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On effectiveness of lowering the toxicity of exhaust gas from a ship diesel engine by simultaneous changing its two control parameters

SUMMARY

The paper continues description of the problems already presented in Polish Maritime Research [1], connected with pollution of the atmosphere by ship engines. In this paper results are described and discussed of further research on the influence of selected control parameters of a high-pressure diesel engine working on heavy fuel oil on its exhaust gas content, carried out at the laboratory of Gdynia Maritime Academy.

INTRODUCTION

Investigations of ship diesel engines with a view to lowering the content of toxic elements in the exhaust gas is a challenging task for scientists, designers, manufacturers and users of diesel engines. Results of such research also contribute to deeper understanding the working process of diesel engine, which helps in searching the effective methods to limit the exhaust gas toxicity.

The challenge has been faced first of all by leading ship diesel engine producers such as : MAN-B&W, Sulzer, MaK and Wärtsilä.

Due to the legislative actions initiated in this area [1] research efforts were first focussed on reduction of NOx emission.

Ship diesel engine producers and environment protection organizations accepted the IMO proposals presented in the form of the permissible NOx emission curve versus the rotational speed of the engine, n, (see e.g. Fig.1 of [1]). From the proposals it results that :

- **for low-speed engines of n < 130 rpm**
  the permissible NOx emission is 17 g/kWh
- **for engines of 130 < n < 2000 rpm**
  the emission is limited by the following relationship :
  $limit\ NOx = 45\ n^{-0.2}\ g/kWh$
- **for high-speed engines of n > 2000 rpm**
  the permissible NOx emission is equal to 9.8 g/kWh.

The NOx emission is to be determined at different engine loads in compliance with the provisions of ISO 8178 standard [2]. However for a given diesel engine it should be determined by measuring e.g. during manufacturer stand tests of the engine, because usually the emission values predicted by calculations do not agree with those measured. One of the reasons may be a dependence of the NOx emission on fuel oil consumption. So far 5% tolerance is deemed acceptable in determining the fuel oil consumption by the engine.

When the IMO regulations come into force this tolerance should be lower, probably of 3% only, to avoid excessive discrepancies of NOx emission levels.

The methods of possible lowering the exhaust gas toxicity, especially NOx content, were already described in detail in [1].

In the previous investigations [1] the influence of the supercharging air pressure p_d and fuel injection advance angle α_{ww} on the exhaust gas content was tested separately. In this paper results are presented of investigations on a „combined" influence of both, earlier separately changed parameters as it has been expected to be a more effective approach.

LABORATORY TESTS

Test object and stand

The one-cylinder, two-stroke, crosshead engine of longitudinal scavenging was the test object, the same as used at the previous stage of investigations and described in [1].

Similarly in these investigations the same test stand as already described in [1], consisting of the engine and water brake, was applied and equipped with the same measurement and control instruments.

Scope of tests

The aim of the tests was to establish a „combined" influence of two following factors on the exhaust gas content :

- the supercharging air pressure changed from 0.02 MPa to 0.1 MPa with 0.02 MPa pressure step

- the fuel injection advance angle changed with 3^0 step from the nominal value of -13^0 up to -7^0 of crankshaft rotation.

The engine operated at the constant, abt. 55% nominal load level and IF 40 heavy oil supply.

Description of the tests and their results

The specified load was applied by means of the water brake. As previously, changing the supercharging air pressure was effected by changing the rotational speed of the Roots blower, and changing the injection advance angle by 3^0 and 6^0 of crankshaft rotation with respect to its nominal value was effected by means of a special mechanism co-operating with the roller of the injection pump push rod. Results of the tests are presented in Tab.1 and 2 and Fig.1÷4.

Analysis of results

From the performed tests it unambiguously results that the simultaneous decreasing the supercharging air pressure and increasing the fuel injection advance angle causes NOx content in the exhaust gas to drop. In comparison with the previous investigation results when seperate influence either of the supercharging air pressure or the fuel injection advance angle was tested, a greater reduction of NOx content in the exhaust gas has now been obtained by combining the effect of both parameters.

Previously at 60% nominal load of the engine, the decrease of supercharging air pressure from its nominal value of 0.1 MPa to 0.02 MPa resulted in 32% reduction of NOx content; and the increase of the fuel injection advance angle by 6^0 i.e. from -13^0 to -7^0 of crankshaft rotation, caused NOx reduction in the exhaust gas by 25%.

At present at approximately the same engine load level, as high as 41% reduction of NOx content in the exhaust gas was obtained by simultaneous changing both the pressure p_d (within the same 0.02 ÷ 0.10 MPa range) and fuel injection advance angle α_{ww} (by the same 6^0 i.e. from -13^0 to -7^0).

