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On possible lowering of the toxicity of exhaust gas from ship diesel engines by changing their control parameters

SUMMARY

The paper is devoted to problems connected with pollution of the atmosphere by ship engines. Results of the tests are presented on the influence of charging air pressure and injection advance angle on content of exhaust gas from a high-pressure diesel engine working on heavy fuel oil, carried out at the laboratory of Gdynia Maritime Academy.

INTRODUCTION

Nowadays the ship engine is to meet more and more stringent requirements for limitation of emission of toxic combustion products to the atmosphere in view of marine environment protection.

Typical content of the exhaust gas emitted by ship diesel engines is shown in Fig.1.

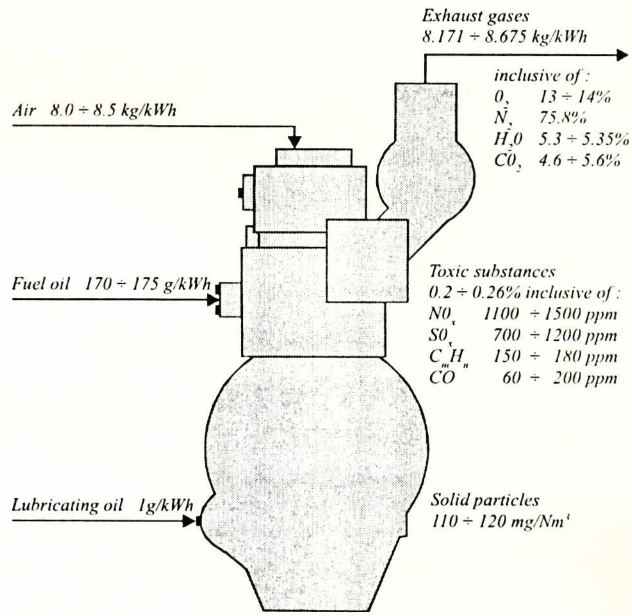

Fig.1. Balance of substrates and combustion products of the typical ship diesel engine

In 1990 the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) proposed to lower the then emission level of NO_x by 70% and SO_x by 50% till 2000 although the share of the engines in the worldwide toxic product emission was only 7% in the case of nitric oxides (NO_x) and 4 to 5 % of sulphur oxides (SO_x). Legal instruments in this area are initiated at three levels :

* international (IMO)
* national (e.g. Environmental Protection Agency - EPA, USA)
* regional (e.g. California Air Resources Board - CARB, USA).

Proposals on limitation of exhaust gas toxic elements have been elaborated at each legislation level. The permissible NO_x emission level according to IMO provisions is shown in Fig.2 and that of the EPA in Fig.3.

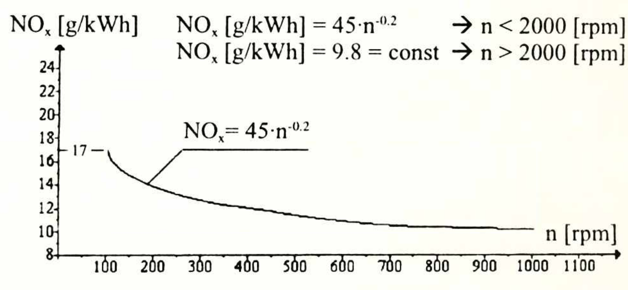

Fig.2. The permissible NO_x emission level in function of the engine rotational speed n according to IMO

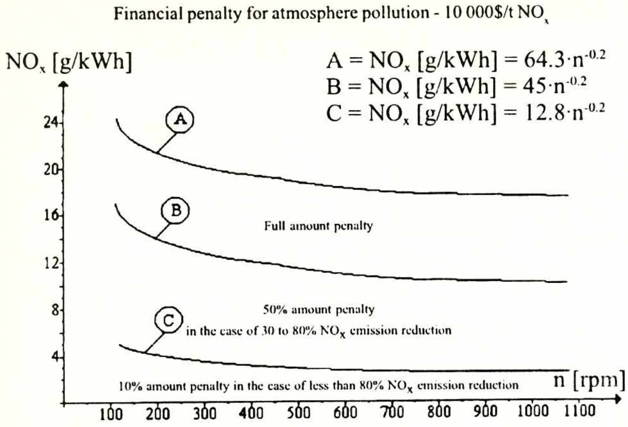

Fig.3. The permissible NO_x emission level in function of the engine rotational speed n according to EPA

