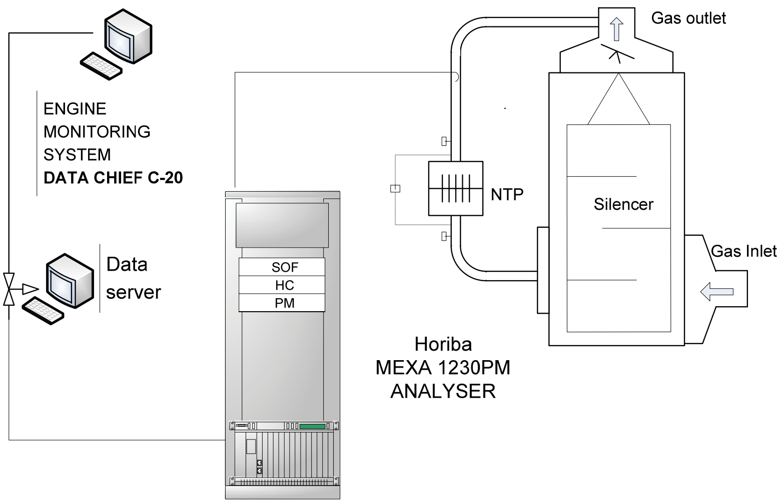

Fig. 4. Acquisition system set up

The emission measurements were carried out on engine at steady-state operation under idle load. The sampling gas was distributed to the analysers. During the test-cycle each measurement phase consists of two periods: without NTP (plasma off) and with NTP (plasma on) operation. This measurement procedure helps distinguish the NTP reactor effectiveness and provided real gas composition records strictly to operation stage. The power supply unit input was varied in five steps, ranged within 130 to 290 [W] of active power. The trial schedule allowed the reactor to heating up for stable conditions, adequately to engine exhaust system and outlet gas conditions.

Particulate matters were measured using Horiba analyser. MEXA-1230 PM which allowed obtaining the concentration of soot, soluble organic fraction (SOF), and total particulate matter (PM) in engine exhausts gas. Exclusively, this analyser has the ability to measure the soot by means of diffusion charging and SOF the dual-FID methods. The SOF measuring methodology is based on two heated flame ionization detectors (HFID). The total PM is obtained as the sum of soot and SOF. The PM analyser system consists very sophisticated pre-sampling unit incorporating soot diluter operating on ejector principles, main cabinet incorporating soot analyzer, SOF analyzer, and automated sampling unit that provide monitoring operation.

6. Results

The test was provided into seven stages. Reactor power increased linearly with the input power ranged from 130 to 400 [W]. The reactor supply voltage frequency reached the maximum value of 25 [kHz]. Electrical efficiency of the reactor was 62% (increasing with the input power), reaching saturation at about 200 [W] input – in fourth stage. Measurements results are shown on the Fig. 5 - PM, SOF and soot parameters. The highest SOF reduction has been recorded at the seventh stage of test – under maximum of the reactor load condition. On each stage of the test, soot parameter increased with the highest value at the beginning when the density of energy was very low, 3 [W/dm^3]. Fig. 6 shows effect of NTP treatment on PM concentration. On the three first stages the effect was very weak. The next stages show reduction of PM concentration at 12%.

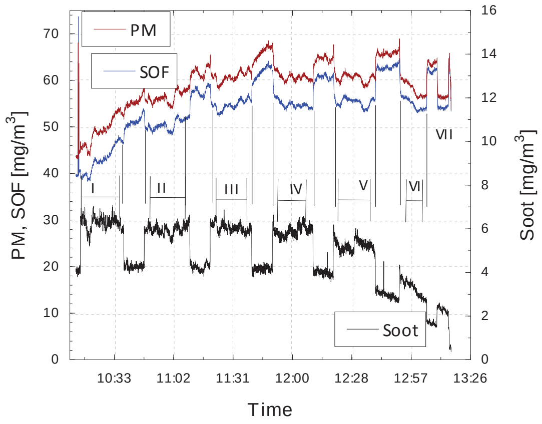

Fig. 5. PM and related (SOF, Soot) components concentrations during test

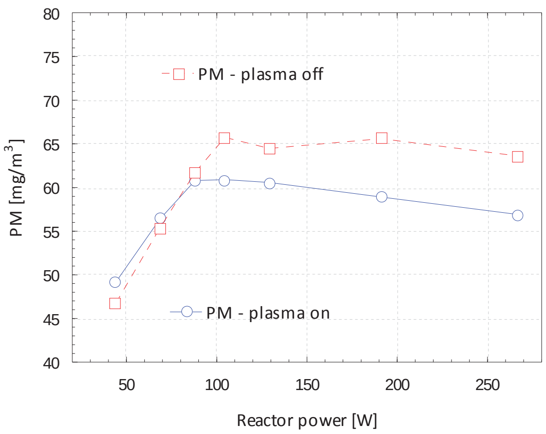

Fig. 6. PM concentration function of reactor power

The correlation between the Soot and SOF composition is shown in the Fig. 6. Due to Soot - SOF concentration relation, total PM removal process has different effectiveness - coupled with energy density. The increase in PM efficiency removal was associated with the main PM component - SOF. The other PM constituent - soot reduction degree was much slower and weaker.

