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The concept of research on ecological, energy and reliability effects of modified marine fuel oils application to supply compression-ignition engines in real conditions

Within the article, basic assumptions of the research project financed by Regional Fund for Environmental Protection and Water in Gdansk were described. The project concerns the experimental investigations carried out on laboratory compression-ignition engine in conditions of its supply with a non-standard marine fuel oil. Configuration and measuring capability of laboratory test bed presently being constructed were introduced. The concept of engine tests implementation as well as a general outline of research methodology was characterised. After being accepted by Polish Committee for Stardarization they could become an effective and efficient verification tool for various types of modified fuel oils introduced on the market, both for the maritime administration officies and shipyards as well as ship owners in operation.

Key words: *compression ignition engine, modified marine fuel oils, laboratory research test bed, concept of research implementation*

1. Introduction

A tightening the regulations that limit the emissions of pollutants emitted by ship engines imposes the necessity of new technologies development, which enable complying the requirements within this scope. It is in accordance with policy of Commission for Environmental Protection of International Maritime Organization, which sets the regulations for international shipping. This Organization, during its 70th Session organised in London on 24–28 October 2016, decided to radically decrease the permissible content of sulphur compounds in fuel oils applied in shipping from present maximum 3.5% to 0.5% per unit of mass. It was enacted that the new standard will be in force since 1 January 2020 and will apply to ships operating on all international waters (except for the SECA *Sulphur Emission Control Area*, where since 1 January 2015 sulphur content in fuel oil cannot exceed 0.1% per unit of mass) [1].

It is a long awaited decision of IMO, fundamental for natural environmental protection, not only for inshore areas, but also deep into the land. It is anticipated that limiting the emissions of sulphur oxides to the atmosphere will have immense impact on decrease of expenses on public health and only for the EU the savings are estimated on the level of 15–34 billion euros [IMO Report, 2016]. On the other hand, the considered decision of IMO is raising the justified anxiety of ship owners, who will be forced to bear additional costs of adjusting the owned ships to new law regulations in scope of sea transport. It can be expected that the average exploitation costs of ships can increase twice, what will intensify already experienced (after 1 January 2015) slowdown in the development of the widely considered maritime trade.

In this case, two ways of action are possible:

1. Equipment of exhaust gases systems of marine power plants with devices reducing the emissions of sulphur oxides to the atmosphere (wet methods – so called ‘scrubbers’ or dry methods – so called ‘sorbers’).
2. Applying modified low sulphur fuel oils or alternative fuel oils to supply marine engines.

In both cases it is necessary to conduct research works aimed an evaluation of technical and economical efficiency of the applied solution. However, wet and dry desulphurization of exhaust gases from the engine are quite well worked out and more and more often applied (despite considerable investment cost of 4–5 million euros), applying so called modified or alternative marine fuel oils is still stirring controversy and is putting a question mark for all ship owners interested in not only protection of sea environement, but also in high efficiency and reliability (durability) of engines installed on the board of already exploited as well as ordered ship.

It appears that there are not many research facilities conducting this kind of research on real objects, mainly because of its complex nature. Admittedly, producers of ship engines dispose of adequately equipped research engine test bed, but conducted programmes deal with only testing newly implemented construction solutions of produced engines, with applying standard fuel oils. Basic energy parameters of the given type of engine are then determined as well as the guaranteed time of its constructional subsystems operation. Another problem represents a considerable risk of undertaking trials to supply a serial ship engine, which can cost even up to several mln euros, with a non-standard fuel, having no knowledge on its actual impact on performance and efficiency of the engine, and on the constructional structure of its main functional elements. Moreover, long-lasting character of such research contributes to respectively high cost of their realisation. Due to this, the research is conducted on the specially adjusted laboratory test bed, performed in multiple times lower scale, though still with maintaining each constructional and process similarities with respect to the real object. This kind test beds must comply with specific requirements regarding safety of research implementation and protection of natural environment. This way, amount of fuel oil used for test is being minimized (from several or several dozen tons to several kilos), together with the emissivity of harmful substances in exhaust gases (practically to 0) and costs of reconstruction of technical state of used elements and constructional subsystems (from tens thousands euros to several hundred euros). Confronting the problem, in the research project undertaken by the authors of the article, a specialised laboratory test bed of Diesel engine will be constructed, adjusted to burn modified marine fuel oils – Fig. 2. It will be equipped with measuring-diagnostic equipment enabling the evaluation of ecological, energy and reliability effects of applying other than standard types of fuel oils. A methodology of conducting engine tests with the use of modified marine fuel oils will also elaborated. Its implementation should contribute to the increase of the level of natural environment protection, increase of shipping safety and considerable reduction of exploitation costs of marine engines. It will constitute a significant supplement to ISO 8178 standard *„Combustion piston engines – measurements of exhaust gases emissions. Part 10: Cycles and research procedures of exploitation measurements of smoke of exhaust gases of compression-ignition engines operating in undetermined conditions"* [3], which is applied to research on engines operating in undetermined conditions, where rotational velocity of crankshaft of the engine or load, or both parameters change in time.

