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ANALYSIS OF THE OPERATION OF MARINE DIESEL ENGINES WHEN USING ENGINE OILS WITH DIFFERENT STRUCTURAL CHARACTERISTICS

The object of research is the process of lubrication of marine trunk diesel engines. The subject of research is marine diesel engine oils, which provide lubrication, cooling and separation of friction surfaces.

The analysis of the operation of marine diesel engines using motor oils with different structural characteristics is carried out. The studies are carried out on Yanmar 6EY18AL diesel engines of a Multipurpose Vessel class ship with deadweight of 27540 tons. The objective of research is to determine the effect of the structural characteristics of the oil layer (contact angle and thickness) on the performance parameters of a marine diesel engine and the performance characteristics of the oil used in its circulating lubrication system. At the same time, the compression pressure, the concentration of nitrogen oxides in the exhaust gases, and the temperature of the exhaust gases after the cylinder are considered as the operating parameters of the diesel engine; as performance characteristics of the oil – its Base Number, as well as its Wear and Contaminant Elements. The studies are carried out on two diesel engines of the same type, in the circulating lubrication system of which oils with different structural characteristics were used. Structural characteristics of the oil layer were determined by ellipsometry. The operational characteristics of the diesel engine – using the Doctor diagnostic system. Oil performance – by spectrographic analysis. It has been established that an increase in the contact angles of wetting and the thickness of the oil layer improves the heat and power and environmental performance of a diesel engine. At the same time (for the period of operation of diesel engines 500–1000 hours), the decrease in compression pressure in the cylinder slows down, the temperature of gases after the cylinder decreases, and the emission of nitrogen oxides with exhaust gases decreases. In addition, the wear of diesel parts and oil oxidation are reduced.

The information obtained in the course of the study on the structural characteristics of motor oils will provide the possibility of their selection and further use of those that will contribute to a better maintenance of the operational performance of marine diesel engines.

Keywords: *marine trunk diesel engines, lubrication of marine diesel engines, engine oil, lubricating layer thickness, wetting contact angle.*

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1. Introduction

Internal combustion engines (diesels) are the most common heat engines used on ships of sea and inland water transport [1, 2]. Depending on the layout of the crank mechanism, diesel engines are divided into crosshead and trunk. Crosshead diesel engines perform the functions of the main engines – they transfer their power to the propeller and provide the ship movement. The effective power of trunk diesel engines can be converted either into the rotation of the screw, or into the rotation of the rotor of an electric generator. In the first case, they (like crossheads) are considered the main engines. In the second – auxiliary and provide electrical energy to ship mechanisms, systems, navigation equipment.

Crosshead diesel engines are installed on sea ships with a deadweight of 10,000 tons and above, trunk diesel engines (due to the fact that they ensure the operation of electric generators) – on all ships, regardless of their deadweight, class and purpose [3–5].

The functioning of marine diesel engines is provided by the fuel system and air supply system (which provide the combustion process), the oil system and fresh and sea water cooling systems (which provide lubrication and cooling modes), as well as the exhaust gas removal system.

Depending on the design, marine diesel engines have two or one lubrication system. In crosshead diesel engines (which operate on a two-stroke cycle), lubrication of the cylinder group is provided by a lubricating lubrication system; lubrication of the crankshaft, frame, crank, crosshead bearings, as well as piston cooling – by a circulation system [6, 7]. In trunk diesel engines (which operate on a four-stroke cycle), lubrication of all elements is provided by only one circulation system [8, 9].

The movement of oil in the circulation system during lubrication of the frame and crank bearings occurs along the internal drillings of the crankshaft, and the head – along the drillings in the connecting rod (Fig. 1). In this case, the lubrication circuit inside the shaft and connecting rod is closed and the movement of oil inside the shaft and connecting rod occurs without leakage. The lubrication of bearing assemblies is accompanied by oil leakage from the liner-shaft interface, due to the fact that at these points the circuit becomes open, and the oil is subjected to internal (from the circulation pump) and external (from the pressure of the shaft and connecting rod) forces. The oil, which is in the liner-shaft interface, provides hydraulic tightness and prevents direct contact of this friction pair.

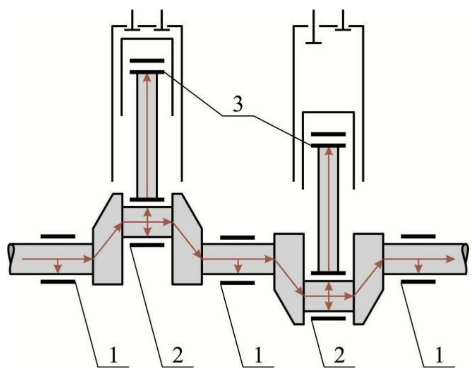

Fig. 1. The movement of oil in the circulation system (fragment): 1 – frame bearing; 2 – crank bearing; 3 – head bearing

An increase in leakage in the liner-shaft interface reduces the damping properties of the oil, which can lead to increased wear of the liners and an increase in oil consumption for waste. Metal particles that enter the oil as a result of wear of the liners move in the circulation system in the oil flow. At the same time, they contribute to an increase in the intensity of wear in friction pairs and accelerate the process of oil oxidation [10, 11].

The process of lubrication of marine diesel engines is one of the main ones that ensure its functioning, as well as reliable and safe operation. Violation of the lubrication process (a critical decrease in pressure or a critical increase in oil temperature) can lead to an increase in thermal and mechanical stresses and an emergency situation (breakage of piston rings, piston jamming in the cylinder, rotation of bearing shells). The importance of the lubrication process is confirmed by the following fact: in the event of a «blackout» of the ship, one of the mechanisms that the emergency generator must ensure is the oil pump of the circulating lubrication system. Reliable operation of lubrication systems for marine trunk diesel engines ensures the safe operation of the entire marine ship [12, 13]. Trunk diesel engines (which perform the functions of ship auxiliary generators) provide electrical energy for navigation equipment, cargo devices, and a steering gear. Even a short stop of these diesel engines (both during the sea/ocean passage and while staying in the port/on the roads) can lead to a serious accident (collision of ships, damage to the ship and ship equipment, disruption of cargo operations, environmental pollution of the sea and coastal area). Therefore, maintaining reliable and safe operation of lubrication systems for marine trunk diesel engines (as one of the main systems that ensure their operation) is an urgent scientific and applied task.

