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NON-THERMAL PLASMA REACTOR WORKING WITH EXHAUST GAS SYSTEM IN MARINE DIESEL ENGINE

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Abstract

Recently, we HAVE BEEN faced with the regulation of NO_x from combustion exhaust gases, because it have caused smog, acid rain, and some diseases. The largest pollution sources in the world belongs to big seagoing vessels. The vessels are responsible for an estimated 14% of emission of nitrogen from fossil fuels and 16% of the emissions of sulfur from petroleum uses into the atmosphere. The Protocol adopted in 1997 includes the new Annex VI of Marpol 73/78, which entered into force on 19 May 2005. Nitrogen oxide emissions from ships were put at around 5 million tons per year – about 7% of total global emissions. This paper describes the experimental method – using non-thermal plasma reactor to clean exhaust gases. NTP reactor was built as the aftertreatment module in exhaust gas system in marine diesel engine. The main aim is to analyze exhaust gas compounds during steady load of engine, before and after NTP module.

Keywords: *marine diesel engine, exhaust emission gas treatment, non-thermal plasma reactor.*

1. Introduction

Maritime transport plays a significant role while considering transfer of materials and products. Intensified ship traffic near shoreline areas causes considerable changes to ecosystems. It is assumed that maritime economy uses about 3% of worldwide amount of produced fuels, which in most of the cases are of inferior quality, with higher contents of sulphur. As a result of the combustion process of this type of fuel, the following amounts of overall air pollution are released to the atmosphere: about 7% of with sulfur oxides and 11÷13% of nitrogen oxides. A proposal of International Maritime Organisation rules, concerning limiting of NO_x emission to the atmosphere, within “Prevention Of Air Pollution From Ships” program, aims at constraining nitrogen oxides emission by 30% comparing to 1990 levels.

In September 1997 Appendix VI was accepted at the MARPOL Convention 73/78, which incorporates regulations such as rules concerning emission of nitrogen oxides, sulfur oxides and Volatile Organic Compounds:

- Regulation 13 determines the maximum level of nitrogen oxides in exhaust gases produced by ship engines of power above 130kW, depending on engine speed;
- Regulation 14 concerns restrictions of sulfur oxides SO_x emission. The accepted content of sulfur in fuel was established at 1,5% for closed sea areas, such as the Baltic. In case of using on such areas a type of fuel exceeding this norm, a ship should be equipped then with a specialist installation limiting of SO_x emission to the level of 6g/kWh.
- Regulation 15 is related to Volatile Organic Compounds in tanker loading bases.

Exhaust gases emission sources in sea-going vessels are devices installed on board. Among them, there are mainly diesel ship engines of main propulsion, auxiliary engines, gas turbines, incinerators and main and auxiliary boilers. As a result of fossil fuels combustion, toxic compounds are released to atmosphere, such as carbon dioxide CO_2, carbon monoxide CO, sulfur oxides SO_x, nitrogen oxides NO_x, hydrocarbon HC and particulate matter PM.

Exhaust gases include particles originating from:
- incompletely combusted fuel,
- fuel ashes,
- residual materials from combustion chamber and exhaust duct.

Incompletely combusted particles of fuel delivered to combustion chamber sediment as residual materials inside the combustion chamber and in exhaust ducts. The majority of them is conveyed to atmosphere with exhaust gases. Hydrocarbon chains of some fuel particles are disintegrated in high temperatures, releasing hydrogen but not being oxidized. The rest of the matter left after hydrocarbon disintegration forms soot, mainly composed of carbon. The amounts of particulate matters are diverse, depending on the contents and properties of fuel (ash content, Condradson number).

2. 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. They can be divided into three groups:
- methods connected with preliminary fuel treatment,
- methods leading to construction changes of combustion chamber, ways of fuel injection, etc.
- methods connected with exhaust gases treatment.