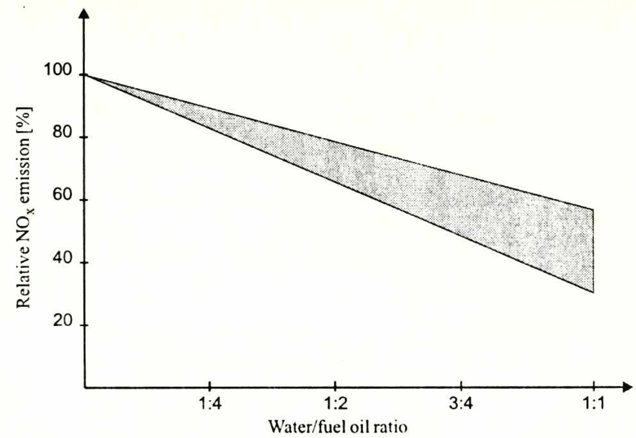

Fig.4. Effectiveness of application of water/fuel oil emulsion for lowering NO_x content [5]

The increasing requirements for purity of the exhaust gas emitted from ship diesel engines and following legislative activities induce the shipowners to observe them because additional operation cost may appear due to financial penalties for pollution of the atmosphere from ships. Therefore the producers of ship diesel engines carry out investigations on adaptation of the today manufactured engines to fulfil the exhaust gas purity standards. A great number of the diesel engines still in service do not fulfil the standards. It is necessary to search for simple and inexpensive methods applicable to existing ships with a view to effective lowering of the toxic content of exhaust gas from their engines.

As far as the methods of NO_x content lowering are concerned, new technical solutions applicable to ship power plants are required. A dozen or so methods of lowering NO_x content are elaborated. They can be divided into two main groups :

- basic methods enabling to limit NO_x production during combustion process
- additional methods enabling to reduce NO_x content in exhaust gases by their purification behind the diesel engine.

The basic methods are based on change of combustion process organization and chemical content of the media supplied to the engine cylinders. NO_x amount generated during combustion process in the diesel engines depends on many parameters. However the most decisive are :

- the combustion temperature and
  oxygen and nitrogen partial pressures as well as
- combustion time period.

Today therefore the dominating role will play the methods based on lowering the maximum combustion temperature. Those are the following :

⇒ supplying the engine with water/fuel oil emulsion
⇒ direct injection of water to the cylinder
⇒ fuel injection delay
⇒ stepwise fuel injection
⇒ application of special injector tips to optimize combustion process with respect to NO_x content in exhaust gases
⇒ moisturing the charging air
⇒ exhaust gas re-circulation
⇒ change of compression ratio
⇒ lowering the charging air pressure.

Supplying the engine with water/fuel oil emulsion is an easy and effective method applicable to ship power plants without any excessive investment cost. All recognized ship engine producers carry out investigations in this area. It was revealed that one percent of water in fuel oil causes lowering NO_x content in exhaust gases by about one percent too. The possible relative reduction of NO_x content is plotted against water/fuel oil ratio in Fig.4 [5].

The obtainable NO_x content reduction by supplying the emulsion of 20÷30% water content and using the typical engine injection system is about 30%. To this point injection pumps still work correctly. At higher water/fuel oil ratios direct emulsion forming within the engine combustion chamber is usually applied.

Already in the 1980s MAN-B&W carried out extensive investigations on possible application of water/fuel oil emulsion for supplying the engines in order to lower NO_x emission. In 1984 7L90 GSCA diesel engine of 20 000 kW installed in a land-based electric power plant, Puerto Rico, underwent such tests under supervision and assessement of the EPA which clearly confirmed effectiveness of the method [4]. Results of further investigations performed in this area by MAN-B&W as well as by other diesel engine producers (SULZER, WARTSILA, MaK) also supported the conclusion. In the meantime WARTSILA and MaK made definite progress in designing and applying a special injection system for simultaneous supplying the engine with water and fuel oil to form emulsion directly within the combustion chamber [3].

The direct water injection method if combined with such methods as :

- increase of compression ratio
- application of changeable timing angle system
- exhaust gas re-circulation

is able to reduce NO_x content by even more than 50%.

