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THE ISSUE OF THE ATMOSPHERE PROTECTION AGAINST TOXIC COMPOUNDS GAS EMISSIONS IN MARITIME TRANSPORT

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Abstract

The paper discusses influence of the charging air parameters marine diesel engine on the emission toxic compounds in aspect of protecting the atmosphere against pollution from the sea vessels, pointed to the possibility of reducing NO_x emissions by changing the parameters of charging air. In this group of activities undertaken to reduce nitric oxides emissions applied inter alia cooling the air and changes in pressure at the beginning of compression stroke.

This is discussed in the background of normative acts, in particular the 73/78 MARPOL Convention (International Convention for the Prevention of Pollution from Ships) referring to prevention against marine environment pollution, and later amendments to the Convention with Annex VI (Regulation for the Prevention of Air Pollution from Ships) dealing with reducing the emission of nitric oxides and sulphur oxides into the atmosphere by sea vessels engines. It was also discussed the issue of air humidification as a method to reduce NO_x by injecting hot water into a stream of pumped air. This is an overview on the example of two methods proposed for using in marine engines: CASS (Combustion Air Saturation System), HAM (Humid Air Motor system).

The results of experimental tests of the influence of charging air pressure on content of exhaust gas, especially content nitric oxides (NO_x), of ship diesel engine supplied with marine heavy fuel oil IF40 have been presented in this paper.

Keywords: *laboratory tests, supercharging air pressure, exhaust gas content, emission of nitric oxides, vessels propulsions, diesel engines, air humidification, Miller systems*

1. Introductions

Marine engine designers in recent years have had to address the challenge of tightening controls on noxious exhaust gas emissions imposed by national, regional and international authorities responding to concern over atmospheric pollution and its impact on human health and climate change.

The exhaust gases emissions for ship diesel engines are, inter alia, nitrogen, oxygen, carbon dioxide and water vapour, small amounts of carbon monoxide, sulphur and nitrogen oxides, hydrocarbons and particulates.

Typical content of the exhaust gases emitted by two-stroke low-speed ship diesel engines and the four-stroke ship diesel engines [4] are shown in Tab. 1.

2. Regulatory restrictions normative acts to control reduce toxic compounds gas emissions in maritime transport

Marine engine designers in recent years have had to address the challenge of tightening controls on noxious exhaust gas emissions imposed by national, regional and international authorities responding to concern over atmospheric pollution and its impact on human health and climate change.

Tab. 1. Typical exhaust emissions from a modern marine low-speed two stroke diesel engine and from a modern marine medium speed four stroke diesel engine, burning fuel with an average 3 per cent sulphur content (MAN Diesel)

Exhaust component		Exhaust gases emissions from a marine diesel engine	
		4 stroke	2 stroke
Nitrogen	N_2	75%	75.8%
Oxygen	O_2	12.3%	13-14%
Inert gases	Ar	0.9%	5.6%
Carbon dioxide	CO_2	5.6%	4.6-5.6%
Water (water vapour)	H_2O	6%	5.3-5.35%
Sulphur dioxide[1)]	SO_2	12 g /kWh	700-1200 ppm
Nitrogen oxides[2)]	NO_2	16 g /kWh	1100-1500 ppm
Carbon monoxide	CO	0.6 g /kWh	60-200 ppm
Hydrocarbons	HC	0.4 g /kWh	150-180 ppm
Soot[3)]		0.05 g /kWh	110-120 mg/Nm^3

[1)]*The value for the concentration of sulphur in the fuel 3%*
[2)]*The figure for the total NO_x emissions is marked as nitrogen dioxide NO_2*
[3)]*The figure for emissions of carbon black without taking into account other components of ash and solid particles.*

Legal instruments to control and reduce **toxic compounds gas** emissions of initiated at three levels:

- international (IMO – the International Maritime Organization),
- national (e.g. U.S. EPA – Environmental Protection Agency),
- regional (e.g., U.S. CARB – California Air Resources Bard).

Global approach to the control of toxic compounds emissions by the ships has been undertaken by the IMO through Annex VI to MARPOL 73/78 (Regulations for the Prevention of Air Pollution from Ships) [3], which was adopted at a diplomatic conference in 1997.