Non-thermal plasma is currently a promising field of research when considering its application in exhaust gases purification process [3, 5]. In the described experiment, a reactor with cylindrical electrodes with barrier discharge is used – DBD. The advantage of the barrier discharge is a low relation between discharge parameters and chemical compound of gases. The disadvantage is a small distance between electrodes (a few mm) and therefore - small capacity of reactor. An electrode of high voltage is a plate made of stainless steel, and a low voltage electrode – a rod, made also of stainless steel. A barrier is a quartz glass pipe. Exhaust gases flow inside and outside the pipe, through the area of discharge between electrodes. A single element of the reactor is presented on Fig 1.

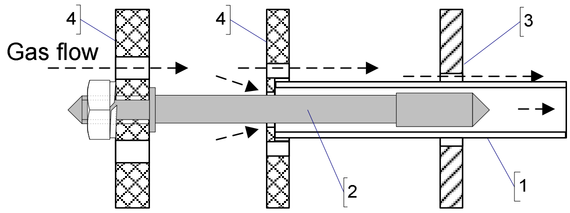

FIG.1 Basic element of non-thermal plasma reactor: 1 – quartz glass tube;
2 – rod – low voltage electrode; 3,4 – plate – high voltage electrode; arrows – gas stream direction.

The phenomenon of discharge occurs when the voltage through the plate exceeds the insulating effect of the quartz tube. The duration of these discharges is measured in nano-seconds. In a DBD field, the oxygen molecules split into two atoms of oxygen O^+ and O^+. The elemental oxygen radical, being very reactive, will form ozone - O_3. Oxygen radicals react with carbon monoxide – CO – to form carbon dioxide - CO_2, sulfur dioxide - SO_2 – and nitrogen oxide - NO_x – to form nitric acid - HNO_3 in the presence of moisture. Particulate matters – PM – could be reburned in discharge zone of DBD reactor [1, 2, 4], according to following reaction:

- soluble organic fraction - SOF:

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

- particulate matters - PM:

$$C_x + OH \rightarrow C_{x-1} + CO + 1/2H_2 \quad (2)$$
$$C_x + 2OH \rightarrow C_{x-1} + CO_2 + H_2 \quad (3)$$
$$C_x + O \rightarrow C_{x-1} + CO \quad (4)$$
$$C_x + 2O \rightarrow C_{x-1} + CO_2 \quad (5)$$
$$C_x + 2NO_2 \rightarrow C_{x-1} + CO_2 + 2NO \quad (6)$$
$$C_x + NO_2 \rightarrow C_{x-1} + CO + NO \quad (7)$$

Due to the reason mentioned above – predicted chemical reactions, the reduction of particulate matters was expected after leaving the discharge zone of DBD reactor.

3. Test bed and apparatus set up.

In the described experiment, the exhaust gas from marine engine was measured. Engine specification data is shown below:

type	Sulzer 6AL20/24, 4 – stroke, turbocharged;
nominal power	P_{nom}=324 kW,
nominal revolution	n_{nom}=720 rev/min,
specific fuel consumption	b=218,3 g/kWh,
cylinder diameter	200 mm,
piston bore	240 mm.

NTP module was built on a by-pass system – a part of a real exhaust system from marine diesel engine. DBD plasma reactor could work as:

- gas by-pass system,
- ozone doze to exhaust gas,
- hybrid equipment with catalyst module.

Emission measurements were carried out on an engine at steady-state operation. Sampling gas was distributed to all analyzers. The performance measurement procedure of marine engines on test beds was performed in accordance with Annex VI of Marpol 73/78 convention - with the specification given in the IMO NO_x Technical Code and ISO-8178 standard. All tests were covered by test-cycles procedure D-2 and E-2. The test performed with the selected marine distillate fuel DMX in accordance with ISO-8217 standard. All engine performances were carried out continuously and simultaneously together with exhaust gas components concentration recorded by means of measurement assemble:

- AVL-Pierburg CEB II Combustion Emission Bench (NO_x, CO_2, CO, O_2, THC),
- MIR FT – Fourier Transform Infrared spectroscopy multigaz analyzer (NO, NO_2, N_2O, NH_3, CH_4, C_2H_4, C_2H_6, C_3H_6, C_7H_8, H_2O, SO_2, CO, CO_2, O_2),
- HORIBA MEXA-1230PM – (PM – particulate matter, SOF – soluble organic fraction and SOOT).
- Ambient pressure, temperature and humidity,
- Monitoring and acquisition data from marine engine by Kongsberg DCC system.

