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POLISH MARITIME RESEARCH 4 (116) 2022 Vol. 29; pp. 77-87
10.2478/pomr-2022-0045

ENERGY AND EMISSION QUALITY RANKING OF NEWLY PRODUCED LOW-SULPHUR MARINE FUELS

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ABSTRACT

The article describes the methodology of engine tests on new types of low-sulphur marine fuels in laboratory conditions in order to conduct a comprehensive assessment of their suitability for powering full-size marine engines. The innovativeness of the proposed solution consists of adapting the laboratory Diesel Engine Test Bed to carry out experimental tests using residual and alternative fuels so that it is possible to imitate the real operating conditions of the ship engine. The main aim of the research program was to assess the energy efficiency of six different low-sulphur marine fuels and their impact on the chemical emissivity of engine exhaust gases and air pollution with toxic and harmful chemical compounds. In order to achieve the research purpose formulated in this way, it was necessary to: (1) equip the constructed laboratory stand with highly specialised measuring equipment and (2) develop a technology for determining diagnostic parameters representing the basis for developing a ranking of the energy and emission quality of the tested marine fuels according to the proposed physical model. The model distinguishes 10 diagnostic parameters that, after normalisation, form two subsets of evaluation parameters - stimulant and destimulant. Determining their values made it possible to estimate a synthetic variable, according to which all the tested fuels were adjusted in the order from the "best" to the "worst", in accordance with the adopted qualitative criteria of such an assessment. The results of the laboratory tests show that among the considered fuels, i.e., MDO, MGO, RMD 80/L, RMD 80/S, RME 180, and RMG 380 type, the best solution is to use MDO distillate fuel to power full-size marine engines. However, taking into account its high purchase price, a rational alternative decision is to choose RMG 380 type residual fuel, which ranks second in the ranking of the functional quality of the tested marine fuels.

Keywords: low-sulphur marine fuels, engine tests, ranking of energy and emission quality

INTRODUCTION

The decisive tightening of the IMO regulations limiting the amount of toxic and harmful chemical compounds emitted into the marine atmosphere in the exhaust of ship engines requires, among other things, an application of low-sulphur, so-called modified, marine fuels. For this reason, refineries are undertaking intensive technological works aimed at reducing the production costs of this type of fuel while maintaining their high functional quality [2, 22]. Such works also require research examinations, especially numerical simulations, as well as engine tests to assess the combustion, emission, and structural effects of these fuels' application [11, 14, 16, 17, 18, 20, 23]. It turns out that there are few countries in the world that are conducting this type of research on real objects, i.e., full-size marine engines, mainly due to their complex nature [12, 24]. Although the manufacturers of marine engines possess appropriately equipped test engine stands, the tests being carried out concern only the newly implemented design solutions of the manufactured engines fed with standard fuels. The basic energy and emission parameters (static and dynamic) of a specific type of engine are then determined, as well as the guaranteed working time of its structural components. Another problem in the implementation of this type of research is the significant risk involved in attempting to power a serial ship engine (costing up to several million euros) with non-standard fuel without knowing its actual impact on the structure of the main functional systems, especially the working spaces. Moreover, the long-term nature of such research means that the costs of implementation are also correspondingly high. For this reason, tests are carried out in laboratory conditions on specially adapted and metered engine stands made on a much smaller scale but with all the features of construction and process similar to the real object [11]. This minimises the amount of fuel used for testing (from a few or even several dozen tonnes to several dozen or at most several hundred kilograms), the emission to the atmosphere of toxic and harmful substances contained in engine exhaust, as well as the costs of rinsing the fuel system and replacing lubricating oil1[1] and reconstructing the technical condition of worn engine elements and components (several hundred euros to tens of thousands of euros)2[2].

On the other hand, this is not an easy undertaking in the case of marine fuels, as they are primarily the so-called modified residual fuels of high density and viscosity that require heating to a temperature from 60°C to even 150°C in order to remain in liquid form during transport and spraying. The main technological issue that determines the correct functioning of the test engine and its technical condition is the continuous maintenance of the viscosity of the fuel injected into the combustion chamber, as required by its manufacturer, with an accuracy of 0.5 cSt. A particularly sensitive process is the adjustment of the fuel viscosity under the conditions of switching the engine feed from distillate fuel (start-up and lay-off) to the residual fuel (prolonged operation) and vice versa[3]. Such test beds must also fulfill the appropriate safety requirements for the implementation of experimental research and for environmental protection.

Engine testing of newly produced marine fuel in laboratory conditions should be carried out according to the methodology that allows for the formulation of an unequivocal assessment of its suitability for the implementation of the next stage of testing, i.e., the implementation in feed systems of full-size marine engines [10]. Such research is then a passive experiment in nature that is based on the results of many years of observation of the usage of a large number of tested engines, preferably of the same type, subject to periodic assessment of their technical condition [13].

RESEARCH METHODOLOGY AND APPLIED MEASURING APPARATUS

The basis for the construction of the laboratory stand for testing modified marine fuels, as shown in Fig. 1, is a classic single-cylinder diesel engine with an appropriately modified fuel feed system [7]. For the construction of the stand, a single-cylinder, four-stroke, naturally aspirated D10 type Farymann Diesel engine driving a DC generator through a belt transmission has been selected. The generator, in turn, powers the heating system of the residual marine fuels („heavy fuels") in the centrifugation process. The very important advantage of the applied engine type is the maximally simplified structure of its functional systems: fuel and air feeding, as well as cooling and lubrication, which greatly facilitates balancing the realised energy processes.

When designing the external fuel supply installation of the research engine, it was necessary to select individual components that would guarantee the achievement and precise maintenance of the desired values of the injected fuel parameters during operation, in particular, its kinematic viscosity. This problem is particularly critical in the process of switching the engine power system operation from distillate fuel to residual fuel (and vice versa). In the proposed solution, both types of fuel are mixed by hand using three-way valves. It is not a simple task, taking into account the minimal dimensions of individual flow elements compared to full-size marine engines and, therefore, also the mass flux and heat capacity of the flowing fuel. Such an installation is not thermally stable and is very sensitive to any flow disturbances, even those resulting from alterations in the engine load. Therefore, it was necessary, on the one hand (operational), to maintain an appropriate time for changing the operation variant of the power supply system when switching to another fuel and, on the other hand (structural), to thoroughly insulate the service (measuring) tank and pipelines and to equip all fuel tanks with paddle mixers.