As far as the additional methods are concerned the engine producers engaged high financial resources into developing catalytic converters of their own design. The selective catalytic reduction method (SCR) is widely used in the land-based power plants, but the catalyzers applied there are not applicable to ship power plants due to a.o. their large size and flow resistance. MAN-B&W and SULZER developed and tested on full scale engines catalytic installations of very compact designs. WARTSILA tests its original SCR installation on a passenger-cargo ferry ship. A single compact casing of the design contains simultaneously two devices : catalyzer and silencer [2].

LABORATORY TESTS

Laboratory investigations on a special test stand were initiated by the Ship Power Plant Department, Gdynia Maritime Academy, to better identify phenomena and processes appearing during combustion of heavy fuel oils in view of prevention of atmosphere pollution.

Test object

An one-cylinder, two-stroke, crosshead engine of longitudinal scavenging, charged with the use of Roots blower was the test object.

The test stand was equipped with the fuel oil supply installation which made it possible to supply the engine with diesel oil, heavy oil or their mixture. A special oil heating system was provided to heat heavy fuel oil up to 150°C.

The stand consisted of the engine and water brake. The laboratory service installations, similar to those applied to ship power plants but also adjusted to land conditions, ensured the engine-brake system to work correctly.

The installed measurement instruments made it possible :

- *to measure :*
  - torque – by using the brake directly or the torsiometer installed on the engine-brake shaft
  - rotational speed – by using an electronic system (marker, transducer)
- *to test :*
  - combustion and fuel injection processes - by using special transducers and computerized recording system
  - exhaust gas content - by using Wimmer electronic analyzer.

An additional device was installed on the engine for stepless changing the injection advance angle α_{ww}. A test stand block diagram is shown in Fig.5.

The stand was used to investigate influence of selected control parameters of the engine on exhaust gas purity.

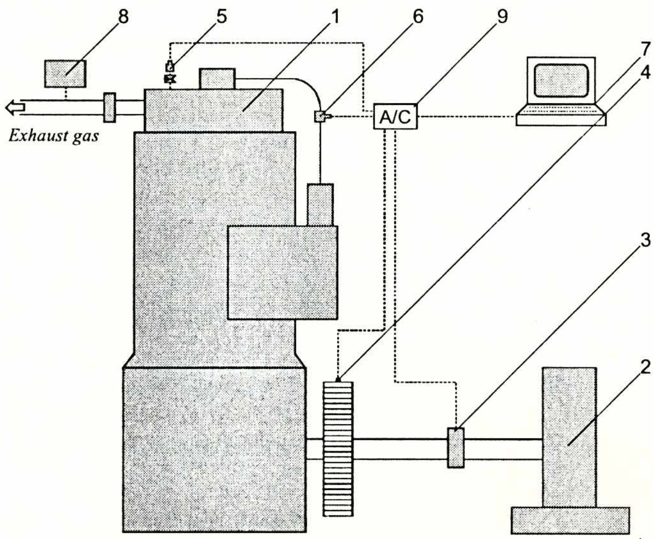

***Fig.5.** Test stand block diagram*
1 – L-22 diesel engine, 2 – water brake, 3 – torsiometer, 4- gauge for crankshaft position marking and rotational speed measuring, 5 – combustion pressure transducer, 6 – injection pressure transducer, 7 – computer, 8 – exhaust gas analyzer, 9 – analog/digital converter

Scope of tests

The aim of the tests was to establish influence of the following factors on exhaust gas content :

- the super charging air pressure at IF30 heavy fuel oil supply and different engine load levels : 50, 60 and 70% M_n ; at each load level the super charging air pressure was changed from 0.02 to 0.1 MPa
- the fuel injection advance angle at IF40 heavy fuel oil supply and different load levels : 25, 40, 50, 60, 70 and 80 % M_n and at the nominal value of α_{ww} = -13° of crankshaft rotation , as well as at α_{ww} = -10° and -7°.

Description of the tests and their results

The specified engine loads were applied by means of the water brake. Changing the super charging air pressure was effected by changing the rotational speed of the Roots blower. Changing the injection advance angle was possible due to a special mechanism co-operating with the roller of the injection pump push rod. In effect it was possible to obtain the fuel injection delay of about 3° and 6° in respect of its nominal value.

Results of the tests are presented in Tab.1 and 2 and in Fig.6 to 9.