***Tab.1.** Values of injection and combustion parameters (measured by using electronic indicator) and torque, power and rotational speed of the engine (by torque meter)*

Measurement number	Supercharging air pressure p_d	Fuel injection advance angle α_{ww}	Max combustion pressure P_{max}	p_{max} location with respect to UDC $(\alpha_p)_{max}$	Mean indicated pressure p_i	Decompression pressure p_{36}	Max. fuel injection pressure $(p_{wtr})_{max}$	Engine rotation speed n	Engine relative moment M/M_{nom}	Engine relative power N/N_{nom}
	[MPa]	[^{0}] of crank-shaft rot.	[MPa]	[^{0}] of crank-shaft rot.	[MPa]	[MPa]	[MPa]	[rpm]	[%]	[%]
1.	0.02	-13^0	4.5	13	0.85	3.4	30.8	299.1	69.9	54.6
2.	0.04		4.6	17	0.82	3.3	29.9	299.5	74.0	55.3
3.	0.06		4.8	11	0.87	3.4	29.9	299.9	74.1	55.5
4.	0.08		4.8	11	0.90	3.4	32.2	299.7	74.0	55.3
5.	0.10		4.9	11	0.90	3.5	31.0	299.5	73.8	55.5
6.	0.02	-10^0	4.2	16	0.85	3.3	32.4	298.8	73.9	55.3
7.	0.04		4.4	14	0.91	3.5	32.5	298.1	73.1	54.5
8.	0.06		4.6	14	0.89	3.5	33.7	299.1	74.1	55.4
9.	0.08		4.6	14	0.88	3.6	33.3	299.0	73.3	54.7
10.	0.10		5.0	14	0.87	3.5	31.2	298.8	73.5	55.0
11.	0.02	-7^0	4.2	19	0.84	3.2	33.7	298.9	73.6	55.1
12.	0.04		4.6	19	0.87	3.4	33.4	299.2	74.0	55.4
13.	0.06		4.5	20	0.92	3.5	32.7	299.2	73.6	55.1
14.	0.08		4.6	20	0.89	3.6	34.7	293.3	73.3	54.8
15.	0.10		4.7	20	0.91	3.6	34.3	298.6	73.5	55.0

***Tab.2.** Analysis results of exhaust gas content*

Measurement number	Supercharging air pressure p_d	Fuel injection advance angle α_{ww}	O_2	CO	SO_2	NO_X		CO_2	Combustion effectiveness η	Air surplus factor λ
	[MPa]	[^{0}] of crank-shaft rot.	[%]	[ppm]	[ppm]	[ppm]	[mg/m^3]	[%]	[%]	[-]
1.	0.02	-13^0	17.1	364	52	316	434	2.8	60.1	5.5
2.	0.04		17.3	261	85	372	511	2.7	60.5	5.7
3.	0.06		17.4	260	89	396	544	2.6	59.1	5.92
4.	0.08		17.4	256	100	420	577	2.6	59.9	5.92
5.	0.10		16.9	269	112	462	634	2.9	63.7	5.31
6.	0.02	-10^0	17.0	403	171	318	436	2.9	60.2	5.31
7.	0.04		17.4	318	164	336	461	2.6	58.8	5.92
8.	0.06		17.3	325	155	353	485	2.7	59.8	5.7
9.	0.08		17.2	271	163	393	539	2.7	60.4	5.7
10.	0.10		17.1	260	171	432	593	2.8	62.3	5.5
11.	0.02	-7^0	17.1	467	212	273	375	2.8	58.6	5.5
12.	0.04		17.2	399	202	297	408	2.7	58.0	5.7
13.	0.06		17.2	341	211	320	439	2.7	58.6	5.7
14.	0.08		17.0	324	211	335	460	2.9	61.1	5.31
15.	0.10		16.6	298	213	373	512	3.2	65.1	4.81

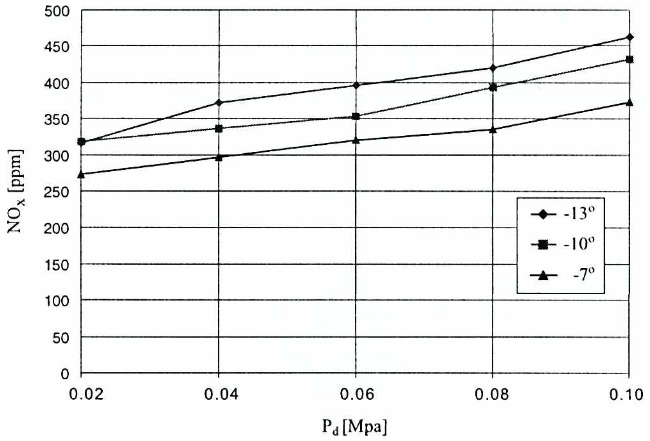

Fig.1. Change of NO_X content in the exhaust gas due to simultaneous change of the supercharging air pressure p_d (within 0.02 ÷ 0.10 MPa range) and fuel injection advance angle α_{ww} (set values : -13⁰, -10⁰, -7⁰)