The intensity of fuel heating in tanks and its temperature stabilisation is ensured by precise electronic thermostats with PID regulation[4]. Electric plate heaters and paddle agitators are used to evenly heat the fuel in the distribution and backup tanks, which are made of a copper alloy. The viscosity and temperature of the fuel supplied to the engine are measured using a HAAKE VT1 Plus rotational viscometer with a measuring range of 1.5 to 330 mPa·s and a semiconductor thermistor with a measuring range of -50°C to 150°C.

The scheme of the organisation of the engine tests with the application of modified marine fuels is presented in Fig 2. In the first stage, the delivered sample of the tested fuel should be cleaned of water and solid particles on the centrifuge stand, operating in the purifier variant[5]. This treatment is primarily aimed at protecting the test engine against the destructive effects of contaminated fuel on its injection system and working space. A very important operational issue is maintaining the highest possible temperature of the swirled fuel during the whole centrifugation process[6], as well as the correct adjustment of the

1 Each time fuel tests are carried out on a full-size marine engine, it is necessary to rinse the entire fuel feed system with a large amount (several hundred kilograms) of expensive distillate fuel and replace the many times more expensive lubricating oil (even several tons)

2 The approximate cost of purchasing a cylinder liner for a contemporary 25 MW marine engine can reach EUR 40,000, a piston along with a set of rings - EUR 21,000, and a set of injectors - several thousand euro.

3 In marine power plants, this process, which can last up to 40–60 min, is supported by the operation of an automatic fuel viscosity control system.

4 Proportional-integral-derivative controller with the function of automatic selection of the value of all three parts of the controller. The achieved accuracy of the fuel temperature setting is less than ±1°C.

5 For this reason, inter alia, the minimum amount of fuel sample delivered for testing should not be less than 50 kg.

6 Even at temperatures below 70°C, paraffin compounds may be released in the centrifugation of the residual fuel. In order to achieve the required minimum temperature of the swirled fuel at the level of 90–95°C, synthetic electrically insulating oil should be applied for its heating.

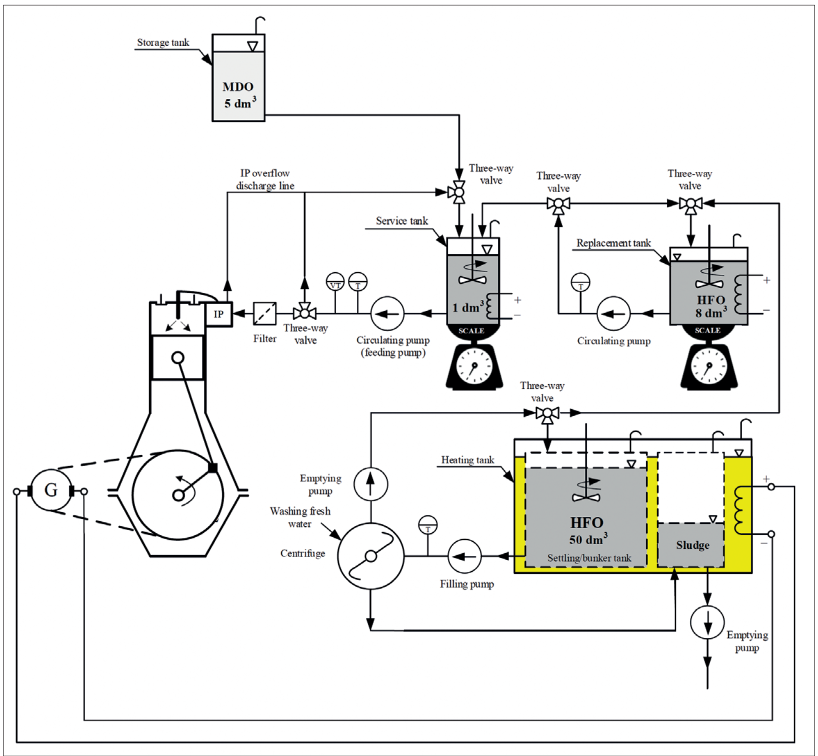

Fig. 1. Schematic diagram of the fuel feed system of the laboratory Farymann Diesel engine D10 type: MDO - (Marine Diesel Oil) marine distillate fuel; HFO - (Heavy Fuel Oil) marine residual fuel; IP - injection pump; VT - viscometer; T – thermometer

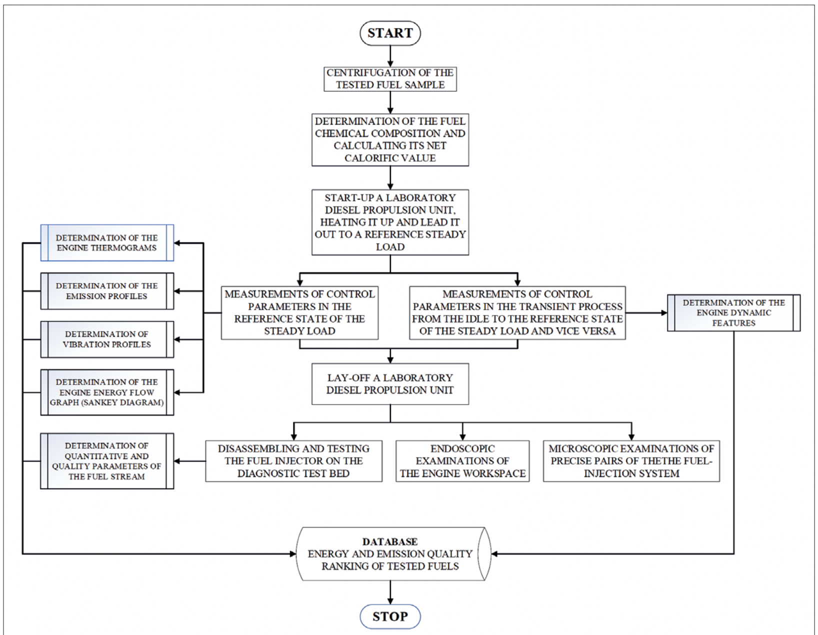

Fig. 2. The execution algorithm of engine tests with the application of modified marine fuels

selection cover and maintaining a constant position of the phase division plane. It should be remembered that "too thorough" centrifugation of the fuel sample does not correspond to the actual conditions of its usage for feeding engines on ships, where the amount of separated sludge usually does not exceed 3% of the total fuel uplift.

