

Enhancing Fuel Efficiency and Environmental Specifications of a Marine Diesel When using Fuel Additives

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Abstract

Objectives: The article is aimed at discussing the results of application of marine motor fuel additives. Method: A method for improving fuel performance properties by applying fuel additives has been proposed. A 6N21L medium-speed four-stroke cycle diesel by Yanmar was used for this research. A RME25 marine fuel, viscosity of 25 sSt at 100°C and sulphur content of 2.8 w.w%, was applied. An additive containing active oxygen-bearing groups and modified with light metal salts was used as a fuel additive. Findings: Experiments were done, using three diesels of the same type, which allowed for one diesel to run on the basic fuel, and for feeding the additive-containing fuel into cylinders of two other diesels (following additional equipment of the fuel system with a flow meter and a dispenser). Specific fuel oil consumption, exit gas temperature, NO_x and SO_x concentration in the exit gases, and technical condition of fuel system and cylinder-piston group elements were determined in this experiment. It was shown that the use of fuel additives improves fuel efficiency of a marine diesel, in particular reduces specific fuel oil consumption by 3.5 to 5.8% subject to diesel load and additive concentration in the fuel. Improved environmental performance of the diesel, i.e. NO_x reduction by 1.4 to 4.3% and SO_x reduction by 15.6 to 22.9% in exit gases, was also found. It was shown that additive concentration is of optimal importance, can be determined experimentally and depends on diesel and fuel specification. Improvements: Improved technical condition of diesel cylinder-piston group and gas outlet system elements was determined as a result of visual inspection, thus reducing work labor input for diesel purging by 20 to 25%.

Keywords: Environmental Diesel Performance, Fuel Additives, Fuel Efficiency, Intensified Fuel Combustion, Marine Internal Combustion Engine, Marine Diesel Fuel, NO_x and SO_x Concentration in Exit Gases, Specific Fuel Oil Consumption, Thermal Diesel Factor

1. Introduction

Fluid liquid is the principal source of energy for heat engines of ship power plants (diesels, gas turbines and tanks). The results of implementation of various studies in possible use of carbon dust, dimethyl ether, rape oil and a number of other alternative fuels in ocean ship power plants are scarce. Moreover, such studies were done for internal combustion engines of rather low power (up to 50kW) that are installed in fixed power plants.

Effective and efficient operation of transport ships is affected directly by fuel cost, with the share of such cost in total financial operation costs being the largest¹. Optimized fuel consumption and improved utilization

efficiency due to activation of output performance of such fuel facilitates better performance of the whole propulsion unit².

Marine internal combustion engines are the most popular heat engines used in ocean and river ships. As compared with power plants of any other types (steam turbine and gas turbine), which are used to power a marine propulsion unit, marine diesels are known for their minimum fuel consumption per unit of power (kg/kW×h) and per unit of ship mileage (kg/mile).

Marine combustion engines are the largest consumers of fluid fuel. Power of main and auxiliary engines of ship power plants varies from a few hundreds to tens of thousands kilowatts. Daily fuel consumption by the main

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engine can be up to 200...500 tons per day, and up to 10...12 tons per day with auxiliary engines (the number of such engines may be up to four with three working simultaneously on modern ships) at average specific effective fuel consumption of 180...185 g/(kW×h). Even the slightest reduction of fuel consumption by 3...4 g/(kW×h) under the conditions ensures significant fuel saving and decrease in operating cost.

According to ISO DIS DP-8217, distillate fuels of two grades are used in marine combustion engines: DBM clean diesel fuel and DMC blended fuel, and also RM refined fuel. Viscosity of the DMB and DMC fuels ranges 5 to 10 sSt at 100°C and density of such fuels is 820...850 kg/m³ at 15°C. Therefore, such fuel grades are called light. Viscosity of the RM (RMG, RMH, RMK) fuels is 35...55 sSt at 100°C and density of such fuels is 990...1010 kg/m³ at 15°C, which makes them heavy fuels. Heavy grades are cheaper, as compared with light a grade, which determines their usage in marine diesels to cut fuel costs. One should also mention that fuel of heavy grades is used for operation of marine diesels in all conditions, including startup and reversal. Operation of diesels under the conditions can not be reliable, unless a fuel preparation process is applied. Complex fuel preparation for marine diesels is done, starting from felling ships and finishing with fuel feeding to the engine cylinder³.