Constructed laboratory test bed will not require high expenditures for its maintenance, as it is in case of real objects, where every time after conducting verification tests it is necessary to rinse the fuel installation with large amount (several tons) of costly marine diesel oil and exchange of several times more expensive lubricant oil (even up to several hundred kilos).

2. Research test bed

A development (and competitiveness) of sea transport is strictly determined by numerous restrictions within applied marine fuel oils. On one hand, they need to be cheap enough, with maintaining high energy value, on the other – they need to comply with high ecological requirements, in the sense of permissible emissivity of exhaust gases of shipping machines, and reliability in scope of their readiness and durability guaranteed by producers. These restrictions are a challenge both for producers of fuel oils and ship engines, as well as for researchers conducting investigations on engine processes, considering the diagnostics and reliability aspects. It is even more significant and urgent problem, as recently business sector is sending numerous queries to Polish universities of technology to have the possibility to test new type of marine fuel oil on real objects, namely on adequately equipped laboratory test bed of combustion engines (last years mainly computer simulations of working processes were applied). In case of standard marine fuel oils, it is not an easy issue, as they are mainly so called residual fuel oils, of considerable density and viscosity, which in order to obtain liquid form, for transport and pulverisation, need to be heated up to the temperature in range between 35 and even up to 150ºC. However, the key technological element, determinative for the proper operation of the engine (and its technical condition), is continuous in time maintaining of required by the producer viscosity of the fuel oil injected to the combustion chamber, at the accuracy of 0.5 cSt. Especially critical process is the regulation of viscosity of the fuel oil in conditions of switching from supplying the engine with marine diesel oil fuel (start-up and lay-off) to heavy fuel oil (long-lasting operation) and reverse. Similar problems are connected with testing the biofuels e.g. methanol, more often applied in sea transport. Thus, most urgent metrological problem of constructed laboratory test bed was to select and properly assembly the viscometer, which would enable for the quick enough (several seconds) measurement of the kinematic viscosity of the fuel at the inlet of the injection pump of the engine. After analysis of the offers available on the Polish market, it was decided to select a portable rotational viscometer of VT1 Plus type, produced by HAAKE company, of measurement range 1.5–330 mPa·s – Fig. 1. In order to estimate the momentary kinematic viscosity of the fuel in place of the VT1 Plus viscometer installation, it is necessary to shut equally quick electronic thermometer.

Fig. 1. General view of portable rotational viscometer VT1 Plus type produced by HAAKE [4]

Liquid fuel oils applied in combustion power plants are to smaller or bigger extent contaminated with foreign bodies, as e.g.: sand, dust, rust, water etc., which get to the fuel oil during its transport and storage in containers. In order to reduce the consequences of the contaminants presence to the highest possible level, each fuel oil sample of minimum amount of 20 dm^3 requires special preparation for the research. The fuel oil is first filtrated by a reticular filter, and then heated up to the temperature 70–90ºC (heating temperature depends on nominal viscosity) in a settling tank of 30 dm^3 (Fig. 2) surrounded by a water jacket of 200 dm^3, temperature of which is stabilised by an electronic thermostat. Then, the fuel oil is centrifuged in a centrifugal separator type MAB104, operating first as a purifier, and then as a clarifier.