***Tab.1.** The exhaust gas content analyzed at different engine load and super charging air pressure values. IF30 heavy oil supply*

Engine load level	Super charging air pressure	Results of exhaust gas analysis					
M/M_n	p_d	O_2	CO	SO_2	NO_x	NO_x	CO_2
%	MPa	%	ppm	ppm	ppm	mg/m³	%
50	0.02	15.6	638	3	259	355	3.9
	0.04	16.6	498	1	270	370	3.2
	0.06	17.8	307	0	248	340	2.3
	0.08	17.9	322	0	279	383	2.2
	0.10	17.9	272	0	306	420	2.2
60	0.02	15.3	1446	48	241	331	4.1
	0.04	16.3	1136	76	284	390	3.4
	0.06	16.3	836	104	330	453	3.4
	0.08	16.8	660	93	348	478	3.0
	0.10	16.7	450	87	394	541	3.1
70	0.02	14.2	4807	291	220	302	4.9
	0.04	13.7	4873	370	233	320	5.3
	0.06	14.7	1081	249	400	549	4.6
	0.08	15.2	825	216	477	655	4.2
	0.10	14.8	845	206	601	825	4.5

***Tab.2.** The exhaust gas content analyzed at different engine load and injection advance angle values. IF40 heavy oil supply*

Injection advance angle	Engine load level	Results of exhaust gas analysis					
α_{ww}	M/M_n	O_2	CO	SO_2	NO_x	NO_x	CO_2
[°]	%	%	Ppm	ppm	ppm	mg/m³	%
-13	25	18.5	263	0	210	288	1.8
	40	18.4	223	17	246	338	1.8
	50	18.1	249	47	298	409	2.1
	60	17.5	281	84	354	486	2.5
	70	15.8	611	155	450	618	3.8
	80	13.1	4126	330	542	744	5.7
-10	25	18.9	290	96	190	261	1.5
	40	18.7	263	105	217	298	1.6
	50	18.3	277	127	262	359	1.9
	60	17.9	300	166	318	436	2.2
	70	16.3	590	258	415	570	3.4
	80	13.6	3015	444	498	684	5.4
-7	25	19.0	212	73	150	206	1.4
	40	18.8	247	86	169	232	1.5
	50	18.3	293	118	218	299	1.9
	60	17.8	340	165	266	365	2.4
	70	15.4	1020	287	378	519	4.1
	80	13.6	3045	416	440	604	5.4

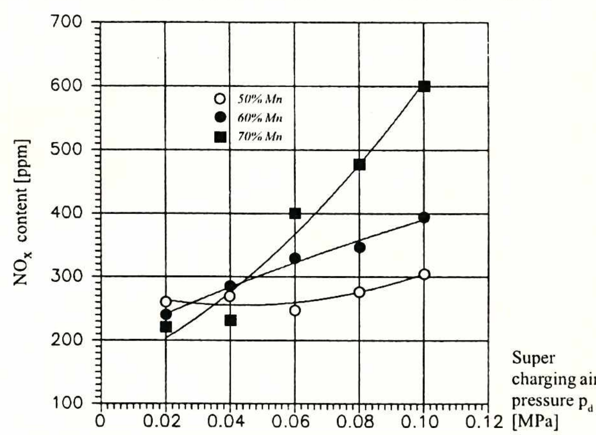

***Fig.6.** NO_x content in the exhaust gas plotted against super charging air pressure at three different engine load levels*

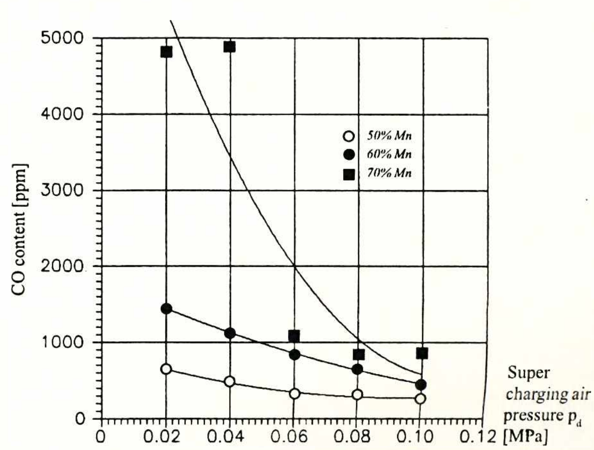

***Fig.7.** CO content in the exhaust gas plotted against super charging air pressure at three different engine load levels*