2. Concept Headings

Modification of physical and chemical composition of a fuel is a way to treat the fuel and may be divided into:

1. decontamination; and
2. chemical treatment.

The first group involves sedimentation, separation and filtration and the second group involves introduction of fuel additives.

For now, design and technology of marine internal combustion engines reached perfection, ensuring lowest fuel consumption rates by heat engines of these types, as compared to other engines (steam generators and gas turbines). Thus and so, application of fuel additives is considered a way of enhancing fuel efficiency of diesels.

Numerous works^{4,5} were dedicated to an effect of fuel additives on heat engine performance, while application of additives even in such energy intensive and demanding power settings as nuclear power engineering was considered^{6,7}.

Fuel additives are designed to improve fuel performance, starting from pumpability and ending with flash point, while dispersing, enhanced lubricating power, and combustion process activation are primary functions of fuel additives. Place of introduction of additives into the fuel system (Figure 1) depends on overall system configuration, diesel specification and tasks such additives are designed for.

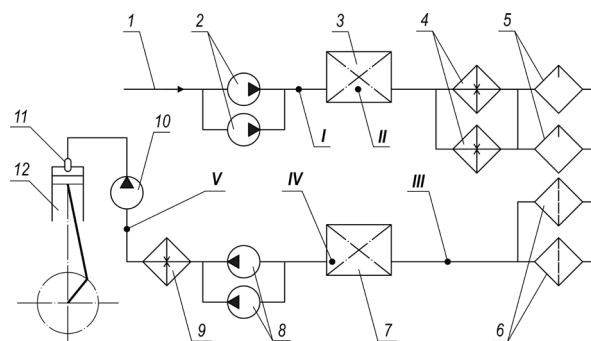
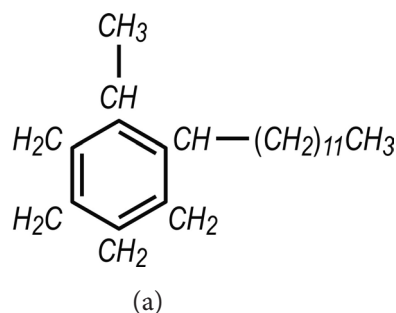


Figure 1. Possible points of introduction of additives into a marine diesel fuel system: 1 –feeder feed line; 2 – fuel pumps; 3 – slop tank; 4 – fuel heaters 5 – fuel separators; 6 – fuel filters; 7 – service tank; 8 – buster pumps; 9 – fuel heater; 10 – HP fuel pump; 11 – nozzle; 12 – diesel; I, II, III, IV, V – recommended points of introduction of additives.

Marine fuel additives are now rather popular on ships; however, their performance is not evaluated the same way. This is due to a variety of reasons, primarily marine diesel and diesel power unit specification and ensuring right application technology of additives.

Therefore, determination of an effect of fuel additives on power, economic and environmental properties of a marine internal combustion engine was the objective of this research.

Schematic fuel diagram for marine diesels may be presented in the form of monocyclic naphthene hydrocarbons comprising long low-branched (Figure 2a) or highly-branched (Figure 2b) side chains.



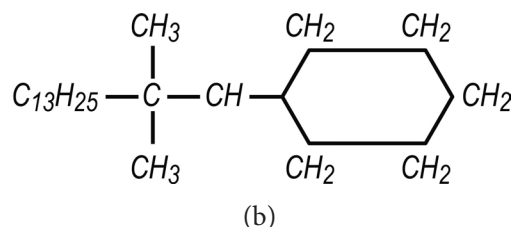


Figure 2. Schematic fuel diagram for marine diesels: a) low-branched side chain; b) highly-branched side chain.

Blend composition of additives is more than versatile, while manufacturers do not specify active substances. That said, general diagram of such additives may be illustrated with Figure 3, where R , R_1 , and R_2 designate substances that are purposely introduced into the compound (e.g. metals or metal salts). A benzene ring is the nucleus of such additives and breaks easily, while freeing active radicals.