Ships, which are burned by gas oils and heavy fuels, account for approximately 7 percent of global emissions of NO_x, about 4 percent of global emissions of sulphur dioxide and 2 percent of global carbon dioxide emissions.

3. Control of NO_x emissions

Nitrogen oxides (NO_x) are formed from nitrogen and oxygen at high temperatures of combustion in the cylinder. NO_x emissions are considered as carcinogenic compounds, and they contribute to formation of photochemical smog and acid rain.

Global approach to the control of NO_x emissions has been undertaken by the IMO through Annex VI to MARPOL 73/78.

Annex VI applies to engines with power over 130 kW installed on new ships built after 1 January 2000 (the date the keel was laid) and pre-built engines that are subject to significant technical changes.

Starting NO_x emission level recommended by the IMO (dependent on the rotational speed of the engine crankshaft – n) is as follows:

- 17 g/kWh when diesel engine n is less than 130 rpm,
- $45 \cdot n^{-0.2}$ g/kWh when 2000>n >130,
- 9.84 g/kWh when n>2000 rpm.

Amendments agreed by the IMO in 2008 will set progressively tighter NO_x emission standards for new engines, depending on the date of their installation (see also Tab. 2):

- Tier I applies to diesel engines installed on ships constructed on or after 1 January 2000 and prior to 1 January 2011, and represents the 17 g/kWh NO_x emissions standard stipulated in the original Annex VI,

- Tier II, covering engines installed in a ship constructed on or after 1 January 2011, reduces the NO_x emission limit to 14.4 g/kW h,
- Tier III, covering engines installed in a ship constructed on or after 1 January 2016, reduces the NO_x emissions limit to 3.4 g/kWh when the ship is operating in a designated ECA. Outside such an area, Tier II limits will apply.

Tab. 2. The maximum content of NO_x by MARPOL Annex VI

Year	The maximum content of NO_x in the exhaust gas		
	$n < 130$	$130 \le n < 2000$	$n \ge 2000$
2000	17.0	$45 \cdot n^{-0.2}$	9.8
2011	14.4	$44 \cdot n^{-0.23}$	7.9
2016*	3.4	$9 \cdot n^{-0.2}$	1.96

**The maximum content of NO_x in areas of special control. In areas of common border with the values of 2011.*

Much tougher curbs on NO_x and other emissions are set by regional authorities such as California's Air Resources Board and Sweden has introduced a system of differentiated port, and fairway dues, making ships with higher NO_x emissions pay higher fees than more environment-friendly tonnage of a similar size.

To show compliance, an engine has to be certified according to the NO_x technical code and delivered with an Engine International Air Pollution Prevention (EIAPP) certificate of compliance. The certification process includes NO_x measurement for the engine type concerned, stamping of components that affect NO_x formation and a technical file, which is delivered with the engine.

NO_x technical code-certified engines have a technical file, which includes the applicable survey regime, termed the on-board NO_x verification procedure. The associated parameter check method effectively stipulates the engine components and range of settings to be adopted to ensure that NO_x emissions from he given engine, under reference conditions, will be maintained within the certified value. These NO_x emission critical components are broadly divided into three groups:

- the combustion chamber (including piston, cylinder cover and liner),
- the charge air system (turbocharger and charge air cooler),
- the fuel injection system (fuel pump, injection nozzle and timing cam).

The key settings are the maximum permitted combustion pressures across either the load range or the fuel injection timing.

4. The overall amount of global sulphur oxide emissions at sea and in port areas

Studies on sulphur pollution showed that in 1990 SO_x emissions from ships contributed around 4% to the total in Europe. In 2001, such emissions represented around 12% of the total and could rise to as high as 18%.