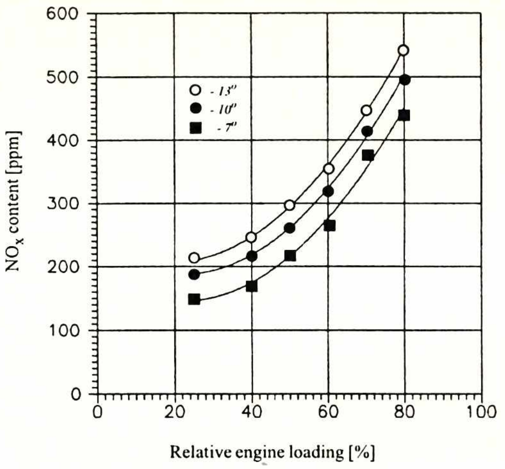

Fig.8. NO_x content in the exhaust gas plotted against relative engine loading at three different values of injection advance angle

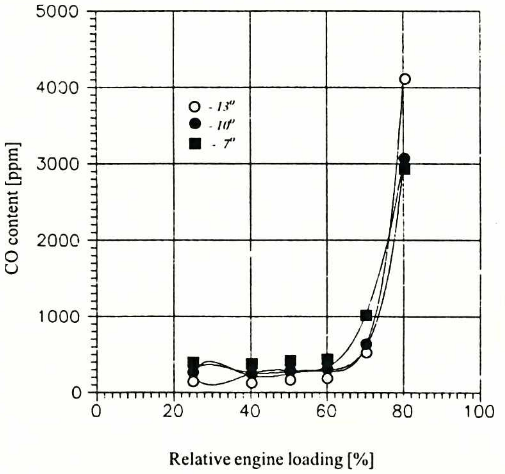

Fig.9. CO content in the exhaust gas plotted against relative engine loading at three different values of injection advance angle

ANALYSIS OF TEST RESULTS, CONCLUSIONS

- It can be stated from the tests that changing both selected parameters, i.e. the super charging air pressure and injection advance angle, affects the exhaust gas content. Their influence on NO_x content is especially important in view of the IMO requirements.
- Reducing the super charging air pressure causes lowering NO_x content in exhaust gas as it can be observed from Tab.1 and Fig.6. The NO_x content drops by about 20% on the average at loadings of 50 and 60% M_n, and even about 65% at 70% M_n. However the large drop of NO_x content was obtained due to the large reduction of super charging air pressure: from 0.1 MPa to 0.02 MPa.
- Delaying the fuel injection by 6° in respect to its nominal value causes distinct dropping of NO_x content at each assumed load level as it can be observed from Tab.2 and Fig.8. It amounts to about 30% at 25 and 40% M_n and is a little lower at remaining load levels (about 20% on average). The obtained reduction of NO_x content can be deemed satisfactory and the method very effective. However simultaneous worsening of the power and economy indices of the engine should be taken into account. It was revealed, when performing electronic indication tests of the engine, that the maximum combustion pressure and mean indicated pressure dropped along with the fuel injection delay, within the entire assumed range of engine loading.
- The super charging air pressure reduction from 0.1 MPa to 0.02 MPa causes a small increase of CO content in exhaust gas at load levels of 50 and 60% M_n, and very large one (about tenfold higher) at 70% M_n (see Tab.1 and Fig.7).
- The fuel injection delay does not influence very much the CO content in exhaust gas. The CO content increases by a large amount at 80% M_n only, at all assumed values of the injection advance angle α_{ww}. This resulted rather from a super charging air deficiency than the influence of fuel injection delay.

GENERAL REMARKS

The following general remarks and recommendations are offered to ship operators :

- The above presented results of the laboratory tests could be directly taken into account by the shipowners as the tests were conducted with the use of IF30 and IF40 heavy fuel oils.
- The engine control methods used during the tests in question seem appropriate, as such actions are feasible in ship service, especially as far as the earlier built engines are concerned which would not be able to comply with the IMO standards without introducing changes to their construction.
- Application of the fuel injection delay method to lower exhaust gas toxicity introduces limitations to engine performance, especially to the indicated power. Hence the method should be considered as a substitute remedy, of a limited applicability. However it could be very useful for the ships operating in the waters to which more stringent requirements apply (e.g. the California Bay, Baltic Sea, ports and port roads in general).

Appraised by Jan Kazimierz Włodarski, Prof.,D.Sc.,M.E.

NOMENCLATURE

M	-	torque
M_n	-	nominal torque
p_d	-	super charging air pressure
α_{ww}	-	fuel injection advance angle

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