In the next stage of the research, the elementary chemical composition[7] and calorific value of the centrifuged sample of the tested fuel should be determined. Marine fuel producers usually provide boundary values for basic physicochemical parameters. As they can differ quite significantly depending on the analysed batch[8] of fuel, it is necessary to evaluate both the gross (by measurements) and net (by calculations) calorific values of the centrifuged fuel sample and determine the mass fractions of its basic components before starting the engine tests. The experimentally determined calorific value of the fuel enables a precise calculation of the amount of chemical energy delivered to the combustion chamber of the tested engine, which is an input value for further analyses of the effectiveness of the working process. It is also necessary, for the sake of comparison, to determine the self-ignition delay of the test fuel by means of the cetane number (distillate fuels) or the CCAI index (residual fuels)[9].

Having the full characteristics of the tested fuel, it is possible to start testing it in the real operating conditions of a compression-ignition engine. In order to obtain comparable test conditions, each engine test, with the application of another fuel, should be preceded by the replacement of the lubricating oil and the fuel injector tips (brand new pintle nozzle). It should also be remembered that the engine injection system must be thoroughly (for at least 15 min) flushed and cleaned with distillate fuel each time before laying it off[10].

Research on the energy and emission profiles of an engine fed with various types of marine fuels can be carried out after reaching a certain thermal state of its construction structure[11]. Based on the results of previous studies of thermal inertia processes in the lubrication and cooling system of the diesel engine applied, it was established that the time constants of these processes are 20 and 12 minutes, respectively [11]. For this reason, it was consequently established that the recording of the control parameters always begins in the last minute of a 20-minute period of steady engine running at a given load.

Achieving a steady thermal state of the engine determines the possibility of implementing the program of engine tests, both static and dynamic (Fig. 3). As the main aim was to perform

7 Mass fractions of carbon, hydrogen, nitrogen, and sulphur in the fuel.
8 "Batch" means an amount of fuel representatively sampled, characterised, and transferred as one shipment.
9 It is necessary to analyse the course of the engine work process. As a rule, marine fuel engine tests are carried out without any regulatory changes to the test engine injection apparatus, regardless of the values of the parameters characterising the self-ignition delay. In extreme cases when it may endanger the durability of the engine (excessive increases in combustion pressure and temperature), it is permissible to adjust the injection advance angle individually for a tested fuel type.
10 Failure to do so may result in solidification in the residual fuel feed system, which usually leads to seizures of the precision pairs of the engine injection system.
11 Determined according to the alterations of the lubricating oil temperature.

a comparative analysis of the tested marine fuels in terms of their functional quality (energy and emission), the registration of control parameters in the steady state is carried out on the same maximum achievable reference load of the engine in three/four measurement series[12]. The basic static profile is then a stream diagram of the energy flow in the tested engine and the entire propulsion unit, the so-called Sankey diagram and histogram of harmful and toxic gas volume fractions in the engine exhaust. A detailed description of the elaborated block algorithm for calculating the results of the measurements carried out is presented in publications [8, 9]. They enable the creation of the appropriate stream bands of various forms of transmitted and transformed energy and the characteristic efficiencies of the energy processes implemented in the research engine and the entire propulsion unit. They are determined on the basis of the engine's basic parameters as well as the parameters characterising its thermal radiation and generated vibrations.

The purpose of testing the engine in unsteady states is to evaluate its dynamic profiles during the transient process from one steady state to another. The capabilities of the research diesel engine control system allow dynamic tests to be carried out by increasing and then reducing the load torque stepwise by appropriately overriding the current setting of the generator's armature.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 3. It used a gen set with Farymann Diesel Engine D10 type and DC generator that is originally intended to drive auxiliary devices in the power plants of fishing boats. A general view of the research gen set is shown in Fig. 4. The basic energy parameters of the engine in the nominal load are as follows: power - 6.0 kW; torque - 38 N·m; rotational speed - 1500 min^{-1}; and distillate fuel consumption per hour - 0.88 kg/h. Its basic design parameters are as follows: bore/stroke – 90/120 mm; displacement - 765 cm^3; and compression ratio - 22.

As shown in the diagram of the measurement signal recording and processing system (Fig. 3), highly specialised stationary and portable measurement equipment was applied in engine tests of a new type of marine fuel. In the experiments, the engine's operating conditions were controlled and their related control parameters were monitored and registered by the analysing computer (MATLAB R2015B software) through the CONVERTER A/C. They were then averaged and subjected to statistical analysis, including elimination of gross errors as well as evaluation of the measurement uncertainty. The dispersions of recorded measurement values around the mean values did not exceed 4%.

In addition to the stationary system, a portable diagnostic system was also used for the measurements (Fig. 5). In-cylinder pressure was collected as well as the crank angle signal acquired by the mobile LEHMAN & MICHELS GmbH electronic indicator of the LEMAG PREMET C type (along with the pressure transducer). The composition of the exhaust gases was analysed by the KIMO Instruments flue gas analyser of the KIGAZ 300PRO type. The applied measurement system allows precise observation of the working (power generation) as well as accompanying (residual) processes during steady operation and transient operation of the engine and the entire propulsion unit. The following processes were additionally observed and registered:

- vibrations of the foundation base by the SVANTEK vibration register and analyser of the SVAN 956 type,
- thermal radiation of the engine by the NEC infrared camera of the THERMO GEAR G30 type.

The measurement system also enables assessment of the technical condition of the engine's working space by an endoscopic method (the EVEREST digital measurement video endoscope of the XLG3), as well as the engine's injection system on a test bed equipped with a camera for quick image recording (the Sony cyber-shot digital still camera of the DSC-RX10 III type). Such an assessment is carried out twice - before and after fuel testing.

Table 1 summarises the recorded control parameters of the propulsion unit, which serve as the basis for determining the diagnostic parameters in the field of the energy and emission quality of the tested fuel.