The simplest approach to reducing SO_x emissions is to burn bunkers with low sulphur content. A global heavy fuel oil sulphur content cap of 4.5% and a fuel sulphur limit of 1.5 per cent in certain designated sulphur emission control areas (SECAs) – such as the Baltic Sea, North Sea and English Channel – are currently mandated by the International Maritime Organization (IMO) to reduce SO_x pollution at sea and in port. In 2008, the IMO approved further amendments to curb SO_x emissions (see also Fig. 1):

- the fuel sulphur limit applicable in emission control area (ECA)s from 1 March 2010 would be 1% (10 000 ppm), reduced from the existing 1.5% content (15 000 ppm),
- the global fuel sulphur cap would be reduced to 3.5% (35 000 ppm), reduced from the existing 4.5% (45 000 ppm), effective from 1 January 2012,
- the fuel sulphur limit applicable in ECAs from 1 January 2015 would be 0.1% (1 000 ppm),
- the global fuel sulphur cap would be reduced to 0.5% (5000 ppm) effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018. Should the 2018 review reach a negative conclusion, the effective date would default to 1 January 2025.

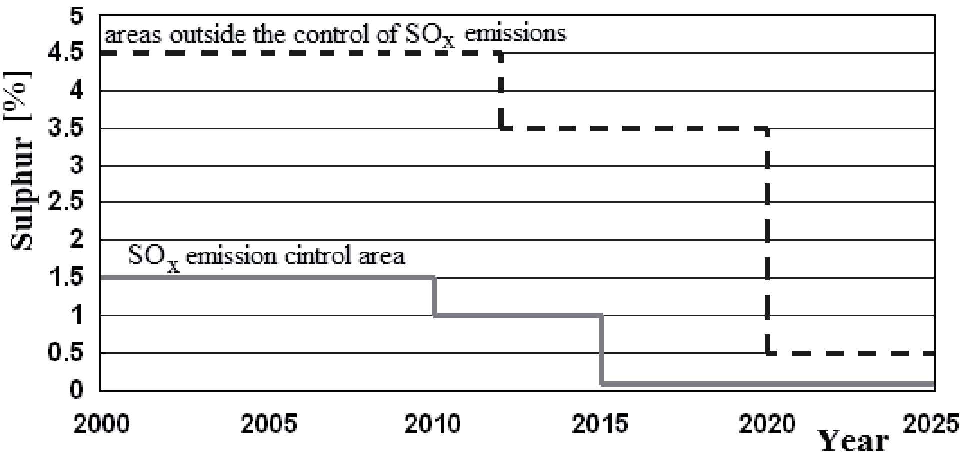

Fig. 1. The maximum sulphur content of marine fuel by the MARPOL Convention

5. Control of CO_2 emissions

6% of the exhaust gas emissions from marine diesel engine is carbon dioxide. Although it is not toxic itself, carbon dioxide contributes to the greenhouse effect (global warming and climate change) and hence to changes in the Earth's atmosphere. This gas is an inevitable product of combustion of all fossil fuels, but emissions from diesel engines—thanks to their thermal efficiency – are the lowest of the all heat engines. A lower fuel consumption translates to reduced carbon dioxide emissions since the amount produced is directly proportional to the volume of fuel used, and therefore to the engine or plant efficiency. As a rough guide, burning of 1 tonne of diesel fuel produces approximately 3 tonnes of carbon dioxide.

International concern over the atmospheric effect of carbon dioxide has stimulated measures and plans to curb the growth of such emissions, and the marine industry must be prepared for future legislation. There are currently no mandatory regulations on carbon dioxide emissions from shipping but they are expected to be. Under international agreements, such as the Kyoto Protocol and the European Union's accord on greenhouse gases, many governments are committed to substantial reductions in total emissions of carbon dioxide.

The Conference of Parties to the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto, held from 15 to 26 September 1997 in conjunction with the Marine Environment Protection Committee's fortieth session, adopted Conference resolution 8, on CO_2 emissions from ships. The Marine Environment Protection Committee, at its fifty-ninth session (13 to 17 July 2009), agreed to circulate the Guidelines for voluntary use of the Ship Energy Efficiency Operational Indicator (EEOI) as set out in the annex. This document constitutes the Guidelines for the use of an Energy Efficiency Operational Indicator (EEOI) for ships. It sets out:

- what the objectives of the IMO CO_2 emissions indicator are,
- how a ship's CO_2 performance should be measured,
- how the index could be used to promote low-emission shipping, in order to help limit the impact of shipping on global climate change.