2. The object of research and its technological audit

The object of research is the process of lubrication of marine trunk diesel engines.

The subject of research is marine diesel engine oils, which provide lubrication, cooling and separation of friction surfaces.

The shaft-bearing bushing system of a marine internal combustion engine belongs to the standard tribological system. This system consists of two metal surfaces that are separated by a layer of oil. Such a system is characterized by:

– composition (surfaces and their properties);
– internal connections (hydrodynamic or boundary regime of lubrication/friction);
– external connections (radial and tangential forces that act from the side of the crankshaft);
– functional characteristics (the presence of an oil film between the surfaces and the absence of contact between them) [14, 15].

Engine oil, which is included in the shaft-bearing shell system, is characterized by structural and mechanical strength and resistance to external loads. Both of these properties of the oil ensure reliable and safe operation of trunk-type diesel engines of marine transport ships. Structural and mechanical strength increases the lubricity of engine oil. Resistance to external loads prevents direct contact between the bearing and shaft surfaces. Both properties increase the hydraulic density in friction units and are clearly manifested precisely for an open lubrication circuit.

The hydraulic density of the metal-oil-metal triad depends on the structural composition and physical characteristics of the oil. These, first of all, include the ability of the oil layer to create a wedging pressure, as well as to prevent spreading over the lubrication surface. The last property (as for any liquid) is determined by the surface tension and wetting angles of the oil layer θ. An increase in the contact angles θ proportionally increases the surface tension forces and prevents oil from flowing out of the tribological interfaces (Fig. 2).

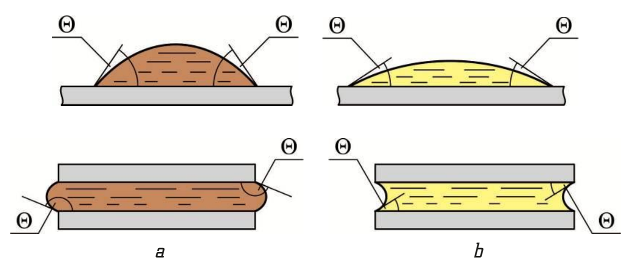

Fig. 2. Influence of contact angles q on the shape of the oil layer: *a* – on the surface; *b* – in tribological conjugation

An increase in the contact angles of wetting both on the open surface (at the metal-oil-air phase boundary) and between the surfaces (at the metal-oil-metal phase boundary) contributes to an increase in the surface tension force, a decrease in oil leakage, and an increase in the bearing capacity of the oil layer [9, 16, 17].

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3. The aim and objectives of research

The aim of research is to determine the influence of the structural characteristics of engine oil (contact angle and thickness) on its performance and performance parameters. At the same time, Total Base Number (TBN), as well as Wear and Contaminant Elements, are considered as oil performance characteristics. The operating parameters of a diesel engine are the compression pressure, the concentration of nitrogen oxides in the exhaust gases and the temperature of the exhaust gases after the cylinder.

To achieve this aim, it is necessary to solve the following objectives:

1. Determine the structural characteristics of motor oils (contact angle and layer thickness) when applied to an open metal surface.
2. Determine the dynamics of wear of diesel parts and contamination of engine oil.
3. Determine the dynamics of changes in the operating parameters of the diesel engine.

4. Research of existing solutions to the problem

Ensuring reliable and safe operation of lubrication systems for trunk diesel engines of marine transport ships is possible by controlling either metal surfaces (cylinder liner, piston rings, bearing shells) or oil.

The control action on metal surfaces can be carried out:

1) by making them or coating them with metals with high hardness – molybdenum, chromium, copper, titanium, vanadium [18, 19];

2) drawing a regular microrelief on them [20, 21];

3) changing their geometry [22, 23].

These methods provide the desired effect, but have certain disadvantages. In the first case, the hardness of local parts of diesel engine parts (the upper part of the cylinder liner, the edges of the piston ring) increases, which reduces their wear [24, 25]. However, the cost of metals that are applied to the surface significantly exceeds the cost of steel alloys from which diesel engine parts are made. The second technology reduces the coefficient of friction between the surfaces and increases the intensity of oil movement between them. This requires special equipment that provides a constant depth and the same step of applying a regular microrelief [26, 27]. In the third case, dry and boundary are excluded, and the hydrodynamic lubrication regime in the metal-oil-metal triad is constantly provided. However, in this case, a change in the geometry of parts reduces their strength [28, 29]. In this regard, the given technologies have a single character.

The control effect on engine oil, which is used in the lubrication systems of trunk diesel engines of marine transport ships, is carried out by dissolving special additives in its volume. This activates the intermolecular forces of the oil and contributes to the occurrence of additional disjoining pressure in the oil layer. The use of this technology requires a preliminary determination of the optimal concentration of additives in the oil, as well as the installation of additional equipment in the oil system, which ensures dosing of the additive [30, 31].

One of the ways to control the metal-oil-metal triad is to apply special liquid antifriction coatings to the metal surface [32, 33]. At the same time, the structure of oil films changes, which ensures reliable and safe operation of trunk-type diesel engines of marine transport ships.

The above technologies were developed and implemented for road transport, as well as for stationary energy (diesel engines and turbines of thermal and electric stations). These technologies have not been adopted for marine diesel engines. First of all, this is due to the autonomy of the operation of sea ships and their power plants, as well as to the periodic replacement of the ship's crew. The first limits logistics (there are problems with the delivery of the required materials to ships), the second forces training for ship engineers on the operation of special equipment.

Comprehensive studies (which make it possible to establish the relationship between the structural characteristics of motor oils and the operational parameters of marine diesel engines) are of a single nature and do not have a systematic approach to this problem.