The engine fuel used in the experiment includes marine light (distillate) fuels - MGO (marked as F1) and MDO (marked as F5), as well as marine residual (modified) fuels - RMG 380 (marked as F2); RME 180 (marked as F4); RMD 80/L (marked as F3); and RMD 80/S (marked as F6). The latter, with less than 0.1% of the weight of sulphur, is also called marine ultra-low sulphur diesel fuel. All the parameters of the test fuels conform to international standard ISO8217:2010.

The LEMAG electronic indicator, equipped with a Thompson adapter, was mounted in the cylinder head's indicator cock and measured the cylinder gas pressure of the engine. The Kistler piezoelectric sensor and TDC laser type sensor were used to obtain the cylinder pressure data at 1.0 crank angle intervals degree. The pressure data were averaged 20 consecutive cycles for the experiment in all engine conditions (all series of measurements). The indicator is adapted to work with an analysing IBM portable computer in which specialised analysis software „WPREMET" and our own application programs have been installed. This allows for statistic assessment of the recorded measurement data. The averages of the pressure data were analysed to compute the indicated power. Its measurement uncertainty did not exceed 6%.

The gaseous emissions from the research engine $CO/NO_x/CO_2/O_2/HC$ were measured by the mobile KIGAZ 300PRO register equipped with electrochemical cells. The recordings of the emitted exhaust parameters were started in the last minute of steady engine running at a given load. The obtained results were approximated with linear functions and then averaged, rejecting the values from the first 30 s. The initial results are burdened with gross errors due to disturbances in the exhaust passage around the analyser measuring probe inserted into the measuring pipeline through the „adapter". The measured data were statistically processed with the analysing computer to create the averages of the considered gaseous emissions. Their measurement uncertainty did not exceed 4%.

Although particulate emissions stand for an important indicator of the emission quality of marine fuels, the currently

12 If the on-line analysis of the measurement uncertainty of the engine control parameters (especially fuel consumption) does not indicate the presence of gross errors, the number of measurement sequences is limited to three.

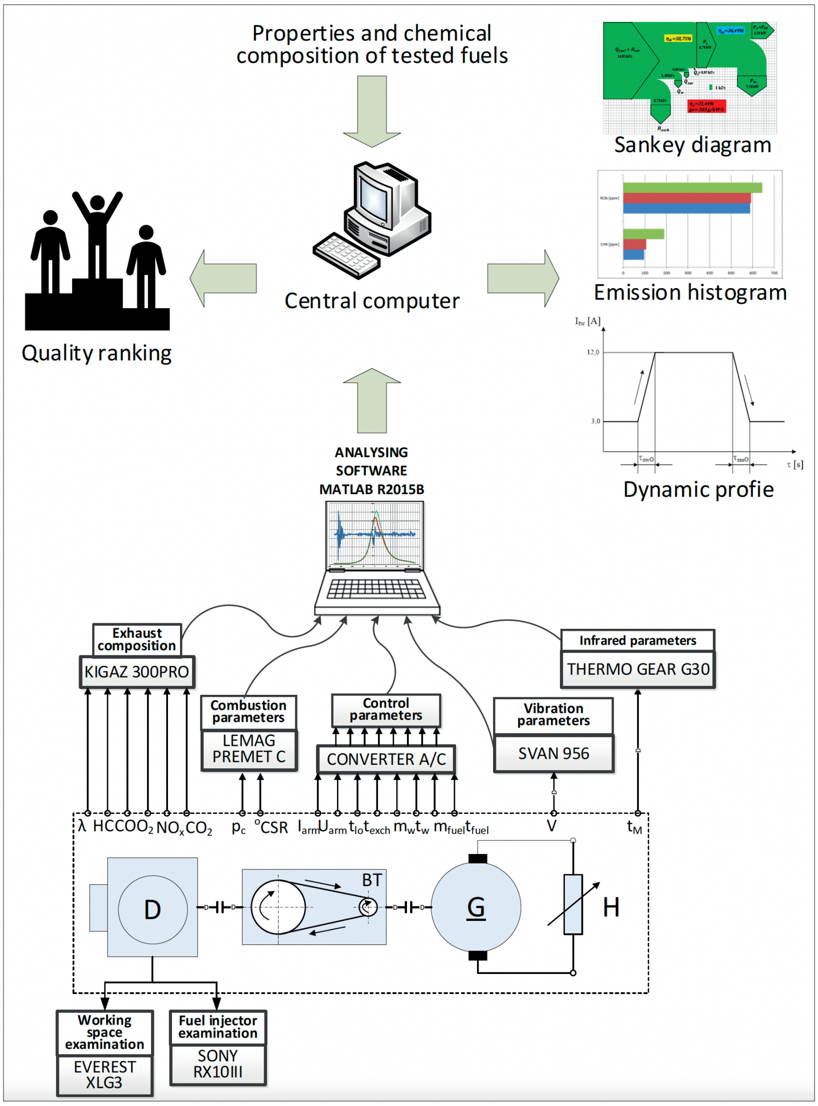

Fig. 3. Diagram of the system for recording and processing measurement signals in engine tests with the application of modified marine fuels: D - single-cylinder Farymann Diesel D10 engine; BT - belt transmission (multiplier i = 0.426); G - direct current generator; H - heater system

binding legal regulations do not yet include the limitations on the emission of particulate matter (PM) in the exhaust of marine engines during operation. However, due to their destructive effect on the human health, it should be expected that they will be introduced in the near future. On the other hand, it might be assumed that the radical reductions of SOx and NOx emissions in the exhaust of the operated marine engines recently implemented by the IMO will also contribute to the minimization of particulate matter (by an application of scrubbers, sorption reactors, and catalytic converters).

In connection with the above, research attempts have already been made, also by the paper's author, to develop an appropriate technology for monitoring PM emissions in the exhaust from marine engines. However, this is a particularly complex issue in terms of measurement technology. On the one hand, it forces interference in the structure of the engine exhaust gas passage. On the other hand, during the diagnostic tests of a marine engine in current operation, the basic safety condition must be kept: the measuring system additionally used must not interfere with the operation of the tested engine and its standard measurement system.

For the foregoing mentioned reasons, this issue was not discussed as part of the manuscript and parameters of the particulate emissions were not taken into consideration as the diagnostic parameters of the created usable quality ranking of the newly produced low-sulphur marine fuels.