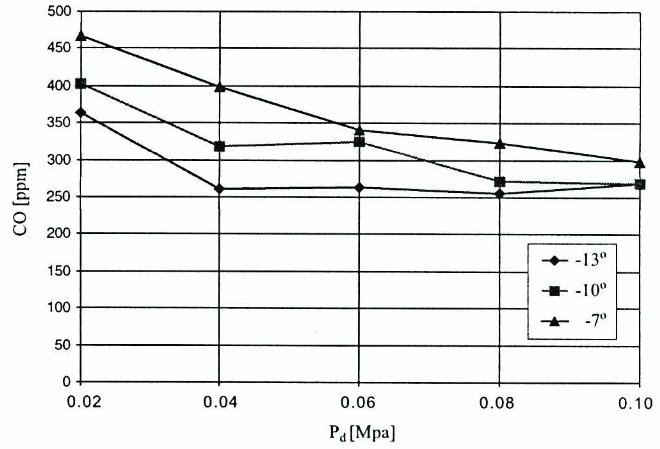

Fig.3. Change of CO content in the exhaust gas due to simultaneous change of the supercharging air pressure p_d (within 0.02 ÷ 0.10 MPa range) and fuel injection advance angle α_{ww} (set values : -13⁰, -10⁰, -7⁰)

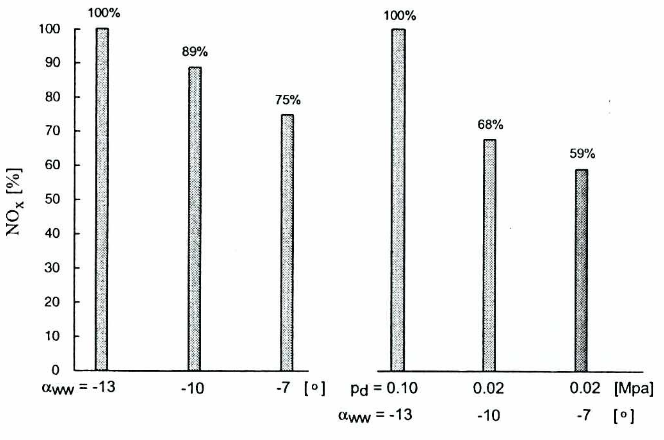

Fig.2. Comparison of NO_X reduction effectiveness obtained by changing the fuel injection advance angle α_{ww} (set values : -13⁰, -10⁰, -7⁰) only, and combined effect of simultaneous changing of the supercharging air pressure p_d and injection advance angle α_{ww}

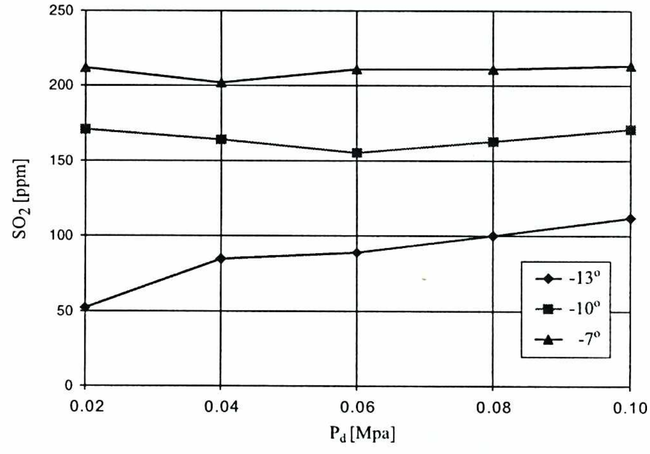

Fig.4. Change of SO_2 content in the exhaust gas due to simultaneous change of the supercharging air pressure p_d (within 0.02 ÷ 0.10 MPa range) and fuel injection advance angle α_{ww} (set values : -13⁰, -10⁰, -7⁰)

However a still important, but lower effectiveness of NOx reduction is achieved in the case if the values of combined changes of both parameters in question are smaller, which is shown in Tab.3.

Tab.3. NO_X reduction effectiveness by combined changes of both parameters in question but of lower values

Fuel injection advance angle α_{ww}	Supercharging air pressure p_d	NOx content reduction relative of its reference value
[⁰] of crankshaft rot.	[MPa]	[%]
-10	0.08	15
-7	0.08	27.5
-10	0.06	23.5
-7	0.06	31
-10	0.04	27
-7	0.04	36.6
-10	0.02	31
-7	0.02	41

Moreover it should be mentioned that the rather important changes of both p_d and α_{ww} resulted in worsening the course of engine working process. From an analysis of indicator diagrams it results that the drop of p_d from 0.1 MPa to 0.02 MPa and delay of fuel injection by 6⁰ of crankshaft rotation caused the maximum combustion pressure p_{max} to drop by 0.7 MPa , i.e. by about 15%, and to shift it with respect to UDC [Upper Dead Centre] by 8⁰ of crankshaft rotation towards the decompression curve. The mean indicated pressure value dropped by 0.06 MPa, i.e. about 7%.