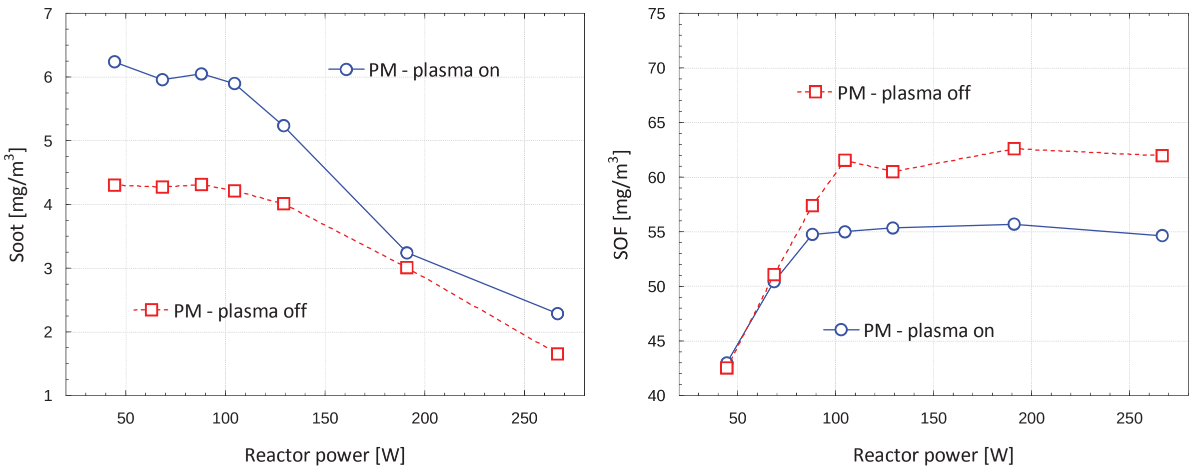

Fig. 7. Soot (right) and SOF (left) component concentrations during test

The residence time of gas in the reactor was short about 0.66 [ms].

7. Conclusions

Technical condition of the reactor was excellent. On the first three stages of test the increasing of total PM was observed. It may cause by deposition of carbon fraction in the exhaust duct during heating up the engine, and then pulling away some PM fraction - SOF in the duct, (due to NTP module operation - oxidants produced in the reactor).

It was a good performance taking into account a low energy density: 3-16 [W/dm^3] in realistic exhaust system - reduction SOF at 12%. It may be supposed that elongation of the residence time inside the reactor - discharge zone may be more effective.

The experiment test bench gives the innovative role in the development exhaust gas after-treatment technology for marine systems. One of the most promising methods to decrease the number of harmful compounds from exhaust gas is implementing of NTP reactor with catalyst as after-treatment module.

References

[1] Dan, Y., Dengshan, G., Gang, Y., Xianglin, S., Fan, G., *An investigation of the treatment of particulate matter from engine exhaust using non-thermal plasma,* Journal of Hazardous Materials B127, pp. 149-155, 2005.

[2] Du, Ch. M., Yan, J. H., Cheron, B. G., *Simultaneous removal of polycyclic aromatic hydrocarbons and soot particles from flue gas by gliding arc discharge treatment,* Plasma chem. Process, pp. 517-525, 2006.

[3] Gore, J. D., *Port Idling Emission Reduction technologies For Large Cargo Vessels,* National Idling Reduction Planning Conference, Department Of Transportation USA 2004.

[4] Lack, D. A., Corbett, J. J., Onasch, T., Lerner, B., Massoli, P., Quinn, P. K., Bates, T. S., Covert, D. S., Coffman, D., Sierau, B., Herndon, S., Allan, J., Baynard, T., Lovejoy E., Ravishankara, A. R., Williams, E., *Particulate emissions from commercial shipping: chemical, physical and optical properties,* Journal of Geophysical Research US, Vol. 114, 2009.

[5] Kraus, M., Eliasson, B., Kogelschatz, U., Wokaun, A., *CO_2 reforming of methane by the combination of dielectric-barrier discharges and catalysis*, Phys. Chem., 3, pp. 294-300, 2001.

[6] Hughes, D. E., McAdams, R., *Non-thermal plasma for marine diesel*, International Council on Combustion Engines CIMAC Congress, Paper No. 231, p. 15, Kyoto (Japan) 2004.

[7] Myśków, J., Borkowski, T., Hołub, M., Kalisiak, S., *Development of non-thermal plasma NOx control system for marine diesel engine*, International Scientific Conference On Combustion Engines, Journal of KONES, Vol. 13, No. 3, pp. 37-44, Warsaw 2008.

[8] Penetrante, B., Schultheis, S. E., *Non-Thermal Plasma Techniques for Pollution Control: Part B - Electron Beam and Electrical Discharge Processing*, Springer-Verlag, Berlin Heidelberg New York 1993.

[9] Starcrest Consulting Group, LLC, *Evaluation Of Low Sulphur Marine Fuel Availability - Pacific Rim,* ADP 030507-513, The Port of Los Angeles 2005.

[10] Wagner, H. E., Brandenburg, R., Kozlov, K. V., Sonnenfeld, A., Michel, P., Behnke, J. F. *The barrier discharge: basic properties and applications to surface treatment,* 71, pp. 417-436, Vacuum 2003.