6. The possibility of reducing NO_x emissions by changing the parameters of charging air

In this group of activities undertaken to reduce nitric oxides emissions applied cooling the air and changes in pressure at the beginning of compression stroke.

The process of cooling the scavenging air means decreasing the inlet air temperature and at the same time decreasing the maximum cylinder temperature. The easiest way is to decrease the air temperature by increasing the efficiency of the air cooler after the compressor. Tests have shown that lowering air temperature of 3 °C causes 1% decrease of NO_x emission. The physical border of cooling the air is defined by the temperature of cooling water, which in the tropics can be 32°C in the tropics. It is believed that the charge air temperature at full engine load should not be higher than 40°C.

Further decreasing of temperature with a conventional radiator is not possible and requires special solutions. On of the solutions is based on compressing and cooling air, and then expansion it which ensures further decrease of its temperature. However, this solution requires another compressor to by install after the air cooler. The disadvantage of such an idea is the additional cost of the system, the decrease of charge efficiency as well as increase of fuel consumption.

The problem can by solved by Miller supercharge system used by Sulzer in four-stroke engines ZA40S. The system concept is to use high-pressure compressor (high pressure – high density – the greater mass of air) in a supercharger system and changing the angle of the intake valve closing. In the system the required mass of charge air can be delivered in a shorter time than in standard system and the air inlet can be closed before the BDC – see Fig. 2. Thereby shortening the period of filling the cylinder. Further movement of the piston in the cylinder causes the expansion to the BDC has closed the air in the cylinder and thereby reducing its temperature. Performed on the engine Sulzer 9S20 studies have shown that this can achieve a reduction of NO_x in the range of 15 to 20% without increasing fuel consumption g_e. This system has been successfully used in ZA40S engines [1, 6].

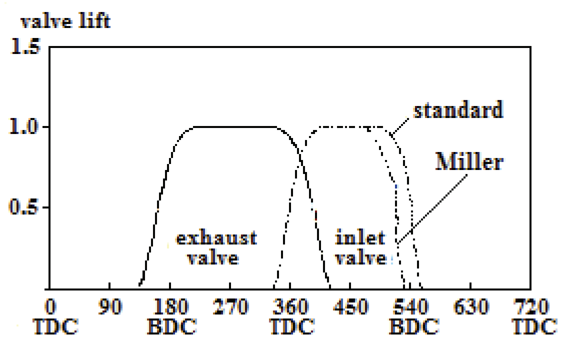

Fig. 2. Valve opening phase of the charge exchange in a four-stroke marine engine – standard and Miller systems: TDC – Top Dead Centre, BDC – Bottom Dead Centre

Another example of solutions aimed to reduce NO_x emissions is the feeding water into the combustion zone. The paper is limited consideration to charge air humidification only by injecting hot water into a stream of air pumped. When applied to ships engines are used in two systems:

- CASS (Combustion Air Saturation System),
- HAM (Humid Air Motor system).

In an embodiment of CASS (Marioff Oy Wärtsilä and Company) through special Hi-Fog, nozzles introduce water directly into the charge air stream after the turbocharger in the form of very small droplets.

Concern MAN attempted to effective reduction of NO_x by increasing the humidity of the air charge by water vapour. Implements this idea in a system of HAM (German company Munters Euroform), in which compressed hot air, by the compressor, is fed to the humidification tower, where is given water vapour obtained from seawater. Scheme of the system shown in Fig. 3. The prototype of such a system is equipped with four-stroke, medium speed marine diesel engine SEMT-Pielstick shown to approximately 25% reduction in NO_x. At the same time, the use of HAM has no significant influence on specific fuel consumption, no significant increase in carbon monoxide and hydrocarbon emissions and no smoke deterioration [5].

Exhaust gas recirculation (EGR) is a method of modifying the inlet air to reduce NO_x emissions at source, an approach widely and successfully used in automotive applications. Some of the exhaust gas is cooled and cleaned before recirculation to the scavenge airside. Its effect on NO_x formation is partly due to a reduction of the oxygen concentration in the combustion zone, and partly due to the content of water and carbon dioxide in the exhaust gas. The higher molar heat capacities of water and carbon dioxide lower the peak combustion temperature, which, in turn, curbs the formation of NO_x. EGR is a very efficient method of reducing NO_x emissions.