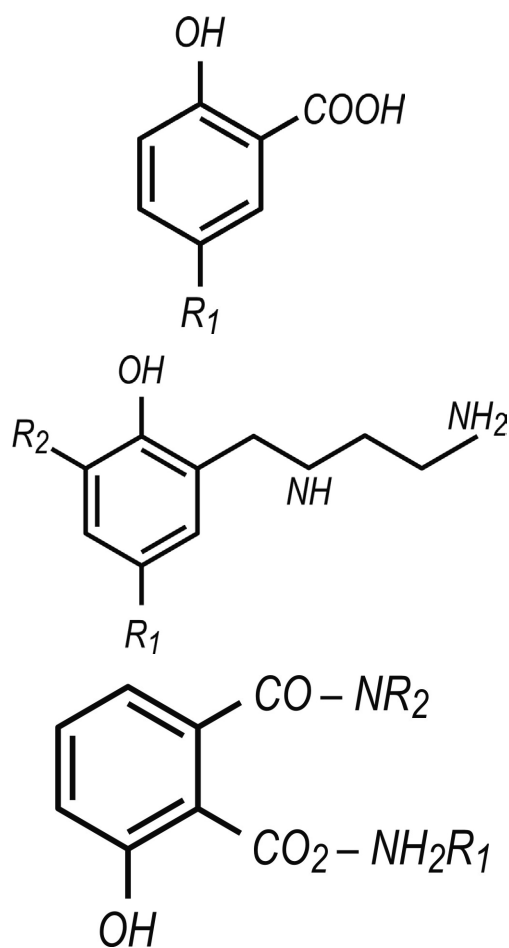


Figure 3. An example of schematic fuel additive diagram.

When additives are used to prevent microbiological

contamination of the fuel, additive components must ensure eradication of any organisms present in the fuel. And a slop tank (item *II* in Figure 1) is their primary place of introduction into the fuel system.

When fuel additives are used as friction modifiers, contributing to reduction of hydraulic resistance in piping and other elements of the fuel unit, soft metals (e.g., copper, tin or potassium) are freed from the additive and create a micron intermediate layer on friction surfaces, and facilitate generation of molecules of oriented structure close to the metal surface^{8,9}. For this purpose, additives may be introduced along the whole passage of fuel in the system (items *I*, *III*, *IV* in Figure 1).

When fuel additives are applied to reduced formation of heavy fraction deposit, they are introduced to a service tank (item *IV* in Figure 1).

When the additive is intended to intensify fuel combustion process, their mechanism of action is freeing O–O bonds and further use of oxygen to ensure fuel combustion. Organic compound with lower flash points are used as active components in such additives,^{10,11} which ensures self-ignition of the additive that is injected into the fuel in the diesel cylinder, before the main fuel portion ignites, and intensified fuel combustion. Weight fraction of carbon and hydrogen is 99.6...99.8 % in these additives, which increases total combustion heat of the fuel portion that is supplied to the diesel¹².

These additives also facilitate weakening of intramolecular bonds in the fuel. At the same time, fuel porosity is increased, thus creating additional conditions for penetration of oxygen and oxygen-containing groups into carbon and hydrogen fuel components. In its turn, oxidation of carbon components is intensified, and the combustion process offsets to the isochoric heat input line^{13,14}. An area upstream the HP power unit (HP fuel pump or nozzle pump) is the primary place of additive introduction into the fuel system - item *V* in Figure 1.

Improved fuel combustion and enhanced fuel efficiency of marine diesel may be achieved by additional fuel cavitation,^{15,16} installation of units that activate the fuel with a magnetic field that is generated by ferromagnetic elements,¹⁷ and by combustion of homogeneous fuel oil emulsions in the diesel cylinder¹⁸. Nevertheless, installation, maintenance and selection of optimum operating conditions of additional energy intensive equipment are required to implement the above methods¹⁹.

Application of additives is of special relevance to auxiliary engines that serve as electric generator drives. These engines are known for their high (as compared to main engines) crankshaft speed and continuous operation as a part of the marine power station (in cruising and harbor modes). The first parameter (high speed) reduces the time of fuel injection, and the second parameter (operation in the harbor mode in seaport waters) poses additional environmental requirements to diesels.