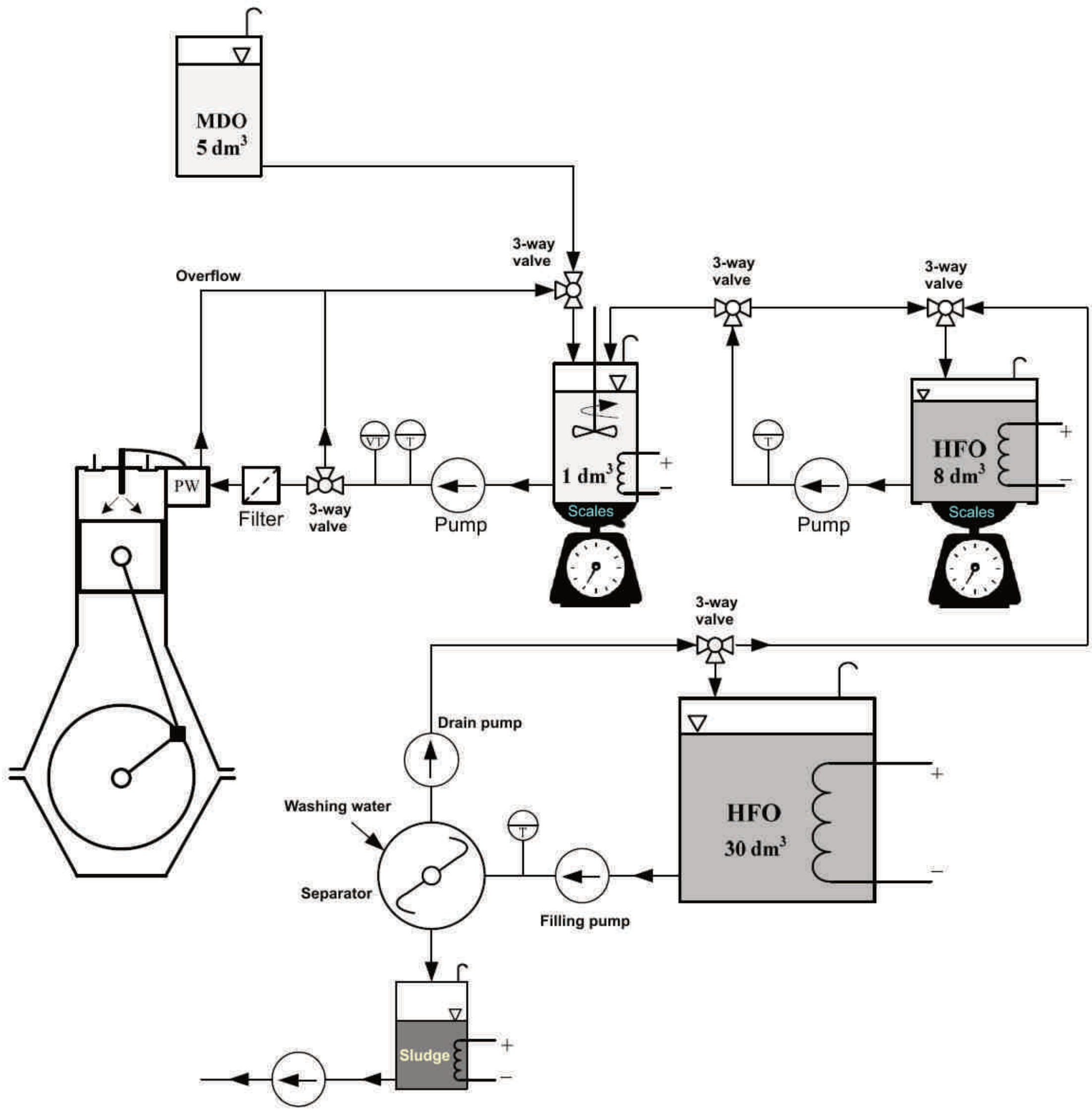

Fig. 2. Conceptual scheme of installation of supplying the laboratory engine Farymann Diesel type D10 with fuel oil: MDO – Marine Diesel Oil; HFO – Heavy Fuel Oil; PW – injection pump, VT – viscometer, T – thermometer