5. Methods of research

The research was carried out in two stages:

1) in a scientific laboratory, the structural characteristics of various motor oils, as well as the content of wear products and contaminants in the oil, were studied;

2) on a marine transport ship, the effect of motor oils with different structural characteristics on the operational parameters of marine diesel engines was studied.

Determining the contact angles θ, as well as the thickness of the oil layer d_{oil}, is possible using an ellipsometric method by analyzing the light rays reflected from the oil and from the surface (Fig. 3) [34, 35].

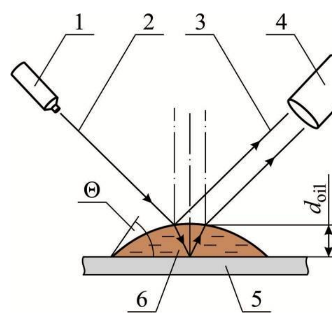

Fig. 3. Schematic diagram of determining the contact angles θ and the thickness of the d_{oil} of oil layer using an ellipsometric method: 1, 4 – elements of the ellipsometric unit; 2 – linearly polarized light; 3 – elliptically polarized light; 5 –metal surface; 6 – oil layer

Currently, there are electronic ellipsometric setups that make it possible to measure these parameters with high accuracy [36].

Studies were carried out for Total Lub Marime AURELIA TI 15/30 and LukLub Marime NAVIGO TPEO 15/30 motor oils. The main characteristics of motor oils are given in Table 1.

Using the optical method of ellipsometry (the scheme of which is shown in Fig. 3), the values of the contact angles of wetting and the thickness of the oil layer were determined. These values are given in Table 2.

Determination of contact angles and thickness of the oil layer was carried out for a volume of oil (equal to 2 ml) deposited on a metal surface polished to a high accuracy class.

The second stage of research was carried out on a Multipurpose Vessel class marine vessel with deadweight of 27,540 tons, the auxiliary power plant of which consisted of three Yanmar 6EY18AL medium-speed marine diesel engines of the same type with the following characteristics:

– cylinder diameter – 180 mm;
– piston stroke – 280 mm;
– rotation frequency – 1000 rpm;
– rated power – 800 kW;
– specific fuel consumption – 193 g/(kWh).

The diesel engines were operated using RME180 and DMAULS marine fuels. Their main characteristics are given in Table 3.

Table 1

Main characteristics of motor oils*

Indicator	Total Lub Marime AURELIA TI 15/30	LukLub Marime NAVIGO TPEO 15/30
SAE grade	30	30
Density at 15 °C, kg/m^3	910	898
Viscosity at 100 °C, sSt	14.1	11.5
Total Base Number (TBN)	14.2	14.2
Flash Point, °C	230	230

Note: * – further in the work, engine oils are arbitrarily designated as Engine oil 1 and Engine oil 2

Table 2

Structural characteristics of motor oils

Parameter	Engine oil 1	Engine oil 2
Wetting angle, θ, grad	20.4	17.5
Oil layer thickness, d_{oil}, mm	3.9	2.6

Table 3

Main characteristics of marine fuels

Parameter	RME180	DMAULS
Density at 15 °C, kg/m^3	935	879
Viscosity at 50 °C, sSt	72.4	5.75
Sulphur, %	0.42	0.065
Net Specific Energy Calc, MJ/kg	41.75	42.38

The operation of diesel engines when the ship was in special environmental areas (Sulphur emission control area – SECA) was carried out on DMAULS fuel. When operating outside ecological areas, RME180 fuel was used [37, 38].

The ship's needs for electricity were provided by one (in the case of a load of up to 500 kW) or two auxiliary engines operating in parallel (in the case of a load of more than 500 kW). The studies were carried out in operating modes when two diesel engines were used. The parallel operation of diesel engines ensured an equal distribution of the load between them. The third diesel engine was either in the stand-by state or was operated at the required load (in the case when one diesel engine was enough to provide power to consumers), while the first and second diesel engines were not in operation.

Providing lubrication regimes for diesel engines of this type is possible with the help of various motor oils that have a viscosity of 12–17 sSt, a base number of 14–17 mgKOH/gOil and belong to the SAE class 30–40.

Diesels had a common fuel system (in which all three diesels were operated on the same grade of fuel) and autonomous oil systems. This made it possible for the two diesel engines on which the studies were carried out to use different engine oils.

Total Lub Marime AURELIA TI 15/30 engine oil was used in the system of one of the diesel engines, LukLub Marime NAVIGO TPEO 15/30 engine oil was used in the lubrication system of the second one. Both motor oils are recommended by Wartsila, MAN Diesel, Caterpillar MaK, Yanmar, Daihatsu, Himsen for use in marine trunk diesel engines.

Before the start of the experiments, the diesel engines were in the same technical condition. On diesel engines, parts of the cylinder-piston group (cylinder bushings, pistons, piston rings) and the crank mechanism (connecting rods and crank bearing shells) were reinstalled.

The studies were carried out during ocean crossings of the ship, the duration of which was 12–18 days. At the same time (due to the absence of shunting and mooring modes, as well as cargo operations), the operation of diesel engines occurred without an abrupt change in load [39].

The condition of the fuel equipment (high-pressure fuel pumps and injectors), as well as its adjustment parameters (discharge pressure, fuel supply start angle) of all diesel engines were identical. In the lubrication and cooling systems of diesel engines, the same values of temperature and pressure were maintained. Before the start of the experiments, the oil in the circulation systems of diesel engines was completely replaced. Compensation for oil consumption for waste for each of the diesel engines was carried out in the amount of 100 liters after 100 hours of operation.

6. Research results

During the experiment, the values of the following diesel performance indicators were recorded: compression pressure – p_c, gas temperature after the cylinder – t_g, concentration of nitrogen oxides in the exhaust gases NO_X, as well as oil *TBN* [40, 41]. In addition, a spectral analysis of the oil was performed at the onshore laboratory in order to determine the amount of impurities (Wear and Contaminant Elements) in it [6, 42].