Studies under the conditions of a marine ship with its dead weight carrying capacity of 51,187 tons were done in a fuel system of a 6N21L diesel by Yanmar with the following specifications:

- type – vertical, water-cooled, 4-cycle diesel engine;
- cylinder bore – 210 mm;
- stroke – 290 mm;
- compression ratio – 15.8;
- rated speed of revolution – 720 min^{-1} (rpm);
- number of cylinder – 6; and
- power – 680 kW.

Marine power unit comprised three such diesels that served as diesel generators. This allowed for two diesels to be used for the experiments and one diesel left as the control one. Diesel fuel system schematic is given in Figure 4. For the purpose of this experiment, the fuel system was also equipped with a flow meter 3 and additive dispenser 4. Such way of feeding the additive into the fuel system ensured the required dispersion and even dissolution in the fuel.

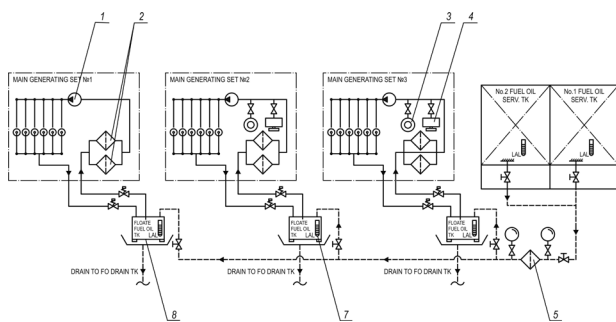


Figure 4. Marine fuel system (a fragment): 1 – HP fuel pump; 2 – fine mesh fuel filters; 3 – flow meter; 4 – additive dispenser; 5 – coarse mesh fuel filter; 7 – level meter; 8 – service tank.

Operation of the engines in experiments was concurrent, which allowed for maintaining equal load on the experimental diesels and on the control diesel. Load was $N_e=300\dots600$ kW at rated power of diesel generators

of $N_{enom}=680$ kW. Diesel power N_e was determined according to $N_e=N_g/\eta_g$ (where N_g – generator power, kW, η_g – generator efficiency). N_g readings were made by a watt meter located on the diesel generator control panel and η_g value was taken from the diesel generator specification and equaled to $\eta_g=0.915$.

To calculate specific fuel oil consumption (SFOC) value according to the level meter (item 7 in figure 4), which is located on each service tank (item 8 in figure 4), current fuel consumption G_{time} was determined. SFOC value was then calculated as $SFOC=G_{time}/(N_e \times t_{work})$, where t_{work} was experiment duration and N_e was averaged diesel power.

Diesel generators were equipped with a separate gas outlet system, which made installation of gas analyzers in the control diesel and experimental diesels possible. Gas analyzers were installed at the distance of 1.5 m from the gas output level in the diesel, which ensured equal temperature and gas flow into their measurement unit.

For the purpose of experiment equivalence, preliminary preparation was done for all diesels before testing. Operating conditions allowed for complete engine purge of the diesels one by one within 40 hours, thus preparing them for the experiment. At the same time, piston group (pistons and piston rings) and basic elements of the HP power system (precision pairs of the HP fuel pump plunger-bushing and needle-nozzle) were replaced in all diesels. Moreover, power unit control and adjustment was done for both engines before the experiments. At the same time, HP fuel pumps were adjusted for the same fuel injection advance angle and engine nozzles were set for the same needle lifting pressure. Operation time and working load on diesels was monitored for the whole duration of the experiment. Diesels were switched to stand-by one by one to ensure equal operation time of the diesels. Power discrepancy of diesel generators under study did not exceed 10kW by way of re-connecting power consumers, which may be considered a non-significant discrepancy and working conditions may be considered identical for such energy intensive items. Engines run on the fuel of the same grade. At the same time, automatic controls maintained continuous fuel viscosity for the duration of the experiment. The grade of circulation oil was also maintained identical, which ensured lubricating conditions and performance. These measures allowed for an assumption that the experiment was done under the same conditions.