Marine diesel engines operating on high sulphur fuel might invite corrosion of turbochargers, intercoolers and scavenging pipes.

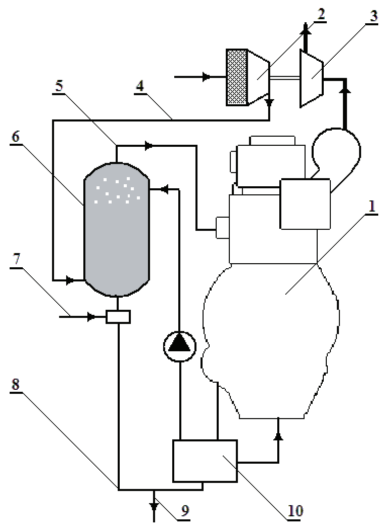

Fig. 3. Schematic diagram of HAM system – supply humid air into the engine to reduce NO_x emissions [5]: 1 – engine, 2 – compressor, 3 – turbine, 4 – hot compressed air, 5 – humidified and cooled air, 6 – humidified tower, 7 – water filing, 8 – water circuit, 9 – bleed off, 10 – heat exchanger

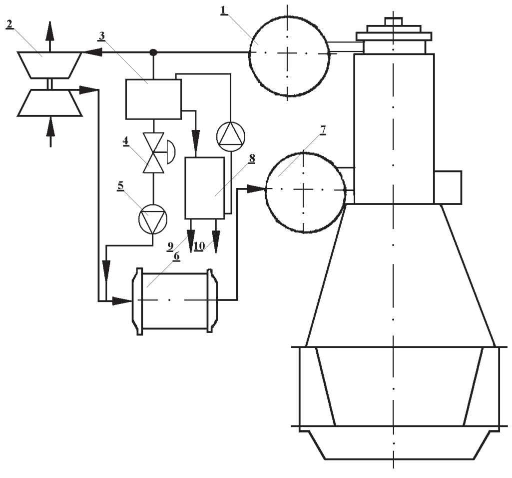

Fig. 4. Schematic diagram of EGR system tested by MAN Diesel on its 4T50ME-X low-speed research engine (developed on the basis of [7]): 1 – exhaust gas receiver; 2 – turbocharger; 3 – scrubber; 4 – EGR valve; 5 – EGR blower; 6 – scavenge air cooler; 7 – scavenging air box; 8 – water treatment system; 9 – sludge out; 10 – clean brine out

An EGR system pursued by MAN Diesel for its two-stroke engines is based on recirculating exhaust gas on the engine side of the turbocharger, part of the exhaust being recirculated from the exhaust gas receiver to the scavenge air system downstream of the turbocharger compressor (Fig. 4). NO_x emissions from MAN Diesel's 4T50ME-X two-stroke research engine at 75% load were reduced by up to 70% (compared with the economy engine layout) with 30% recirculation of exhaust gas.

Effect of charge air pressure on NO_x emission was researched (examined) in the laboratory and the results of this experiment are discussed in chapter 7.

7. Laboratory tests of influence air pressure charging on effects emissions of nitrogen oxides

The tests was conducted on a laboratory stand with a one-cylinder, two-stroke, crosshead engine of longitudinal scavenging, charged with the Roots blower. This test stand allows you to power with heavy fuel engine, which is a mixture of diesel oil and heavy fuel oil.

The laboratory test stand is equipped among others:

- torsiometer,
- electronic indicator with transducers to measuring for pressure in the cylinder and the injection pipe,
- Wimmer electronic analyser – measurement exhaust gas content.

7.1. Experimental procedures and its results

The test program was provided to determine the effect of supercharging air pressure on emissions of nitrogen oxides. The supercharging air pressure changed from 0.02 MPa to 0.1 MPa with 0.02 MPa pressure drop. The engine was working at constant rotational speed of 230 rpm and three selected loads: 50%, 60% and 70% of the nominal torque, and was supplied by heavy fuel oil IF40. The specified engine loads were applied by means of the water brake, and changing the super charging air pressure was effected by changing the rotational speed of the electric motor Roots blower.