The measurement of the vibration velocity on the foundation was carried out in order to indirectly determine the amount of energy dissipated for causing vibrations, which can be treated as an indicator of the system (engine) stability during operation on various types of fuel. The measurements were carried out by means of the portable SVAN 956 digital analyser in accordance with the recommendations of ISO 10816. The processing measuring data giving the RMS value of the vibration velocity were determined using a 10 Hz–1 kHz medium-pass filter. Their measurement uncertainty did not exceed 4%.

The thermal state of the engine structure was measured with the NEC Thermo Gear G30 thermal imaging camera, equipped with an CMOS (Complementary Metal-Oxide-Semiconductor) image detector. Due to the requirement of standardising the emission capacity of the entire outer surface of the test engine, it was necessary to replace its factory paint with a paint coating using matte black alkyd paint, thus allowing the emission value of the engine surface to be increased closer to 1.0, i.e., the blackbody emissivity. The emissivity value for such a paint coverage, as determined by a technical method (using a thermal imaging camera), is $\varepsilon = 0.87$. The camera was mounted on a photographic tripod at a distance from the optical path of the camera to the engine such that the image of the examined surface fills the entire camera frame.

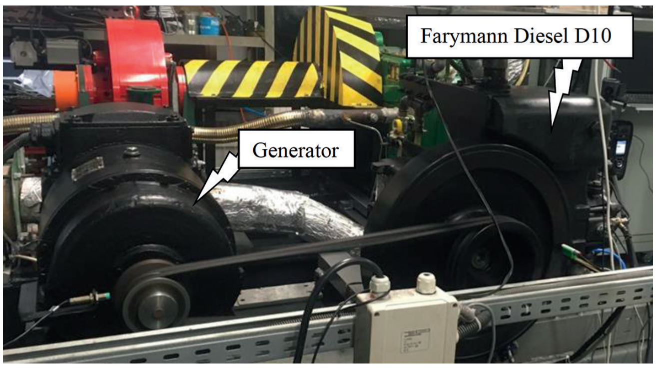

Fig. 4. General view of the laboratory stand of the Farymann Diesel D10 engine

The average temperature of the engine surface in each measurement series was determined with the use of the InfReC Analyzer NS9500 Lite Program, on the basis of thermograms recorded every second. Their measurement uncertainty did not exceed 5%.

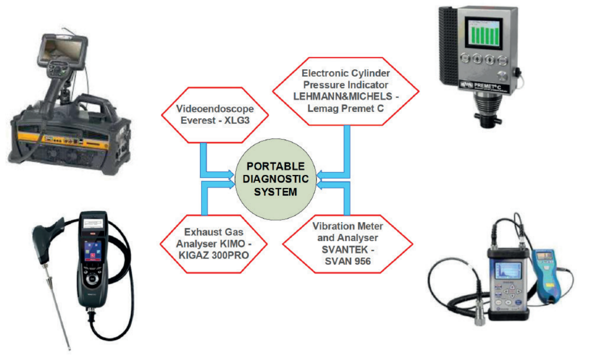

Fig. 5. Portable diagnostic system applied to the engine tests

Tab. 1. Control parameters of a laboratory propulsion test bed with a Farymann Diesel engine D10 type

No.	Parameter	Measuring range	Measuring accuracy FS (% of Full Scale Accuracy)	Sampling cycle
1.	Rotational speed of the engine crankshaft – n	0–3000 rev/min	± 0.1%	0.5 ms
2.	Indicated pressure – p_i	0–23.0 MPa	± 3.0%	15 μs (every 1° CSR)
3.	Fuel consumption – m_{fuel}	0–20 kg	± 0.2%	12.5 ms
4.	Fuel temperature – t_{fuel}	from -55 to +125°C	± 0.2%	93.75 ms
5.	Cooling water consumption (by evaporation) – m_w	0–20 kg	± 0.2%	12.5 ms
6.	Cooling water temperature – t_w	from -55 to +125°C	± 2.0%	93.75 ms
7.	Lube-oil temperature – t_{lo}	from -55 to +125°C	± 2.0%	93.75 ms
8.	Exhaust temperature – t_{exch}	0–350°C	± 1.0%	0.1 ms
9.	Generator (armature) load current – I_{arm}	0–15 A	± 1.5%	0.1 ms
10.	Voltage at the generator armature terminals – U_{arm}	0–250 V	± 1.5%	0.1 ms
11.	CO content in the exhaust	0–8000 ppm	± 0.1%	2 s
12.	NO_x content in the exhaust	0–5155 ppm	± 0.1%	2 s
13.	CO_2 content in the exhaust	0–99%	0.2%	2 s
14.	O_2 content in the exhaust	0–21%	0.2%	2 s
15.	HC content in the exhaust	0–2000 ppm	± 0.1%	2 s
16.	Excess air – λ	1–9.99	1.0%	2 s
17.	Temperature of external surfaces of the engine (thermogram) – t_M	from -20 to +350°C	0.2%	1 s
18.	Vibration acceleration (with SV80 converter)	from 0.01 $m{\cdot}s^{-2}$ RMS to 500 $m{\cdot}s^{-2}$ PEAK(with a sensitivity transducer 10 mV/$m{\cdot}s^{-2}$)	0.1%	20 μs

All averaged values of the recorded control parameters were sent to the so called "Central computer" in order to determine the energy and emission characteristics of the engine, as well as to calculate the selected diagnostic parameters of the fuel usability. In the research, the tests were carried out at the steady state and transient processes to evaluate the effects of the examined marine fuels on the diesel engine's combustion, emission, and economic performance, as well as its wear intensity.

RESULTS AND DISCUSSION

The assessment of the impact of various marine fuels on the energy state of the tested engine, in terms of its performance, efficiency, dynamic characteristics, and chemical emissivity of the exhaust, is a complex phenomenon. It stands for the basis for an operation decision regarding their further application to feed full-size marine engines. For this reason, it is necessary to carry out a multi-criteria assessment of the phenomenon using appropriate tools of the operations research. The operations research as a scientific discipline has not had a very long history compared to other scientific disciplines. It was born during the Second World War and covered the issues of optimizing decisions in the military (logistics) area. After the war, the methods of operations research were successfully applied in econometrics for efficient management in industry, e.g., for planning production. Operations research includes a set of mathematical and statistical tools that allow one to determine a method of solving specific organizational problems related to making a rational decision. It stands for the development of stat art methods, which focus mainly on estimating the randomness of the studied phenomena.