The following parameters were primarily subjected to

control and determination: specific fuel oil consumption, exit gas temperature, NO_x and SO_x content in exit gases, and technical condition of power unit and diesel cylinder-piston group elements.

For the experiments, diesels run on the RME25 fuel with the following specifications:

- density (specific gravity) at $15/4^\circ\text{C}$ – 0.991;
- viscosity at 100°C – 25 sSt;
- flash point – $> 60^\circ\text{C}$; and
- sulphur content 2.8 massa %.

3. Results

Comprehensive research of the effect that additives have on power, economic and environmental properties of diesel fuel has produced the following results:

Specific fuel oil consumption was the primary parameter that was determined in our experiments. This parameter was measured at diesel load of 335, 390, 460, 530 and 585 kW, which corresponded to 0.49, 0.57, 0.68, 0.78 and $0.86N_{\text{enom}}$.

Ratios of specific fuel oil consumption and relative diesel power N_e/N_{enom} of a diesel that runs on a pure fuel (2) and a diesel that runs on an additive-containing fuel (1) are given in figure 5. These data are indicative of a significant SFOC reduction by the fuel additives, in particular in load conditions in the range of $(0.55\dots 0.7)N_{\text{enom}}$, which are most typical for diesel generators.

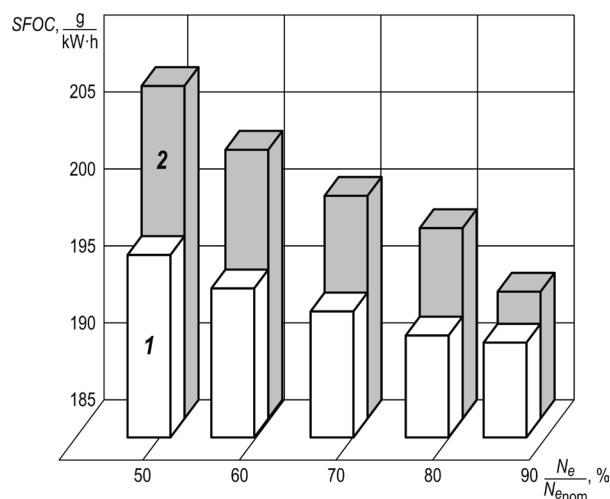


Figure 5. Specific fuel oil consumption and relative power N_e/N_{enom} ratios for a 6N21L diesel: 1 – an experimental diesel that runs on an additive-containing fuel; and 2 – a control diesel.

Dosing rates for the additives vary greatly and depend on the intended use of the additive and fuel system specification. Additives that are introduced into fuel tanks or individual sectors of fuel lines for biological effect on the fuel or reduction of hydraulic losses are used in the ratio of 1:8000...1:12500. Additives that improve the fuel combustion process are introduced in the ratio of 1:1000...1:8000. Dosing may vary in both cases, subject to engine configuration, operating state of the fuel system, fuel contamination rate in tanks, ultimate fuel composition (traces of vanadium, sodium and sulphur). Optimum additive dosing range is determined experimentally; therefore, the following additive and basic fuel ratios were selected: 1:2000, 1:3500, 1:5000, 1:6500 и 1:8000. In addition to the above, the lowest SFOC value was obtained for concentrations of 1:3500 and 1:5000, which were selected for further research. Characteristic SFOC curves for the 6N21L diesel for relative power N_e/N_{enom} for various additive concentrations in the fuel are given in Figure 6.

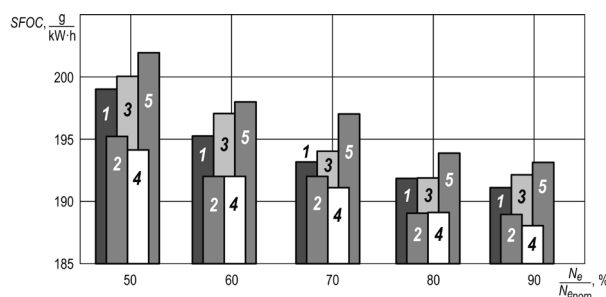


Figure 6. SFOC and relative power N_e/N_{enom} ratios for a 6N21L diesel for various additive concentrations in a fuel: 1 – concentration 1:2000; 2 – concentration 1: 3500; 3 – concentration 1:6500; 4 – concentration 1: 5000; 5 – concentration 1:8000.