The *TBN* (ore base number – *BN*) index characterizes the base number and the amount of anti-corrosion additives dissolved in the oil. The value of *BN* is in the range of 5–100, these numbers express the number of milligrams of potassium hydroxide KOH dissolved in a gram of oil – mgKOH/gOil. The higher the *BN* value, the higher the anti-corrosion properties of the oil. Oil with a high *BN* value (40 or more) is used in two-stroke engines as cylinder oil. Such oil should neutralize the effect of sulfuric H_2SO_4 and sulfurous H_2SO_3 acids, which are formed in the cylinder during fuel combustion. In circulation systems (both two and four-stroke diesel engines), oil with a content of *BN*=5–25 is used, since in such systems the main function of the oil is to provide lubrication of the crankshaft bearings.

During the experiment, the control and diagnosis of the technical condition of the oil was carried out by determining *BN* three times with a sampling interval of 1 hour. The average values of the obtained results of the experiment are given in Table 4.

For all measurement intervals (from 100 to 1000 hours), the *BN* value for diesel AE 2 exceeded the similar value for diesel AE 1. A comparative assessment of the change in

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BN of diesel engines AE 1 and AE 2 can be performed by its relative change, which is determined by the expression:

$$\Delta BN = \frac{BN_{time} - BN_{nom}}{BN_{nom}} \cdot 100\ \%,$$

where BN_{time}, BN_{nom} – the *BN* value in a certain period of time and the nominal value (both grades of oil have BN_{nom}=14.2 – Table 2).

The values of ΔBN are given in Table 4.

The values of the Table 4 show nomograms of the change in *BN* and ΔBN of motor oils – Fig. 4, 5.

Table 4

Changes in *BN* and ΔBN of motor oils under different experimental conditions

Time, h	Engine oil 1		Engine oil 2	
	BN	ΔBN, %	*BN*	ΔBN, %
100	14.1	–0.70	14.0	–1.41
200	13.7	–3.52	13.6	–4.23
300	13.1	–7.75	13.0	–8.45
400	12.8	–9.86	12.6	–11.27
500	12.6	–11.27	12.3	–13.38
600	12.3	–13.38	11.9	–16.20
700	12.0	–15.49	11.5	–19.01
800	11.8	–16.90	11.0	–22.54
900	11.5	–19.01	10.7	–24.65
1000	11.3	–20.42	10.4	–26.76

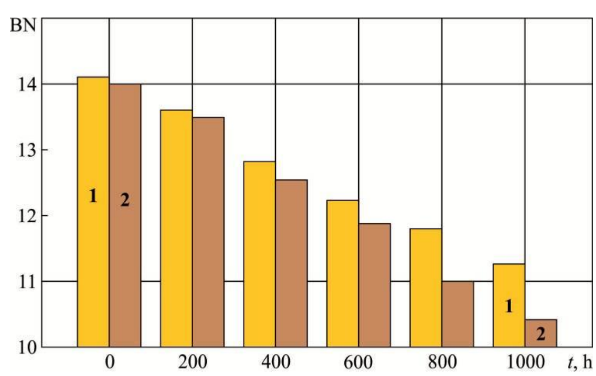

Fig. 4. Change in *BN* of marine motor oils:
1 – Engine oil 1; 2 – Engine oil 2

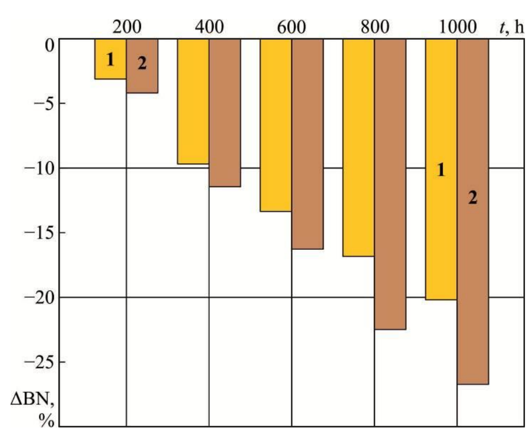

Fig. 5. Relative reduction in ΔBN of marine motor oils:
1 – Engine oil 1; 2 – Engine oil 2

For a better assessment of the condition and determination of the functional characteristics of engine oil, its spectral analysis is performed. This determines the amount of various chemical elements that enter the oil as a result of fuel combustion, wear of diesel parts, and also as a result of direct oxidation of the oil itself. Some of these elements (in accordance with their functional action) are classified as Wear Elements, and some are classified as Contaminant Elements. The results of the spectrographic analysis of engine oils after 1000 hours of operation in the circulation system of the Yanmar 6EY18AL diesel engine are shown in Table 5.

According to the results of Table 5, the nomograms in Fig. 6 are constructed.

Table 5

The results of the spectrographic analysis of engine oils after 1000 hours of operation in the circulation system of the Yanmar 6EY18AL diesel engine

Wear Elements, mg/kg	Engine oil 1	Engine oil 2	Contaminant Elements, mg/kg	Engine oil 1	Engine oil 2
Al (Aluminum)	5	7	B (Boron)	15	17
Cr (Chromium)	1	2	Na (Sodium)	9	23
Cu (Copper)	1	9	Si (Silicon)	4	16
Fe (Iron)	9	23	V (Vanadium)	20	62
Sn (Tin)	1	3	Mo (Molybdenum)	3	4
Pb (Lead)	1	1	Ni (Nickel)	4	21
Sum	18	45	Sum	55	143