Single-cylinder, four-stroke compression-ignition engine applied in the laboratory test bed, is Farymann type D engine, at nominal power of 5.88 kW achieved at rotational velocity of crankshaft equal to 1500 rev/min. Hourly consumption of marine diesel oil at the engine load of 80% P_{nom} is equal to 0.86 kg/h, what corresponds to flow to injection pump equal to approx. 1 dm^3/h. Regarding the small amount of tested fuel oil and its low consumption by the engine, it is troublesome to select the circulating pump of such low efficiency and resistance to high operation temperature (temperature of the fuel oil can be even up to 150ºC). This is why, it was decided to apply gear pumps of type NSZ 10 in function of circulating pumps. These pumps induce the flow of the fuel oil in both service tanks, and can be characterised by nominal efficiency of 900 dm^3/h, at rotational velocity of 1500 rev/min. Due to the fact that fuel oil installation of the laboratory engine is supplied gravitationally, it was designed as low-pressure one. Assumed exchange of fuel oil in a preheater installation is relatively small, so the power needed for operation of pumps is not equal to its nominal power. For driving of the pumps moto reducers with DC engines were applied, with supplying voltage of 24 V and power of 0.45 kW. Such solution enables simple and effective regulation of rotational velocity, and so the efficiency of each of the pumps, with the use of DC pulse width modulation regulators.

Testing the fuel oil sample is every time initiated with the start-up of the engine on diesel oil. After reaching the constant temperature of ~100ºC by the engine (water evaporating cooling), it is loaded up to 80% of its nominal power, with the use of DC alternator. Simultaneously, the process of gradual heating up of the diesel oil is started. Given kinematic viscosity of the fuel during research is obtained in two stages, namely roughly and accurately. The sample of prepared fuel is being poured into the container of a centrifugal separator, to the main service tank of 8 dm^3, where it is heated up being constantly in flow, in a closed system of a fuel installation. Temperature, and indirectly also the viscosity of the fuel in this branch of the piping system, is stabilized by a precise electronic thermostat with PID (proportial – integral – derivative) regulation. When swithing to heavy fuel oil (the tested one), temporary mixing of both fuel oils in a measure service tank of 1 $dm^3$is taking place, with increasing share of the tested fuel oil in the mixture. A this stage, dynamic viscosity and temperature of the fuel are measured. Depending on their values, the intensity of heating up of the fuel is regulated, additionally stabilised by an electronic thermostat. Switching to supply the engine with marine fuel oil (during its stoppage) takes place reversely, namely from the external container of 5 dm^3 the marine fuel oil is supplemented in the service tank (1 dm^3), the whole time controlling the viscosity and gradually decreasing the temperature of a service tank. The share of a tested fuel oil in a mixture of fuels in a measure service tank (1 dm^3) and consumption of the fuel by the engine is determined by measurement of fuels mass in both containers by electronic weights. Both service tanks are fully made of copper alloys, what enables their simultaneous heating up by electric heating elements of power 2 kW. Mixing of the fuels in a service tank is induced by circulating pumps, as well as mechanically – by paddle stirrer. Each container and piping system in the installation of supply the engine with fuel are carefully thermally isolated. In case of testing the fuels of higher viscosities, additional heating up of the piping system is foreseen.

3. Measuring equipment

The most relevant scientific problem in the considered issue is to determine the scope and programme of the required experimental research on the lab marine compression-ignition engine enabling the evaluation of ecological, energy and reliability effects of applying modified (alternative) marine fuel oils. It is thus necessary to elaborate the method of identification of working processes in combustion engine supplied with this type of fuel oils, and also identification of its constructional structure with highly specialised measuring (diagnostic) equipment. What is important, in case of conducting this kind of research by a team of specialists from the Department of Ship and Land Power Plants of the Faculty of Ocean Engineering and Ship Technology at Gdansk University of Technology, it won't be needed to construct the diagnostic system from scratch, as it already exists and is successfully applied in exploitational research on ship engines, contracted out by ship owners, both national and international ones. It will only be necessary to extend it and adapt it to the requirements of considered experiments methodology elaboration. At present, the diagnostic system consists of the following research equipment:

- electronic indicator of LEMAG PREMET® C type, produced by LEHMANN & MICHELS GmbH – determination of performance and efficiency of the compression ignition engine, based on the measurement of inner cylinder pressure and vibrations generated by work of mechanisms connected with cylinder system, transmitted to the measurement point at the surface of the head (determination of average indicated pressure, indicated power, maximum combustion pressure and pace of increase of pressure in the cylinder $d_p/d\alpha_{OWK,}$ as well as characteristic angles of crankshaft rotations, during which the fuel injector's opening and closing takes place, initiation of compression ignition in cylinders and cylinder valves' opening and closing);
- portable exhaust gases analyser of KIGAZ 300 type, produced by KIMO® – characteristics of harmful substances emissions within engine's exhaust gases, based on the measurement and analysis of the composition of exhaust gases in determined and undetermined conditions of engine's operation;
- digital recorder and analyser of vibrations of SVAN 956 type, produced by SVANTEK – evaluation of the mechanical system stability of the engine driving line, based on spectrum-correlation analysis of vibration signal generated by selected construction nodes of driving system;
- measuring videoendoscope of XLG3 type, produced by Everest, equipped with lens of *„ShadowProbe"* type – digital record an dimensional analysis of inner space of the engine (especially identification of damages and evaluation of the wear and tear process intensity of the constructional elements limiting the working space of the cylinder).

What is even more, the Department owns a research ship engine, which was supplied with the a test bed for desulphurisation with a dry method, perfectly adjusted to the analysis of exhaust gases and based on that evaluation of ecological effects of applying different heavy fuel oils. The test bed was designed and constructed within research project, co-financed from the Regional Fund for Environmental Protection and Water Management in Gdansk (project's number: RX-01/2015 + update).

4. Methodological assumptions

Elaborated methodology of engine research must respond to the following detailed questions:

1. Regarding the method of conducting experimental research:
- what and where to measure? (which process: determined or undetermined? Where?)
- how to measure? (which parameter? at which accuracy? how often?)
- how to draw conclusions? (border conditions, categories of conditions)
- when to measure? (either in full scope of energy processes or only in their particular stages)
2. Regarding the exploitational usage of the experimental research results:
- how (in sense of quality and quantity) applying of modified marine fuel oil affects the energy measures of engine operation (its basic parameters)?
- does the change of the fuel oil supplying the engine results in increase of intensity of wear and tear process of the engine's constructional structure or deterioration of rheological properties of lubricant oil?
- what is the impact of modification of marine fuel oil on chemical composition of exhaust gases?

In order to accomplish the assumed aim of the research project, it is required to solve the following detailed issues:

- Design and building an external installation of the laboratory engine for the preparation of marine fuel oil (heavy fuel oil) for combustion. It should take into account the possibility of its heating up, purification and precise regulation of viscosity before applying it to the combustion chamber of the engine;

- Modernisation of the engine's fuel fed system consisting in applying the gradual transition between fuel oils of big differences in viscosities (mixing the marine fuel oil and heavy fuel oil or methanol);
- Optimalisation of the adsorber injecting process in processing reactor, aimed at reduction of harmful substances emissions in exhaust gases;
- Design and constructing a stationary measuring system, enabling an observation of heat-flow processes within the engine's fuel fed and in the exhaust gases system;
- Elaboration of the research programme and conducting pilot tests with the application of the most representative marine fuel oils.

5. Results of pilot research

A separate part of the initial research covered the issue of the impact of basic indications of engine's work, on inclusion of the desulphurisation system of exhaust gases into engine's exhaust system [5].

Relatively big diameters and volumes of flow elements led to assumption that the expected impact would be infinitesimal, especially that in previous stages of research no alarming symptoms of engine operation could be observed (i.e. higher temperature or vibrations etc.).

Diagnostic device used to verify validility of these assumptions was the electronic indicator Lemag Premet C XL. The indicator was produced by Lehman&Michels GmbH. It complies with production requirements of ISO 9001 standard and is wired up to indicative valve of the engine via an adapter.