These data are indicative of better carburation and combustion, and more complete use of additive-containing fuel heat content.

Determination of optimum additive concentration ranges for the fuel allowed us to conduct the next stage of our research, using the following alternative: a control diesel, an experimental diesel, running on additive concentration of 1:3500 and experimental diesel, running on additive concentration of 1:5000. At the same time, temperature of gases downstream a gas turboblower t_{gas} , and NO_x and SO_x concentrations in exit gases were determined.

Gas temperature at the engine output is a parameter that determines quality of the working cycle in the diesel cylinder and degree of thermal factor of its parts. This temperature is most often measured in the output line downstream the gas turboblower. Ratios of temperature of gases at the diesel output that has been averaged for all cylinders t_{gas} and relative diesel power N_e/N_{enom} are given in Figure 9. Measurements were made for the control diesel and experimental diesels, which run on the fuel containing the additive in the optimum concentration (1:3500 and 1:5000). According to Figure 7, application of additives to the fuel facilitates a reduction in temperature of gases at the diesel output, which is indicative of full fuel combustion and maximum use of heat energy of gases in the cylinder. One should also mark out a smaller deviation of gas temperature across cylinders from the averaged value $\square t_{\text{mid}}$, when the additive is used in the fuel. Thus, for the control diesel (at relative diesel power of $N_e/N_{\text{enom}}=78\%$) at $\square t_{\text{mid}}=397^\circ\text{C}$ this value is $\Delta t_{\text{mid}}^+=13^\circ\text{C}$, $\Delta t_{\text{mid}}^-=10^\circ\text{C}$, and for an experimental diesel at $\square t_{\text{mid}}=380^\circ\text{C}$ – $\Delta t_{\text{mid}}^+=8^\circ\text{C}$, $\Delta t_{\text{mid}}^-=6^\circ\text{C}$ (Figure 8).

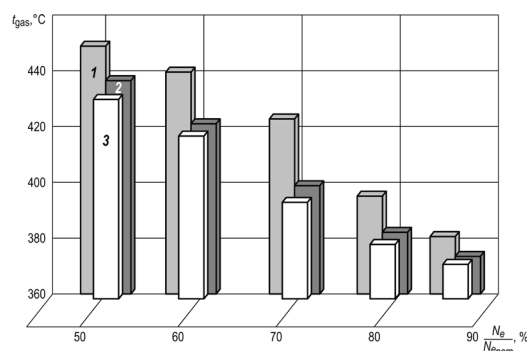


Figure 7. Ratios of averaged exit gas temperature t_{gas} across 6N21L diesel cylinder and relative diesel power N_e/N_{enom} : 1 – control diesel; 2 – experimental diesel (fuel with additive concentration of 1:3500); 3 – experimental diesel (fuel with additive concentration of 1:5000).

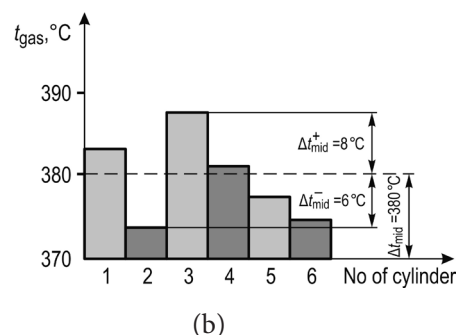
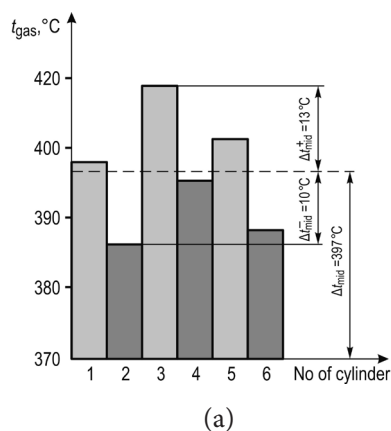


Figure 8. Exit gas temperature discrepancy across 6N21L marine diesel cylinders at different experiment conditions: a) control diesel (no fuel additive used); b) experimental diesel (fuel additive used).