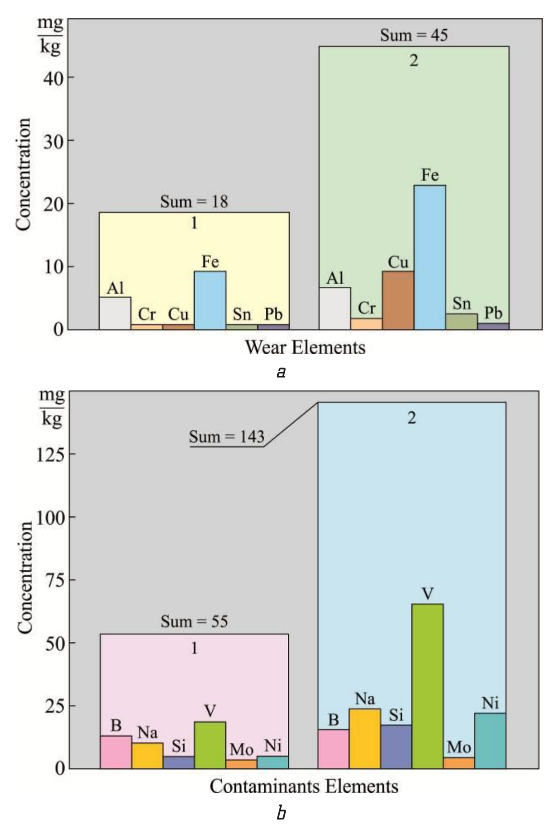

Fig. 6. Results of spectral analysis of motor oils:
a – wear elements; *b* – contaminant elements; 1 – Engine oil 1;
2 – Engine oil 2

The determination of the dynamics of changes in the structural characteristics of engine oil (the contact angle and the thickness of the oil layer) was carried out in a scientific laboratory using an ellipsometric unit (Fig. 3). In this case (similar to previous studies), an oil sample (in a volume of 2 ml) was applied to a metal surface polished to a high accuracy class. Oil sampling was carried out at three different points of the diesel crankcase when it was stopped in the interval of time intervals equivalent to 500 and 1000 hours of operation. The average values of the structural characteristics of engine oil (the contact angle θ and the thickness of the oil layer d_{oil}) are given in Table 6.

Table 6

Dynamics of changes in the structural characteristics of motor oils

Operating time, h	Wetting angle, θ, grad		Oil layer thickness, d_{oil}, mm	
	Engine oil 1 (Diesel AE 1)	Engine oil 2 (Diesel AE 2)	Engine oil 1 (Diesel AE 1)	Engine oil 2 (Diesel AE 2)
0	20.4	17.5	3.9	2.6
500	17.8	12.2	3.1	2.0
1000	16.3	9.7	2.7	1.8

According to Table 6, the constructed nomograms show the dynamics of changes in the structural characteristics of engine oil – Fig. 7.

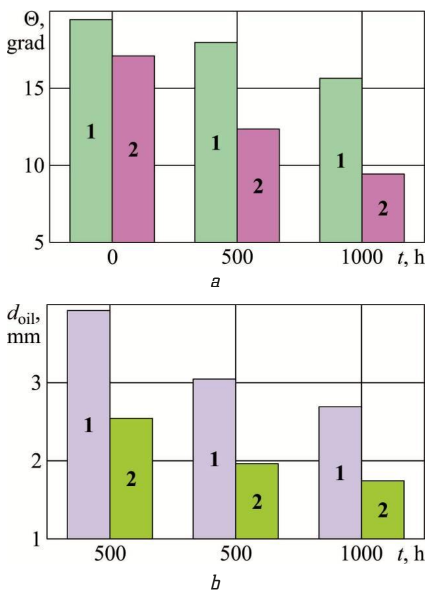

Fig. 7. Dynamics of changes in the structural characteristics of motor oils: *a* – wetting angle, θ, grad; *b* – oil layer thickness, d_{oil}, mm; 1 – Engine oil 1; 2 – Engine oil 2

One of the indicators that characterize the performance of a diesel engine is compression pressure. Its decrease in individual diesel cylinders indicates deterioration in the compression properties of the piston rings, the ingress of metal impurities on the surface of the cylinder liner. A decrease in compression pressure in all cylinders indicates deterioration in the lubrication process.

During the experiment, the value of the compression pressure was determined using the Doctor Ship diagnostic system for each of the diesel cylinders (with the fuel supply to this cylinder turned off). Based on the obtained values, the average value of the compression pressure was calculated. Compression pressure control was performed after the 1st hour of diesel operation and then every 100 hours of operation. At the time intervals at which the compression pressure was controlled (1, 100, 200, 300, 400, 500 hours), diesel engines operated at different, but identical loads (in the range of 450–600 kW). The Doctor diagnostic system allows controlling the parameters of the diesel engine working process with an error of ±1.0 % [43, 44]. The obtained values are given in Table 7.

Table 7

Change in average compression pressure, p_c, MPa, of Yanmar 6EY18AL diesel engine under different experimental conditions

Time, h	Engine oil 1 (Diesel AE 1)	Engine oil 2 (Diesel AE 2)
1	9.17	9.17
100	9.14	9.12
200	9.12	9.06
300	9.11	9.03
400	9.09	8.98
500	9.08	8.94
600	9.07	8.91
700	9.07	8.87
800	9.06	8.85
900	9.05	8.83
1000	9.05	8.82

Separately, let's note that the main criterion in Table 7 is not the change in pressure over time for one of the diesel engines (AE 1 or AE 2), but the pressure over the same period of time for different diesel engines (AE 1 and AE 2). The discrepancy in the values of these values indicates deterioration in the technical condition of the diesel cylinder-piston group.

According to the operating rules, the mismatch of the compression pressure in the diesel cylinders from the average value should not exceed ±2.5 %. The values given in Table 7 indicate that this condition was satisfied during the entire experiment.

To visualize the results obtained, according to the values of Table 7 the diagrams are constructed in Fig. 8.