Many scientists from recognized research centres around the world contributed to the establishment and development of the field of operations research [1,3,19]. However, all of the most important achievements in the field of operations research are discussed in a very extensive book (almost 1000 pages) by Stanford University employees, Professors F.S. Hillier and G.J. Lieberman: „Introduction to Operations Research", the 9th edition of which was published in 2010 [5]. It presents, inter alia, a detailed procedure for examining and assessing the state of complex phenomena in various objects, processes, and systems. Many interesting examples of the application of operations research to decision making in the design and operation of complex technical systems are included in the publication [4]. However, on the other hand, there is a lack of publications concerning the study and evaluation of the complex phenomenon, which is the impact of newly produced low-sulphur marine fuels on the functioning and durability of a diesel engine. This is a brand new operation problem related to the radical limitation (since 1st January 2020 by the International Maritime Organisation) of the sulphur content in marine fuels and the introduction of new types of marine fuels to the fuel market, the so-called modified marine fuels.

Complex phenomena are considered in a multi-criteria manner. They are characterised by many features, the so-called diagnostic variables that have different measurement units and different orders of magnitude. In order to evaluate a complex phenomenon on the basis of the set of diagnostic parameters, their original values should be transformed in such a way that the transformed variables have no measurement units and take values of an approximate order of magnitude. It is said then that the original variables have been normalized. This allows the use of one of the aggregation procedures (usually summation), as a result of which the value of a synthetic (aggregate) variable characterizing each object in terms of the assessed complex phenomenon is obtained. The obtained values of the aggregate variable constitute the basis for building the ranking of objects, i.e., a system in which the objects are ordered from the best to the worst. Knowledge of the ranking of objects creates objective conditions for making rational decisions about their future, for instance, an application. A simplified scheme for determining a synthetic variable and creating a ranking of objects is shown in Fig. 6.

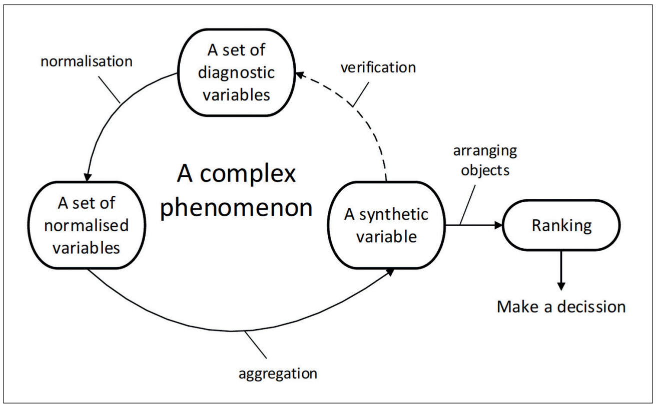

Fig. 6. A simplified scheme for creating a ranking of objects

The methodology of operations research implementation presented above was used to assess the usability of the tested marine fuels according to the proposed physical model (Fig. 7). Following the control compliance of the tested engine type and the measurement (observation) capabilities of the diagnostic system, ten diagnostic parameters were distinguished in the model that are characterised by the greatest sensitivity to changes in the fuel applied. In the next step of the procedure, the identity (role) of the distinguished diagnostic parameters in the performance assessment of the considered marine fuels' functional quality should be examined [6]:

- parameters that positively stimulate the assessment of the fuel's impact on the engine operation - stimulants,
- parameters that negatively stimulate the assessment of the fuel's impact on the engine operation - destimulants,
- parameters that positively stimulate the assessment of the fuel's impact on the engine operation, only for their specific (nominal) values or value ranges - nominants.

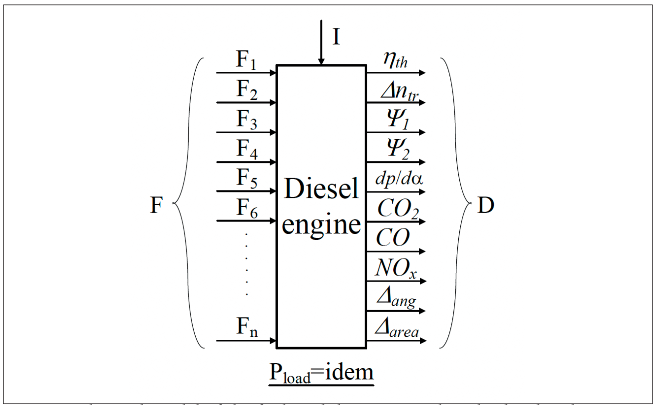

Fig. 7. Physical model of the fuel usability in a single-cylinder diesel engine: F – the set of the considered marine fuels, D - the set of diagnostic parameters, I – interference, Pload - engine output (net) power

Based on the proposed physical model, the set of diagnostic parameters was divided into three subsets:

- a subset of *stimulants*, of which the increase or decrease in value is perceived as, respectively, an increase or a decrease in the evaluation of the fuel functional quality:
  - the engine thermal efficiency, as a percentage - η_{th},
  - the intensity of crankshaft rotational speed alterations in the transient process of the engine, in 1/s^2 - Δn_{tr},
  - the average intensity of injection pressure alterations from the time at which the injector opens itself to the time at which the injection pressure reaches the maximum (taking into account the instantaneous pressure drop in the injection line when the injector is "opened") - $\Psi 1$,
  - the average intensity of injection pressure changes from the time of reaching the maximum injection pressure to the end of injection - $\Psi 2$,
- a subset of *destimulants*, of which the increase or decrease in value is perceived as, respectively, a decrease or an increase in the evaluation of the fuel functional quality:
  - the rate of pressure increase in the cylinder, in MPa/°CSR[13] - $dp/d\alpha$,
  - the percentage contribution of carbon dioxide in the engine exhaust - CO_2,
  - the contribution of carbon monoxide in the engine exhaust, in ppm - CO,
  - the contribution of nitrogen oxides in the engine exhaust, in ppm - NO_x,
  - the total, relative angular deviation of the sprayed fuel stream - Δ_{ang},
  - the total, relative angular deviation of the sprayed fuel stream - Δ_{ang},
  - the total, relative surface deviation of the atomized fuel stream - Δ_{area},
- a subset of *nominants* that, from the point of view of fuel energy quality assessment, has a specific, most advantageous value (nominal value) or should be in a specific (nominal) numerical range. Each deviation of the nominant value from the nominal value or exceeding the established limits of the nominal range means a decrease in the assessment