Indication was conducted twice, after obtaining the determined thermal condition of the engine – temperature of cooling agent was aprox. 95–98ºC – in the following conditions:

a) rotational velocity of the engine set at 1350 rev/min;
b) load of the engine – 5 kW (electric heating system, supplied with an alternator powered by the engine via belt);
c) indication I (I series) – exhaust system of the engine without modification (referential state);
d) indication II (II series) – process reactor of the desulpurisation system with the equipment in the exhaust system of the engine (modified exhaust system);
e) indication III (series III) – processing reactor of the desulpurisation system with the equipment in the exhaust system of the engine (modified exhaust system) and additionally supply of the engine with so called a vacuum diesel oil, at the sulphur content of 0.8%.

Obtained results of indication are presented in Fig. 3 and in Table 1.

Based on obtained results, general conclusion can be formulated, that from practical point of view inclusion of process reactor of desulpurisation system with the equipment, as the element of the exhaust gases system of considered engine, is not affecting significantly the initial indications of its operation parameters.

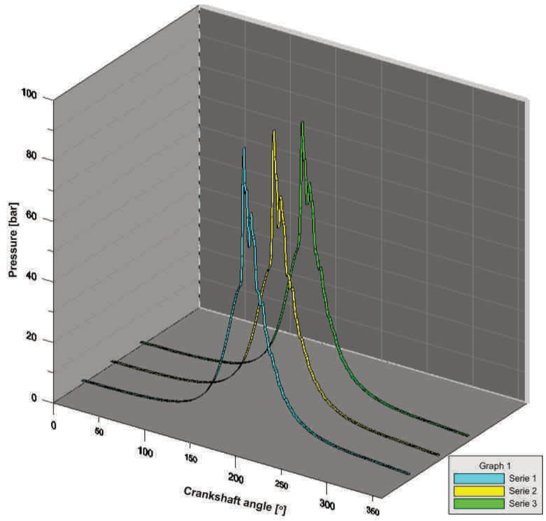

Fig. 3. Pressure changes in the cylinder – tests I, II and III

Table 1. Results of pilot research carried out on the engine with an application of the electronic indicator

No.	Engine performance indicators	Value			Change of value I-II [%]	Change of value I-III [%]
		Series I	Series II	Series III		
1.	Max combustion pressure – p_{max} [bar]	87.1	85.4	84.2	1.95 ⇓	3.3 ⇓
2.	Mean indicated pressure – p_i [bar]	3.7	4.0	3.8	8.1 ⇑	2.7 ⇑
3.	Indicated power – P_i [kW]	4.0	4.2	4.0	5.0 ⇑	0.0
4.	Max pressure angle [^{o} after TDC]	0.5	0.5	0.25	-	-
5.	Exhaust pressure (36 ^{o} after TDC) [bar]	21.5	22.5	21.0	4.6 ⇑	2.3 ⇓
6.	Max value of dp/dα [bar/^{o} CA]	16.2	15.8	15.2	2.5 ⇓	6.2 ⇓

6. Remarks and final conclusions

It is anticipated that in results of project's realisation Polish producers of marine fuel oils. to whom it is primarily addressed. will have the possibility of complex and real evaluation of usability of their products to supply ship engines. This possibility could also be used by ship owners before making decisions on introducing new marine fuel oil for exploitation. Innovative aspect of proposed solution is to adjust the laboratory test bed of Diesel engine to conduct experimental research with an application of heavy fuel oils and alternative fuel oils. so that real conditions of ship engine operation can be simulated. with minimising the negative effects of applying heavy fuel oils on the natural environment.

The main aim of the project realization is to construct a laboratory test bed foreseen for research conduction on energy efficiency of newly produced fuel oils and evaluation of their impact on emissivity of exhaust gases and pollution of the atmosphere with toxic and harmful chemical substances. as well as the effects of their applying in the aspect of intensity of degradation of the engine's constructional elements.

Detailed aims: designing and realization of the laboratory position. which will make possible a realisation of objective investigations by means of complex. high-specialised measuring apparatus. as well as an elaboration of the innovatory methodology of testing new kinds of marine fuels within real operation conditions of the engine work. keeping out the atmosphere pollution.

Except mentioned above cognitive and utilitarian aims of clean technical nature. an intention of authors of the undertaken project is the widest introduction of the suggested verification method for the newly produced and implemented marine fuels. in such a way their influence on natural environment as well as marine engines was earlier well-known and recognisable. An application to this aim computer simulation methods is definitely not sufficient at present.

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