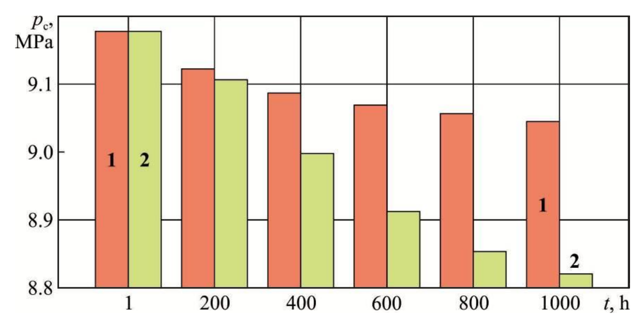

Fig. 8. Change in compression pressure, p_c, MPa, Yanmar 6EY18AL diesel engine under different experimental conditions: 1 – AE 1 diesel engine; 2 – AE 2 diesel engine

During operation, there is a gradual decrease in compression pressure. This is due to a decrease in the compression action of the piston rings and the gradual wear of the cylinder liners. The range of this decrease for the AE 1 diesel engine over a period of 1–500 hours was from 9.17 MPa to 9.05 MPa; for AE 2 diesel engine from 9.17 MPa to 8.82 MPa. The intensity of the compression

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pressure drop over time can be defined as the relative reduction in compression pressure by the expression:

$$\Delta p_c = \frac{p_c^{time} - p_c^{nom}}{p_c^{nom}} \cdot 100\ \%,$$

where p_c^{time}, p_c^{nom} – value of the compression pressure in the diesel cylinders in a certain period of time and the nominal value of the compression pressure, MPa (according to the operating instructions, the nominal compression pressure is p_c^{nom}=9.15 MPa).

Given the values of p_c given in Table 7, as well as the value p_c^{nom}, let's determine the values Δp_c, which summarize in Table 8.

Table 8

Relative change in compression pressure, %, of Yanmar 6EY18AL diesel engine under different experimental conditions

Time, h	Engine oil 1 (Diesel AE 1)	Engine oil 2 (Diesel AE 2)
1	0.22	0.22
100	–0.11	–0.33
200	–0.33	–0.98
300	–0.44	–1.31
400	–0.66	–1.86
500	–0.77	–2.30
600	–0.874	–2.62
700	–0.88	–3.06
800	–0.98	–3.28
900	–1.09	–3.50
1000	–1.09	–3.61

The values given in Table 8 are reflected in the diagram shown in Fig. 9.

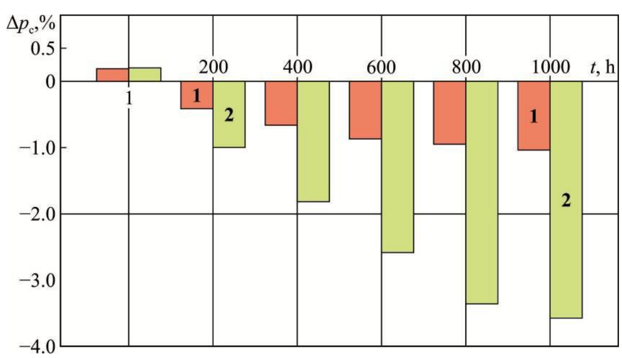

Fig. 9. Relative change in compression pressure, Δp_c, %, Yanmar 6EY18AL diesel engine under different experimental conditions: 1 – diesel AE 1; 2 – diesel AE 2

One of the parameters of the diesel engine, which characterizes the quality of the working process, is the temperature of the gases after the cylinder t_g. An increase in its value for individual diesel cylinders indicates deterioration in the process of fuel combustion in the diesel cylinder (in case of late injection) or an increased amount of oil that falls on the cylinder walls and burns along with the fuel. Gas temperature control after the Yanmar 6EY18AL diesel cylinder was carried out using the built-in diagnostic system that measures the temperature and outputs readings to the computer of the central control post. The measurements were carried out for diesel engines AE 1 and AE 2 in the range of 100–1000 hours, while the diesel engines were operated at different, but equal loads. The range of their change was within 450–600 kW. During the entire period of the experiment, the same parameters were determined in the cooling and lubrication systems of diesel engines (oil temperature at the diesel inlet, water temperature at the diesel outlet, and oil and water pressure at the diesel inlet). The t_g values were determined for each diesel cylinder. Table 9 shows the average values of t_g for all cylinders.

Table 9

Temperature change of gases after the cylinder of Yanmar 6EY18AL diesel engine under different experimental conditions

Time, h	Gas temperature, °C		Relative temperature change, %
	Diesel AE 1	Diesel AE 2	
1	292	293	0.34
100	295	297	0.68
200	286	292	2.10
300	281	288	2.49
400	294	302	2.72
500	287	296	3.14
600	290	301	3.79
700	296	308	4.05
800	290	302	4.14
900	293	307	4.78
1000	271	286	5.54

Yanmar limits the value of the exhaust gas temperature; its maximum value for 6EY18AL diesel engines should not exceed 310 °C. The results, which are given in Table 9, confirm that the operation of diesel engines was carried out in compliance with this requirement. Additionally, let's note that during the experiment, the deviation of the exhaust gas temperature for individual cylinders from the average value did not exceed ±10 °C.

For better visualization, the obtained results are presented in the form of a diagram (Fig. 10).

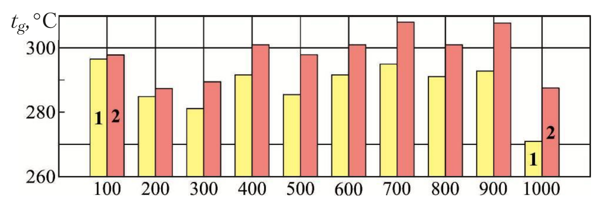

Fig. 10. Change in gas temperature after the diesel cylinder Yanmar 6EY18AL under different experimental conditions: 1 – diesel AE 1; 2 – diesel AE 2

For all measurement intervals (from 100 to 1000 hours), the average gas temperature after the cylinder for diesel AE 2 exceeded the same value for diesel AE 1. A comparative assessment of the change in t_g of diesel engines AE 1 and AE 2 can be performed by the relative change in temperature, which is determined by the expression:

$$\Delta t_g = \frac{t_g^{AE2} - t_g^{AE1}}{t_g^{AE2}} \cdot 100\ \%,$$

where t_g^{AE2}, t_g^{AE1} – the temperature of the exhaust gases of diesel engines AE 2 and AE 1 for the same period of time, °C.

The values are given in Table 9. According to the values of the Table 9, the nomograms are constructed. They show the relative change in gas temperature after the cylinder of the Yanmar 6EY18AL diesel engine under different experimental conditions (Fig. 11).