Selected test results are shown in Fig. 5 and 6.

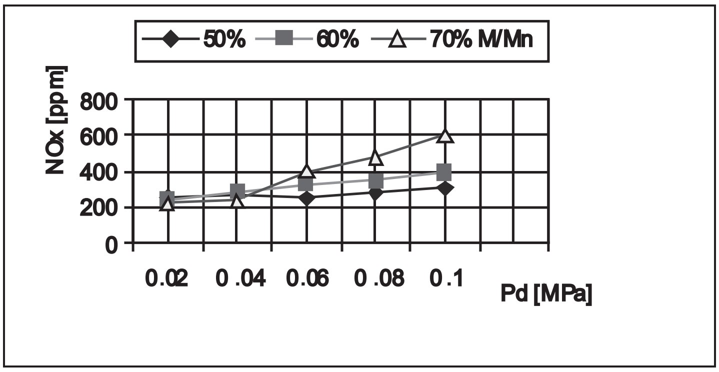

Fig. 5. NO_x content in exhaust gas in function of the supercharging air pressure and of engine load: p_d – supercharging air pressure, M/M_n – different engine load (engine torque/engine nominal torque), NO_x – oxides of nitrogen

It can be stated, there is a clear correlation between the charge super charging air pressure and exhaust gas content. Their influence on NO_x content is especially important in view of the IMO requirements.

Reducing the supercharging air pressure causes lowering NO_x content in exhaust gas, as shown by data presented in the graph in Fig. 5. The course of the formation of nitrogen oxides is mainly dependent on combustion temperature and the concentration of oxygen and nitrogen in the combustion chamber. Supercharge air pressure drop is likely to lead to a reduction of excess air number and thus the concentration of oxygen supplied to the cylinder. NO_x content, to adopt changes of supercharging pressure, for the engine load of 70% M_n decreases nearly tripled (from 601 ppm to 220 ppm). However, it should be noted that a large drop of NO_x content was obtained due to the large reduction of supercharging air pressure from 0.1 MPa to 0.02 MPa.

Reduce the supercharging pressure from 0.1 MPa to 0.02 MPa causes a slight increase in levels of CO in the exhaust gas with 50% and 60% M_n and a very large (about tenfold) for the engine load of 70% M_n (see Fig. 6). Amount of carbon monoxide emitted by diesel engine depends, inter alia, the general and local excess air in the combustion chamber, as well as its pressure and temperature cycle and the oxidation of hydrocarbons. Therefore was to be expected as a result of the supercharging air pressure drop, increased levels of CO in the exhaust gases.

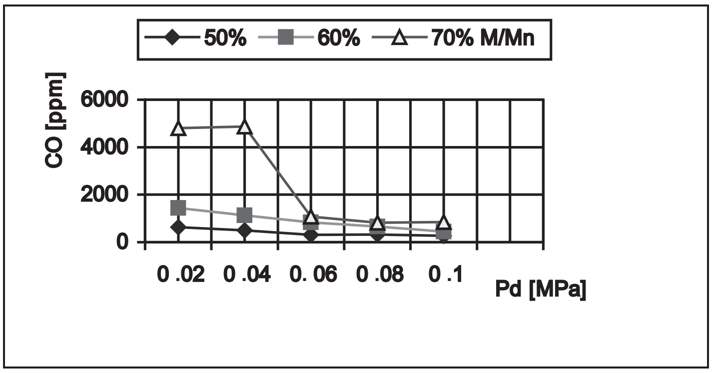

Fig. 6. CO content in exhaust gas in function of the supercharging air pressure and of engine load: p_d – supercharging air pressure, M/M_n – different engine load (engine torque/engine nominal torque), CO – carbon monoxide

8. Summary

1. Therefore was to be expected as a result of the supercharging air pressure drop, increased levels of CO in the exhaust gases.
2. However, please note that recognition of the drop in the supercharging pressure as an effective method of reducing NO_x emissions, to generate an increase of the other components in the exhaust gases in particular carbon monoxide (CO).
3. The presented results can be taken into account by the owners of ships. Although the tests were conducted in laboratory conditions, but the engine was running a heavy fuel oil IF40.

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