13 CSR - crankshaft rotation

of the fuel functional quality. In more in-depth and detailed analyses, the rate of pressure increase $dp/d\alpha$ in the engine cylinder can be treated as a *nominant* and it can be assumed that the optimal value of this parameter should be in the range of, for example, 0.2–0.8 MPa/°CSR. In such a situation, exceeding both the lower limit of the range, which means a reduction in the working process efficiency, and the upper one, indicating too "hard" engine work that leads to excessive loads on its mechanical system, means a reduction of the fuel functional quality rating. It has been established that in treating this parameter as a *destimulant*, it is assumed that the same engine power is achieved with its "softer" (which is desired) running.

Table 2 summarises the values of the diagnostic parameters and their ranges determined during energy tests of the various types of marine fuels that were used to feed the Farymann Diesel D10 research engine [11]. Analyzing the numerical values of the diagnostic parameters that positively stimulate the assessment of the fuel impact on the engine operation, it can be concluded that the *F6* distillate fuel is characterized by the highest functional quality. For this fuel, all the stimulant values are the highest. However, it does not „achieve" such favorable results in terms of parameters that negatively stimulate the assessment of fuel impact on engine operation, the values of which should be as low as possible. It turned out that in this category, the most advantageous fuel is *F2* (residual), for which three of the six destimulants values have reached the minimum values in the range of the combustion process dynamics and gaseous emissions: $dp/d\alpha$ = 0.469333 MPa/°CSR, CO_2 = 7.95%, and NO_x = 392 ppm. In order to finally resolve this doubt and clearly indicate which fuel is of the highest operational quality, an operations research method should be applied.

The numerical data in Table 2 show that the designated diagnostic parameters have different units of measurement and different orders of magnitude. For this reason, it is necessary to make an appropriate conversion (normalisation) of their original values to dimensionless values of an approximate order of magnitude. There are many methods (formulas) of normalising diagnostic variables in various areas of operations research [5,6,21]. In order to solve the considered fuel problem, the method of zero unitarisation [15] was chosen. This method is based on the formula of the ratiometric transformation, which guarantees that the standardised diagnostic parameters will be in the range between 0 and 1. By marking the set of diagnostic parameters as D_j, where j = 1.… .10, and the set of the considered marine fuels as F_i, where i = 1.… 6, the following calculation steps are conducted to determine [15]:

- the range value for each standardised variable, as a constant reference point:

$$R(D_j) = max\, d_{ij} - min\, d_{ij} \tag{1}$$

- stimulant values:

$$u_{ij} = \frac{d_{ij} - min\, d_{ij}}{max\, d_{ij} - min\, d_{ij}} \tag{2}$$

- destimulant values:

$$u_{ij} = \frac{max\, d_{ij} - d_{ij}}{max\, d_{ij} - min\, d_{ij}} \tag{3}$$

- synthetic variable values:

$$Q_i = \sum_{j=1}^{6} u_{ij} \tag{4}$$

Determining the value of the synthetic variable Q_i for each of the investigated marine fuels allows us to build their ranking, i.e., to arrange their order according to non-increasing Q_i values (Table 3, Fig. 8). The "best" fuels are ranked first, followed by the "worst" fuels, according to the adjusted performance evaluation criteria - energy and emission quality. Distillate fuels *F5* and *F1* rank, respectively, first and third in the ranking, followed by modified residual fuels. The values of the synthetic variable Q_i for these fuels were, respectively, 6.455498 and 4.384817. This should not come as a surprise given that distillate fuels are, on average, 30% more expensive than residual fuels. As the purchase price of fuel is certainly a destimulant of the usable quality of marine fuel, in terms of the ability to meet the needs (expectations) of the shipowner, it can be expected that the extension of the diagnostic parameters set with such a diagnostic variable will certainly change the position of the leading distillate fuels in the ranking in favour of modified (residual) fuel *F2*, which is currently in second place (Q_i = 5.71843). Therefore, an alternative, rational solution in such a situation seems to be the application of this

Tab. 2. Summary of the measurement values of diagnostic parameters and their ranges R that characterise the functional quality of marine fuels

Marine fuel i-th	Diagnostic parameter – j-th									
	Stimulants				Destimulants					
	η_{th} [%]	Δn_{tr} [1/s2]	Ψ1 [MPa/°CSR]	Ψ2 [MPa/°CSR]	$dp/d\alpha$ [MPa/°CSR]	CO [ppm]	CO_2 [%]	NO_x [ppm]	Δ_{ang} [%]	Δ_{area} [%]
F1 (MGO)	58.75	0.095	0.0596	0.0758	0.639667	487	8.66	504	13.8	8.1
F2 (RMG 380)	58.58	0.030	0.0617	0.0876	0.469333	364	7.95	392	73.9	49.7
F3 (RMD 80/L)	59.06	0.033	0.0529	0.0568	0.49472	391	8.05	400	83.3	65.0
F4 (RME 180)	58.80	0.032	0.0488	0.0570	0.481667	256	8.37	476	45.9	25.9
F5 (MDO)	61.79	0.165	0.0653	0.0700	0.613	383	8.03	542	57.4	23.8
F6 (RMD 80/S)	60.07	0.043	0.0524	0.0617	0.56	421	8.57	658	71.3	53.1
R(Dj)	**3.21**	**0.135**	**0.0165**	**0.0308**	**0.170334**	**231**	**0.71**	**266**	**69.5**	**56.9**

Tab. 3. List of standardised values of diagnostic parameters and the value of the synthetic variable constituting the basis for multi-criteria evaluation of energy and emission quality of the tested marine fuels