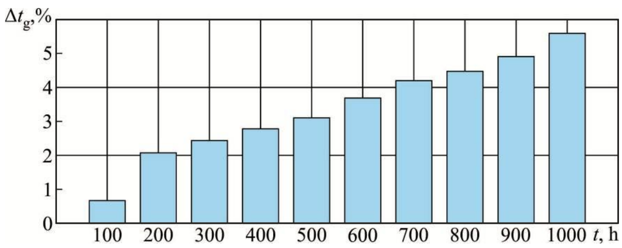

Fig. 11. Relative temperature change of gases after the diesel cylinder Yanmar 6EY18AL

The operation of marine diesel engines is impossible without maintaining their environmental parameters. One of the main environmental parameters, the value of which is regulated by the requirements of the International Maritime Organization (IMO), is the concentration of nitrogen oxides in exhaust gases – NO_X [45, 46]. The IMO provides a tiered approach to NO_X emissions depending on the ship's year of construction: Tier I – for ships built before 2000; Tier II – for ships built before 2011; Tier III – for ships built after 2016. In accordance with these requirements, the Universal Cargo on which the research was carried out belongs to the Tier II. The concentration of nitrogen oxides in the NO_X exhaust gases of marine diesel engines (both main and auxiliary) in this case should not exceed the value:

$$NO_X^{\max} \le 44 n^{-0.23},$$

where n – the diesel shaft speed, rpm.

Considering the characteristics of the Yanmar 6EY18AL diesel engine:

$$NO_X^{\max} \le 44 \cdot 1000^{-0.23} = 8.98 \text{ g/(kW}\cdot\text{h)}.$$

Determination of NO_X concentration in the exhaust gases was performed every 100 hours of operation with a Testo350XL (Germany) gas analyzer. The NO_X emission measurement error was ±1.0 %. At the same time, diesel engines were operated at different, but equal loads. The results are shown in Table 10.

A diagram showing the change in the NO_X concentration in the exhaust gases is shown in Fig. 12.

In addition, let's note that during the experimental studies, the value of the NO_X concentration in the exhaust gases did not exceed the maximum value regulated by the IMO requirements.

For all measurement intervals (from 100 to 1000 hours), the NO_X concentration in the exhaust gases for diesel AE 2 exceeded the same value for diesel AE 1. A comparative assessment of the concentration of NO_X in the exhaust gases of diesel engines AE 1 and AE 2 can be performed by the relative change in ΔNO_X, which is determined by the expression:

$$\Delta NO_X = \frac{NO_X^{AE2} - NO_X^{AE1}}{NO_X^{AE2}} \cdot 100 \text{ \%},$$

where NO_X^{AE2}, NO_X^{AE1} – the NO_X concentration in the exhaust gases of diesel engines AE 2 and AE 1 for the same period of time, g/(kW·h).

The NO_X values are given in Table 10, according to their values the nomograms in Fig. 13 are constructed.

Table 10

NO_X concentration in diesel exhaust gases of Yanmar 6EY18AL under different experimental conditions

Time, h	NO_X concentrations in exhaust gases, g/(kW·h)		Relative change in NO_X concentration in exhaust gases, DNO_X, %
	Diesel AE 1	Diesel AE 2	
1	8.32	8.37	0.60
100	8.52	8.62	1.17
200	8.28	8.41	1.57
300	8.01	8.21	2.50
400	8.32	8.53	2.52
500	8.12	8.36	2.96
600	7.96	8.21	3.14
700	8.47	8.75	3.31
800	8.23	8.51	3.40
900	8.51	8.81	3.53
1000	8.08	8.38	3.71

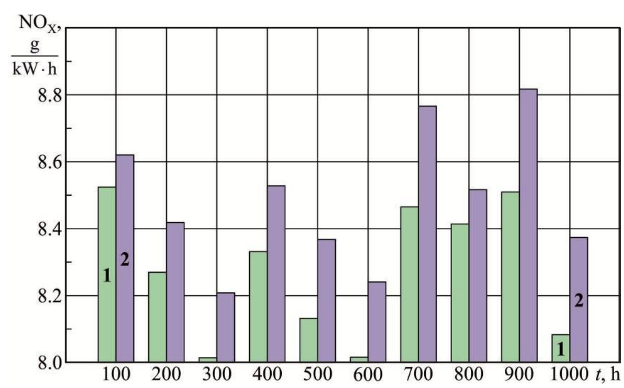

Fig. 12. Change in NO_X concentration in diesel exhaust gases of Yanmar 6EY18AL under different experimental conditions: 1 – diesel AE 1; 2 – diesel AE 2

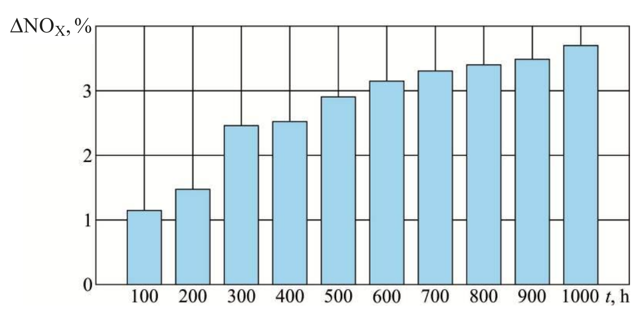

Fig. 13. Change in the relative concentration of NO_X in the exhaust gases of the Yanmar 6EY18AL diesel engine

For a comprehensive assessment of the influence of contact angles on the performance of marine diesel engines, some experimental data are summarized in the form of Table 11.