Modern four-stroke diesels are operated, using fuels of medium (180...380 sSt) and high (up to 500 sSt) viscosity. Diesel startup and ship maneuvering conditions, which require solid self-ignition in the diesel cylinder against variable thermal conditions of cooling, are an exception. Long diesel run on DMB and DMC fuels of low viscosity 5...10 s ST is only typical for environmentally safe regions and it is associated with satisfaction of the requirements of Annex IV of MARPOL²⁰⁻²². Fuels that are used for diesel operation in these regions also have low sulphur content. These fuel grades exhibit lower lubricating power,^{23,24} which increases losses in HP power units and requires higher energy supply of such units²⁵.

The use of additives containing active functional groups and modifying metal surface in the friction zone (in the plunger-bushing pair of the HP pump) creates a micron intermediate layer on the surfaces of HP power units and facilitates generation of additional disjoining forces²⁶. These forces ensure marginal friction regime that excludes any direct surface contact and increases hydraulic density in the plunger-bushing pair²⁷.

Moreover, shifting from one diesel fuel grade to another is associated with current problem of fuel compatibility in marine power engineering, which is especially relevant for four-stroke engines²⁸. Power units of marine diesels demonstrate high precision accuracy, requiring high fuel homogeneity²⁹.

The use of fuel additives that modify metal surfaces in the friction zone prevents diesel from switching to a lower viscosity fuel in conditions that correspond to transient loads and pre-decommissioning conditions³⁰.

Marine emission of harmful substances in exit gases

is a burning problem^{31,32}, and a solution of such problem must ensure environmentally friendly performance of marine diesels in the world's oceans and seas³³ and special regions^{34,35}. Therefore, the effect of fuel additives on environmental properties of the diesel, i.e. SO_x and NO_x content in exit gases, was determined in research. Findings are given in Figures 9 and 10.

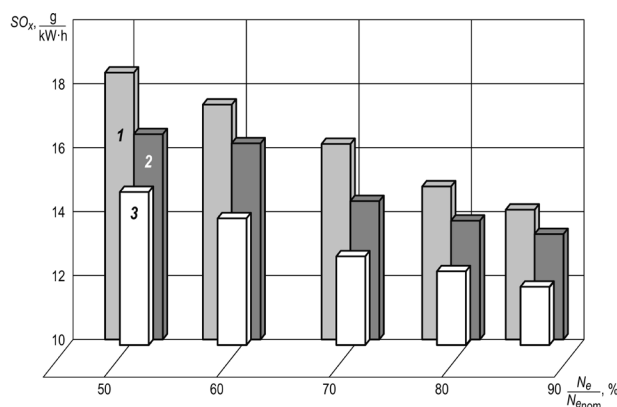


Figure 9. SO_x concentration change in exit gases of a 6N21L marine diesel and relative capacity of the diesel N_e/N_{enom} : 1 – control diesel; 2 – experimental diesel (fuel with additive concentration of 1:3500); 3 – experimental diesel (fuel with additive concentration of 1:5000).

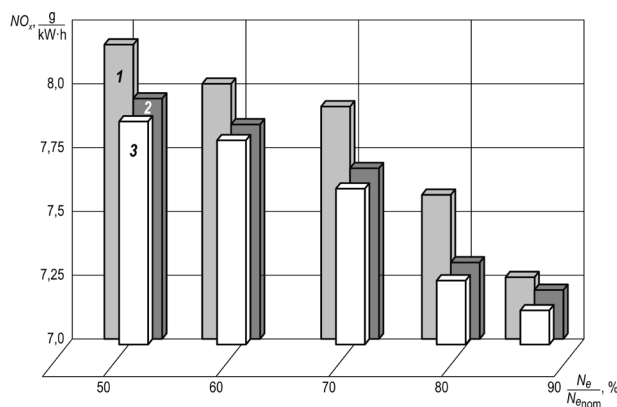


Figure 10. NO_x concentration change in exit gases of a 6N21L marine diesel and relative capacity of the diesel N_e/N_{enom} : 1 – control diesel; 2 – experimental diesel (fuel with additive concentration of 1:3500); 3 – experimental diesel (fuel with additive concentration of 1:5000).