4. Experiment results.

The engine test was provided in two stages: idle and part engine load (25% of the of nominal). On each measurement stage, the engine was in steady state of operation and all parameters were examined without NTP plasma operation (plasma off) and with NTP plasma operation (plasma on). As the first step of experiment, attention was focused on non-thermal plasma reactor influence on PM-particulate matters, SOF-soluble organic fraction and soot. Figures 2, 3 and 4 show changes of above components during engine work (all ranges), and figures 6, 7 and 8 only in idle and 25% load. Figure 5 shows the effect of unstable charge air temperature transferred on PM concentration resulting from NTP reactor operation. Electric power delivered to reactor was 200W and was kept on the same level during the test. Electrical system was working in automatic mode.

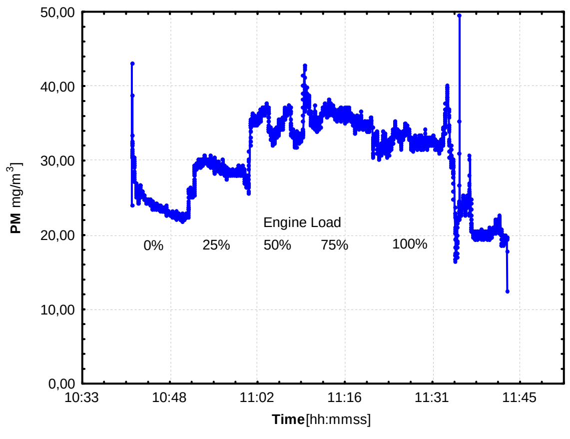

Fig.2 PM concentration during test under variable engine load, without NTP reactor operation.

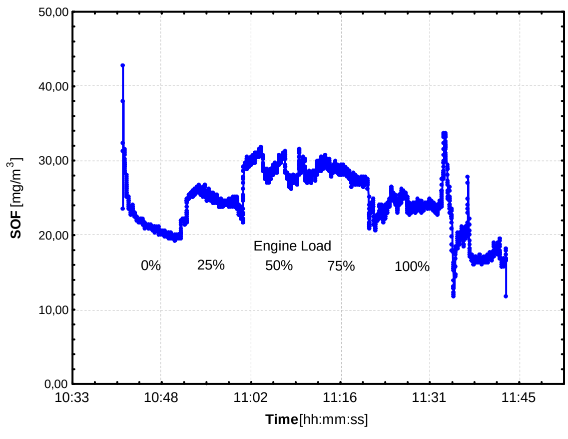

Fig.4 SOF concentration during test under variable engine load, without NTP reactor operation.

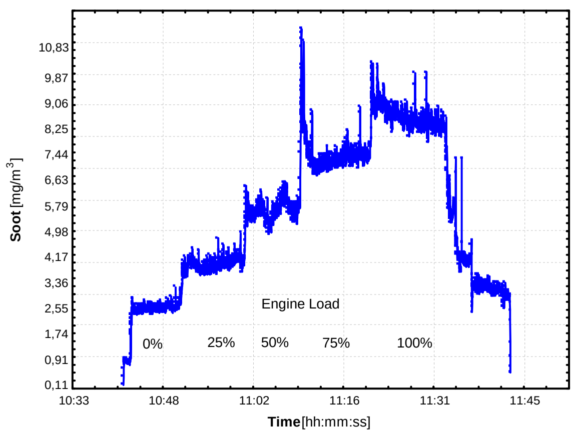

Fig.3 Soot concentration during test under variable engine load, without NTP reactor operation

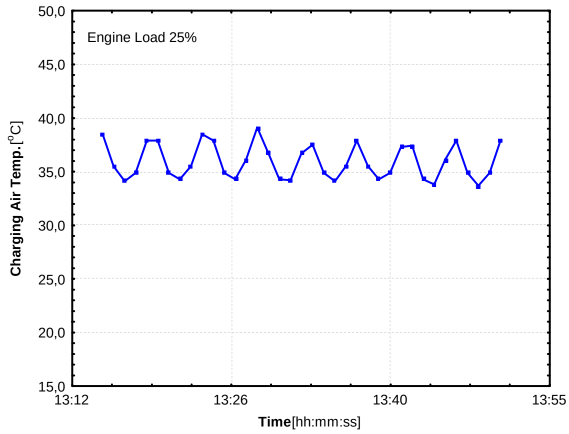

Fig.5 Air temperature at 25% engine load.