It means that the very effective reduction of NOx content due to the combined effect of changing both parameters in question in the same time causes lowering of the mean indicated pressure hence the indicated power of the engine.

From the performed investigations it also results that the method in question leads, apart from causing the important NOx reduction, to 80% increase of SO_2 content and 70% increase of CO content in the exhaust gas.

As the present IMO regulation concerns only the allowable NOx emission from the ship engines, the presented method could be applied to ships in service in spite of its leading to increasing CO and SO_2 content in the exhaust gas. Its advantage is that appropriate adjustments of the supercharging air pressure and fuel injection angle can be performed solely with ship's crew hands.

GENERAL CONCLUSIONS

On the basis of the previous research [1] it was concluded that :

- Fuel injection delay leads to a substantial reduction of NOx content in the exhaust gas from a ship diesel engine working on heavy fuel oil.
- Decrease of the supercharging air pressure also makes it possible to notably reduce NOx content in the exhaust gas from the engine.

The present investigations lead to the following conclusions :

- The simultaneous application of the fuel injection delay and decrease of the supercharging air pressure makes it possible to reduce NOx content even more effectively than in the case of changing any of these parameters separately.
- The combined control method can be deemed suitable, as such actions are feasible in ship service conditions, especially for the earlier built engines which would not be able to satisfy the IMO standards without introducing constructional changes to the engines.
- However application of the method in question is connected with engine's performance limitations, especially of the indicated power, and leads to some increase of the fuel oil consumption.
- Therefore the present method should be also considered as a substitute remedy only, of a limited applicability. However it could be useful for the ships operating in the waters to which more stringent regulations apply (e.g the California Bay, Baltic Sea, port areas and roads).
- Application of the combined method itself would not necessarily be connected with a financial expense, nonetheless after its application operational cost of the engine will grow due to an expected increase of the fuel oil consumption.

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

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Conference

Safety and Reliability
KONBiN '99

The First National Conference on Safety and Reliability gathering scientists and experts dealing with these problems, held on 22 to 25 November in Zakopane, was a great success in to joining together two scientific research circles acting till then seperately.

It became a broad discussion forum devoted to both theoretical and practical aspects of safety, reliability, serviceability and maintainability of man-technology-environment systems.

The conference was attended by 180 participants who had the occasion to hear and discuss 140 papers of very diversified topics. The papers were prepared by authors from 33 Polish universities and research centres and 8 foreign ones (from France, Great Britain, Netherlands, Portugal, Russia, Romania, Slovakia and Ukraine). These numbers show the extent of interest paid to the conference.

Most papers dealt with air and land transport technology, however Polish maritime universities and research centres also strongly manifested their participation in the conference a.o. by presenting altogether 34 papers : 14 of Gdynia Maritime Academy, 8 of Technical University of Gdańsk and 7 of Maritime University of Szczecin.

Within the scope of the conference the „Workshop on reliability models" took also place with Prof. Roger Cooke of Delft University, Netherlands, as its moderator.

The complete conference proceedings were edited in 3 volumes comprising 1187 pages.

Current reports

Gdynia Maritime Academy
Mechanical Faculty

Performance optimization of the sailing ship fitted with an auxiliary diesel engine propulsion system

Contemporary sailing ships are usually fitted with an auxiliary diesel engine propulsion system. In some sea and weather conditions it is reasonable to use both kinds of propulsion, and then the problem of optimum arrangement of their cooperation arises. Which sails are to be set, which ship course is to be chosen as well as what values of the propulsion engine parameters are to be selected to obtain a possible low fuel consumption – –answering all these questions is important in order to optimize the ship propulsion performance.

The problem was studied by Krzysztof Rudzki, M.Sc., of the Department of Basic Engineering Problems, who carried out a research on the theme on board the sailing ship POGORIA.

During her voyages in various waters and environmental conditions, at various sail settings and propulsion engine loadings the following parameters were recorded :

- twisting moment in the propulsion shaft
- fuel oil consumption
- ship speed relative to sea bed and water
- wind velocity and direction
- sea state (wave height, length and direction)
- sea current velocity and direction
- sail setting
- ship heading.

The obtained measurement results were used to elaborate, by applying a dynamic programming method and neural network technique, a multicriterial optimization model for selecting the ship heading and values of cooperation parameters of both propulsion systems of the ship.

The work in question is aimed at elaborating a computer-based system to aid decision-making on the selection of an appropriate ship course, sail setting, CP propeller setting and engine fuel supply system parameters at given sea and weather conditions.