Marine fuel	Standardised values of diagnostic parameters										Synthetic variable values	FUEL RANKING
	Stimulant				Destimulant						Q_i	
	u_{i1}	u_{i2}	u_{i3}	u_{i4}	u_{i5}	u_{i6}	u_{i7}	u_{i8}	u_{i9}	u_{i10}		
F1 (MGO)	0.05296	0.481481	0.654545455	0.616883	0	0	0	0.578947	1	1	**4.384817**	**3**
F2 (RMG 380)	0	0	0.781818182	1	1	0.532468	1	1	0.135252	0.268893	**5.71843**	**2**
F3 (RMD 80/L)	0.149533	0.022222	0.248484848	0	0.850958	0.415584	0.859155	0.969925	0	0	**3.515861**	**5**
F4 (RME 180)	0.068536	0.014815	0	0.006494	0.927589	1	0.408451	0.684211	0.538129	0.68717	**4.335395**	**4**
F5 (MDO)	1	1	1	0.428571	0.156557	0.450216	0.887324	0.43609	0.372662	0.724077	**6.455498**	**1**
F6 (RMD 80/S)	0.53229	0.096296	0.218181818	0.159091	0.46771	0.285714	0.126761	0	0.172662	0.209139	**2.267845**	**6**

type of marine fuel to power full-size marine engines.

The *F6* residual fuel, for which the value of the synthetic variable is Q_i = 2.267845, is characterized by the lowest functional quality according to the adopted evaluation criteria.

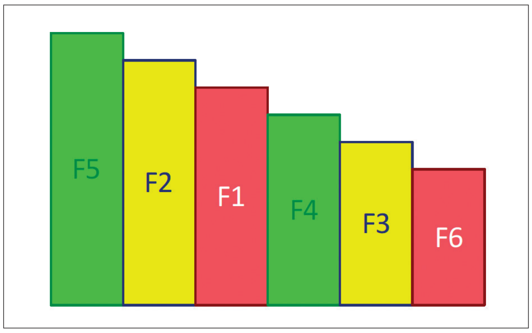

Fig. 8. Energy and emission quality ranking of the tested marine fuels

FINAL REMARKS AND CONCLUSIONS

Experiments were conducted on a Farymann Diesel D10 engine, which is a single-cylinder, four-stroke, naturally aspirated diesel engine widely used as the auxiliary devices in the power plants of fishing boats. Based on six different marine low-sulphur fuels, their influence was evaluated on the engine energy and emission parameters, as well as the engine components' degradation.

The experimental data were used to analyse and evaluate the functional quality of the tested fuels, using known methods of operations research. As a result, this enabled the development of their ranking, which is the basis for making an operation decision regarding their future application to feed full-size marine engines.

Based on the experimental data, the main conclusions are formulated as follows:

1) The highest thermal efficiency, η_c = 61.79%, was achieved by the engine fed with *MDO* (*F5*) distillate fuel. The lowest, η_c = 58.58%, was for the engine fed with *RMG* 380 (*F2*) residual fuel.
2) The best dynamic properties in the transient process were demonstrated by the engine fed with *MDO* (*F5*) distillate fuel, for which the intensity of crankshaft rotational speed alterations Δn_p = 0.165 s^{-2}. The worst was for the engine fed with *RMG* 380 (*F2*) residual fuel, Δn_p = 0.030 s^{-2}.
3) The most favorable working conditions of the injection system were obtained for the engine fed with *MDO* (*F5*) distillate fuel, for which the average intensities of injection pressure alterations were, respectively, $\Psi 1$ = 0.0653 MPa/°CSR and $\Psi 2$ = 0.0700 MPa/°CSR. The least favorable was the engine fed with *RME* 180 (*F4*) residual fuel, for which $\Psi 1$ = 0.0488 MPa/°CSR and $\Psi 2$ = 0.0570 MPa/°CSR.
4) The most favorable course of the combustion process ("soft work") was obtained when the engine was fed with *RMG* 380 (*F2*) residual fuel, for which the rate of pressure increase in the cylinder was $dp/d\alpha$ = 0.469333 MPa/°CSR. The least favorable ("hard work") was for the engine fed with *MGO* (F1) distillate fuel, $dp/d\alpha$ = 0.639667 MPa/°CSR.
5) The lowest emission of carbon monoxide, CO = 256 ppm, was achieved for the engine fed with *RME* 180 (*F4*) residual fuel, and the highest was for the engine fed with *MGO* (*F1*) distillate fuel, CO = 487 ppm.
6) The lowest emission of carbon dioxide, CO_2 = 7.95%, was achieved for the engine fed with *RMG* 380 (*F2*) residual fuel, and the highest was for the engine fed with *MGO* (*F1*) distillate fuel, CO_2 = 8.66%.
7) The lowest emission of nitrogen oxides, NO_x = 392 ppm, was achieved for the engine fed with *RMG* 380 (*F2*) residual fuel, and the highest was for the engine fed with RMD 80/S (*F6*) residual fuel, NO_x = 658.
8) The most favorable working conditions of the injector were obtained for the engine fed with *MGO* (*F1*) distillate fuel, for which the total, relative angular deviations of the sprayed fuel stream are, respectively, Δ_{ang} = 13.8% and Δ_{area} = 8.1%. The least favorable was for the engine fed with *RMD 80/L*

($F3$) residual fuel, Δ_{ang} = 83.3% and Δ_{area} = 65.0%.

9) The highest functional quality, evaluated a multi-criteria basis, by means of the synthetic variable Q_i, revealed *MDO* (*F5*) distillate fuel for which Q_i = 6.455498, the lowest one - RMD 80/S (F6) residual fuel for which Q_i = 2.267845. However, taking into account the highest price of MDO fuels, an alternative, rational solution is to apply the much cheaper *RMG* 380 (*F2*) residual fuel for feeding full-size marine engines, that takes the second position in the elaborated quality ranking of newly produced low-sulphur marine fuels (Q_i = 5.71843).

It might be generally concluded that on the basis of the experimental research program conducted, an innovative methodology for testing newly produced marine fuels was developed in real operating conditions of a diesel engine. This represents a kind of methodological guide for producers of marine fuels who will be able to comprehensively assess the suitability of their products for feeding marine engines. Shipowners of sea-going vessels will also be able to take advantage of this possibility before deciding to implement a new type of marine fuel into operation.

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