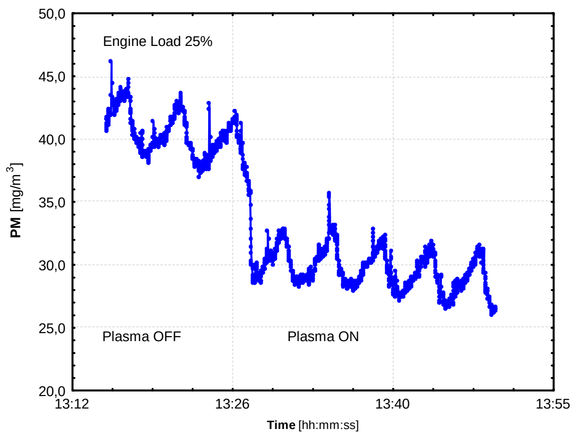

Fig.6 Changing PM parameters during test at 25% of engine load.

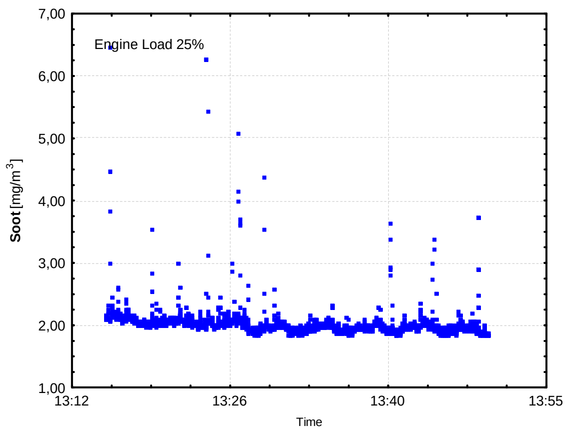

Fig.8 Changing Soot parameters during test at 25% of engine load.

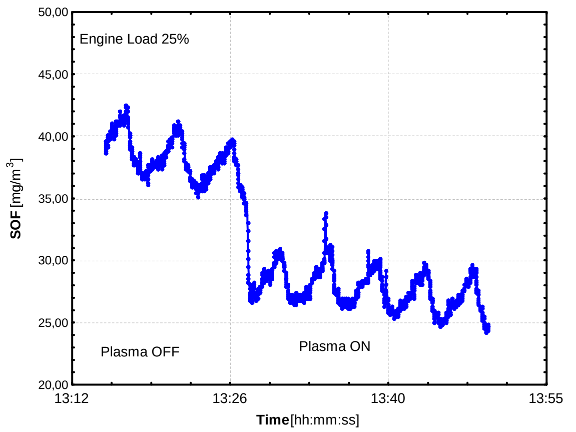

Fig.7 Changing SOF parameters during test at 25% of engine load.

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5. Conclusions and observations.

During test at 25% of engine load, the reduction of PM concentration was recorded at 28% with working DBD plasma reactor. 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. The increased coefficient rate of PM oxidation resulting from exhaust gas temperature increase has additional influence on CO concentration rise. The CO concentration rise was noticed in both engine loads. Some fluctuations of PM concentration were recorded - to establish the reason, the engine operational parameters were investigated. It has been found that there is strong influence of temperature of charging air on simultaneous PM concentration changes. The charge air temperature is controlled by means of external water cooling system with thermostatic valve with single value set-point.

Experimental study involving a NTP reactor operation with a realistic exhaust gas of marine engine was performed. Technical condition of the reactor after experimental trials (approximately 150 running hours) was excellent. As the next step it is proposed a two-stage plasma-chemical process for the control of harmful compounds: non-thermal plasma reactor and catalyst. This combination should be more effective and probably give the reduction with more efficiency of harmful exhaust gas compounds.

6. References

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