The results given in Figures 9 and 10 are indicative of improved environmental performance of the diesel; at the same time, the best reduction in harmful emissions between experimental and control diesels is observed in the load range of 65 to 80%, which is most typical for operation of auxiliary marine engines.

Improved technical condition of the diesel and power units was visually determined in our experiments, when fuel additives were used. Thus, it was observed in the process of diesel engine purge that cylinder-piston group elements of the diesel that runs on the fuel additive demonstrated less carbon deposits on the heating surfaces (in particular, on the piston cap, cylinder lid and more flexible piston rings), as compared to the diesel that runs on the additive-free fuel. Moreover, almost no carbon deposits were observed around nozzle openings and injection nozzles were less worn out in the diesel that used the fuel additive. This is again indicative of intensified carburation and combustion, when the additive-containing fuel was used.

4. Discussion

Our results correspond to the similar work done in this field,^{36,37} which confirms that the offered model is adequate and the hypothesis is correct.

Experimental results that prove SFOC reduction, when fuel additives are used, is indicative of intensified carburation and combustion process. At the same time, different SFOC reduction is observed for different additive concentration in the basic fuel. We contribute it to the fact that some free additive radicals remain unengaged in disruption of intramolecular bonds of the fuel and combustible ingredient activation.

Reduced exit gas temperature is also the result of improved fuel combustion process and this process offset to the isochoric heat input line. This is due to fuel additives facilitating the combustion process in the diesel cylinder along the stationary-state combustion line, instead of chain reaction line resulting in detonation³⁸.

SFOC decrease and associated full use of fuel heat content reduces the amount of fuel that is burned out in process of expansion and in the outlet collector, which is indicated by visual control of gas outlet surface state. Similar results were also observed in other studies³⁹.

Decreased gas temperature, when using an additive-containing fuel, improves environmental diesel performance. In particular, this leads to reduced NO_x and SO_x concentration in exit gases. Our results corresponds to theoretical^{32,40} and experimental⁴¹ data of the research done in this field.

Improved technical condition of HP power unit elements (precision plunger-bush and nozzle-nozzle

needle pairs), which is observed for fuel additives used, is due to increased lubricating power of the fuel⁴². Disjoining pressure is generated at the same time, which prevents direct surface contact.

All the above results were obtained for experimental studies done, using a 6N21L four-stroke cycle marine diesel by Yanmar.

5. Conclusion

Therefore, the following conclusions are possible, based on the results presented:

1. The use of fuel additives, which may be added to the fuel system in various points: a slop tank, a feed tank, fuel line or immediately before feed to a diesel cylinder (HP diesel pump upstream), is a method of improving fuel performance properties.
2. The use of fuel additives leads to an improved fuel efficiency of a marine diesel. Thus, SFOC reduction by 3.5 to 5.8% may be achieved, when using fuel additives for various four-stroke diesel conditions. At the same time, maximum increase in fuel efficiency of 50 to 60% of the diesel load, i.e. in conditions of the longest operation and high thermal factor, is gained. By using fuel additives, not only total fuel consumption is reduced, but also exit gas temperature drop by 3.3 to 7.2 % and lesser temperature shift across diesel cylinders are facilitated, thus equalizing heat load on individual cylinders.
3. Environmental diesel performance is greatly improved, when fuel additives are used. Thus, the use of additives facilitates exit gas NO_x concentration decrease by 1.4 to 4.3%. Moreover, exit gas SO_x concentration is reduced by 15.6 to 22.9%, when fuel additives are used. The above facts are of special importance with view to the requirements of Annex IV MARPOL73/78 and particularly for four-stroke diesels that operate for along time in off-shore strips and seaport waters.
4. The use of fuel additives facilitates improved technical condition of diesel cylinder-piston group elements and gas outlet system and reduces work labor input for diesel purging by 20 to 25%.
5. Additive concentration is optimum; it is determined experimentally and depends on diesel and fuel specification.

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