Table 11

Dynamics of change of controlled values

Time, h	Wetting angle,q, grad		Medium compression pressure, p_c, MPa		Gas temperature after the cylinder, t_g, °C		NO_X concentrations in exhaust gases, g/(kW·h)	
	Engine oil 1	Engine oil 2	AE 1	AE 2	AE 1	AE 2	AE 1	AE 2
0–1*	20.4	17.5	9.17	9.17	292	293	8.32	8.37
500	17.8	12.2	9.08	8.94	287	296	8.12	8.36
1000	16.3	9.7	9.05	8.82	271	286	8.08	8.38

Note: * – 0 hours corresponds to the value of the contact angles of wetting when they are determined in a scientific laboratory by the ellipsometry method; 1 hour corresponds to the values of p_c, t_g, NO_X when they are determined after the 1st hour of diesel operation

Table 11 characterizes the dynamics of changes in the controlled parameters. Based on its data, the diagrams in Fig. 14 are constructed.

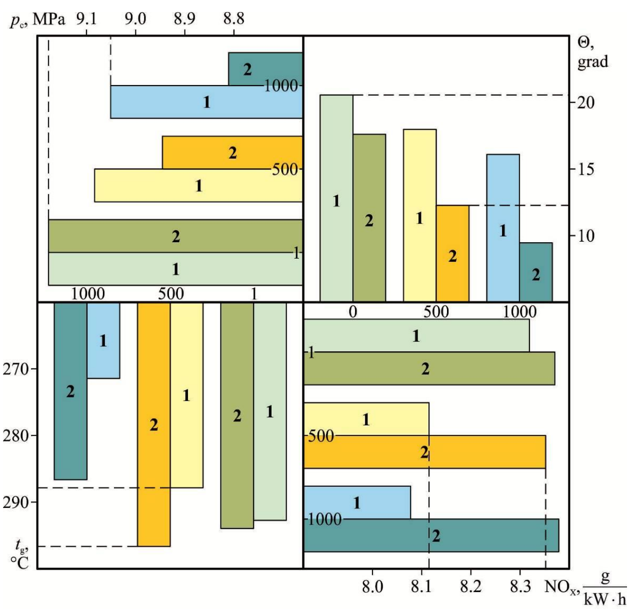

Fig. 14. Complex diagram of changes in controlled parameters

For the diagrams presented in Fig. 14, let's note the following. For the values of the wetting angle θ, the determining factor is the difference in the heights of the bars at different times (change in the height of bars 1 at times of 0, 500, 1000 hours and the height of bars 2 at times of 0, 500, 1000 hours). Their decrease indicates a decrease in the forces of surface tension of the oil. The more intense the decrease, the faster the destruction of the structure of the oil layer. For the values of the average compression pressure pc, the temperature of the gases after the cylinder t_g, the NO_X concentration in the exhaust gases, the determining factor is the difference in the heights of bars 1 and 2 at the same time (at a time of 1, 500, 1000 hours). Its increase indicates deterioration in the technical condition of the diesel cylinder-piston group.

7. SWOT analysis of research results

Strengths. The strengths of this study are that the relationship between the structural characteristics of motor oils (wetting angle and layer thickness) and its performance, as well as the performance parameters of a marine diesel engine, has been established. This allows selecting motor oils and performing a preliminary assessment of the possibility of their use to ensure the lubrication of diesel parts. The results obtained are in good agreement with the data presented in a number of works devoted to similar studies [2, 47–49].

Weaknesses. The weaknesses of the study are related to the fact that the determination of the structural characteristics of motor oils is not always possible directly on the ship. In addition, their implementation requires special training of ship engineers.

Opportunities. The considered technological equipment makes it possible to carry out research for any types and grades of oil (mineral, synthetic, high and low viscosity, used both in marine diesel engines and in marine hydraulic machines).

Threats. The option for assessing the technical condition and operational parameters of marine diesel engines proposed in this paper is based on experimental studies. To analytically determine the dynamics of changes in the operating parameters of a diesel engine when using oils with different structural characteristics, it is necessary to solve a system of equations that describe the processes of energy dissipation in the cylinder-piston group and the lubrication system.

8. Conclusions

1. Engine oils used in circulating lubrication systems for marine diesel engines must provide hydraulic density in the metal-oil-metal triad. This is facilitated by such a structural characteristic of the oil as contact angles. Optical studies have established that an increase in the contact angles contributes to an increase in the thickness of the oil layer that forms on the metal surface.

For marine motor oils (in particular, Total Lub Marime AURELIA TI 15/30 and LukLub Marime NAVIGO TPEO 15/30), the structural characteristics of the oil are within the following limits: contact angle θ=17.5–20.4 grad; oil layer thickness d_{oil}=2.6–3.9 mm.

High temperatures and pressures in the diesel cylinder contribute to the oxidation of the oil and worsen its structural characteristics. After 500 hours of operation, the value of these indicators decreases to θ=12.2–17.8 grad; oil layer thickness d_{oil}=2.0–3.1 mm. After 100 hours of operation – up to θ=9.7–16.3 grad; oil layer thickness d_{oil}=1.8–2.7 mm. This is one of the reasons for the decrease in hydraulic density in the tribological conjugations of the cylinder sleeve-oil-piston ring and shaft-oil-bearing shell.

2. Comprehensive studies have established a relationship between the structural characteristics of motor oils and the change in their performance characteristics (base number – *BN*) and the amount of impurities that form

in their volume as a result of wear of diesel parts (Wear and Contaminant Elements).

The conducted spectrographic analysis of oils for the composition of Wear and Contaminant Elements shows that oil with higher values of the contact angle provides:

– less decrease in BN (which indicates less oil oxidation);

– a lower concentration in the oil of all metal particles: Al, Cr, Cu, Fe, Sn, Pb, Ni, as well as B, Na, Si, V, Mo (which indicates an increase in hydraulic density and prevention of contacts in friction units).

3. It is experimentally determined that the use of oil with higher structural characteristics improves the thermal power and environmental performance of a diesel engine. For marine diesel engines Yanmar 6EY18AL for different, but equal loads of diesel engines for an operating period of 1–1000 hours, the following is established:

– stabilization of compression pressure;

– decrease in gas temperature after the cylinder in the range of 0.34–5.54 %;

– reduction of NO_X concentration in exhaust gases in the range of 0.60–3.71 %.

Conflict of interests

The author declares that there is no conflict of interest regarding this research, including financial, personal nature, authorship or other nature that could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

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