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ANALYSIS OF MECHANICAL ENERGY LOSSES IN MARINE DIESELS

The object of research is marine diesel engine oils, which provide lubrication, cooling and separation of friction surfaces. The subject of the research is the process of ensuring minimum mechanical losses in marine diesel engines. A problematic point in ensuring the lubrication of the cylinder-piston group and motion bearings is the lack of analytical and experimental studies that establish the relationship between the structural characteristics of engine oils and mechanical losses arising in marine internal combustion engines. The degree of orientational ordering of molecules and the thickness of the boundary lubricating layer are considered as the structural characteristics of engine oils. The determination of these values was carried out using the optical method based on the anisotropy of the light absorption coefficient by the boundary lubricant layer and the isotropic volume of the liquid (engine oil). The assessment of the level of mechanical losses arising in marine diesel engines was carried out according to an indirect indicator – the overshoot of the rotational speed and the time to reach the steady state of operation in the event of a change in load. It has been experimentally established that for engine oils used in marine internal combustion engines, the thickness of the boundary layer can be 15–17.5 μm. *Motor oils, which are characterized by a higher ordering of molecules and a thickness of the boundary lubricant layer, ensure the flow of transient dynamic processes with less overshoot and a shorter transient time. This ensures the level of minimal mechanical losses occurring in marine diesel engines. The technology for determining the structural characteristics of engine oils can be used for any type and grade of oil (mineral or synthetic; high or low viscosity; used in both circulating and cylinder lubrication systems). The method of indirect assessment of mechanical losses of marine diesel engines can be used for any types of internal combustion engines of ships of sea and river transport (low-, medium- and high-speed; as well as performing the functions of both main and auxiliary engines).*

Keywords: *marine diesel engine, lubrication system, engine oil, optical anisotropy, boundary lubricating layer, mechanical losses.*

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1. Introduction

Power complexes of sea and river means of transport are multicomponent structural objects, while:

– their functioning begins with the acceptance on board the vessel of working fluids (fuel, oil, water);
– their main operational task is the conversion of fuel energy into useful work, providing either the movement of the vessel, or the generation of heat and electrical energy;
– the final stage of their production cycle is the removal of waste gases and coolants into the environment.

Fuel (liquid or gaseous) is the main source of energy for heat engines. When converting the calorific value of the fuel into the kinetic energy of its combustion products, useful work is obtained [1, 2]. The heat engines of ship power plants of river and sea transport vehicles are steam boilers, gas turbines and internal combustion engines (diesels). Moreover, it is diesel engines that have now become dominant on all river and sea vessels without exception, regardless of their displacement, type and purpose. Leading diesel-building concerns and firms produce marine diesel engines in a wide range of sizes (cylinder diameter from 0.1 to 0.98 m), number of cylinders (from 4 to 18) and power (from 100 to almost 100,000 kW) [3, 4].

The functioning of a marine diesel engine is impossible without the use of working substances – fuel, air, water and oil, which ensure the receipt of energy and its transfer to consumers with minimal thermal and mechanical losses. Even with an ideal organization of the working process in a diesel engine, mechanical losses amount to 10 % and are primarily determined by energy losses to overcome friction forces. The reduction of mechanical losses is primarily ensured by the oil system, one of the functional tasks of which is to create and maintain a thin lubricating layer that separates the friction surfaces and prevents their direct contacts. A disruption in the operation of the oil system leads to an increase in mechanical losses, and under critical conditions, to a stop of the diesel engine.

The above factors confirm the relevance of the scientific and applied problem – ensuring minimal losses of mechanical energy in marine diesel engines.

2. The object of research and its technological audit

The object of research is marine diesel engine oils, which provide lubrication, cooling and separation of friction surfaces. *The subject of research* is the process of ensuring minimum mechanical losses in marine diesel engines.

In the process of polymolecular adsorption of a number of technical fluids (in particular, motor oil and fuel) on a metal surface, a relatively large value of intermolecular forces causes a possible change in the characteristics of the boundary lubricating layer. This effect has been studied most thoroughly and in detail for aromatic compounds belonging to the class of monosubstituted benzenes [5]. In this case, the asymmetric field of surface forces, which acts from the side of the solid surface, leads to the orientational ordering of molecules in the boundary layer. Such boundary lubricating layers have special physicochemical properties (heat capacity, anisotropy of optical characteristics, the presence of a structural component of the wedging pressure). These properties are so different from bulk properties that the boundary lubricating layers are considered as a separate boundary phase – liquid crystal.

The presence of the liquid crystal structure of the boundary lubricating layer contributes to a decrease in shear resistance forces, which is especially important for the tribological system «shaft – lubricant layer – bearing shell», which makes a rotational motion. Reducing shear resistance forces reduces friction losses (the main component of mechanical energy losses in marine diesel engines) and stabilizes the radial displacements of the shaft relative to the bearing.

Marine diesel engine oils are dispersed systems. Their performance characteristics in thin lubricating layers differ from bulk properties and are determined by the orientational ordering of molecules, which contributes to the appearance of additional wedging pressure between the contact surfaces. The parameters that qualitatively and quantitatively characterize the structure of the lubricating layers are the degree of orientational ordering of the molecules of the boundary layer S and the layer thickness d_S. The structural characteristics of the lubricating layers can be controlled by applying organic coatings to the contact surfaces, as well as by adding surfactants to the oil.

The deviation from zero of the orientational order parameter S in the range of thickness of the boundary lubricant layer leads to anisometry of the optical characteristics, in particular, the refractive index of light passing through the isotropic (bulk) phase and the boundary lubricant layer. It was found by the optical birefringence method that engine oils exhibit the ability to form boundary lubricating layers near metal surfaces. These layers have the properties of liquid crystals, and their thickness reaches 8–12 μm. The type of molecular orientation depends on the characteristics of the solid surface; however, predominantly (in 85–90 % of cases) the molecules of motor oils in the boundary lubricating layer are located homeotropically to the surface [5].

3. The aim and objectives of research

The aim of research is to determine the influence of the structural characteristics of engine oils on the loss of mechanical energy arising in marine diesel engines.

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

1. Determine the structural characteristics of engine oils (the degree of orientational ordering of the molecules of the boundary layer S and the thickness of the boundary lubricating layer d_S) in the range corresponding to the technological gap in the tribological system «shaft – lubricating layer – bearing shell of a marine diesel engine».
2. Determine the mechanical losses of marine diesel engines during their operation on engine oils with different structural characteristics.

4. Research of existing solutions to the problem

Structural and technological measures that ensure the reduction of mechanical energy losses during the operation of marine diesel engines were considered in various works. At the same time, attention was paid to:

– modification of the surfaces of the cylinder-piston group;
– ensuring the minimum fuel consumption;
– improvement of the general methodology for assessing heat flows;
– regeneration of the properties of the working surfaces of the main elements of the diesel engine.

In studies [6, 7] it was found that the boundary layers have increased viscosity. However, these works were devoted to the study of the properties of aromatic liquids, the use of which in ship power plants is limited.

In [8], a variant of reducing energy losses through the use of organosilicon additives is proposed. At the same time, the studies performed were related to emulsions of water and oil products. For their use in marine diesel engines, additional research is needed to determine their durability.

The authors of [9] proposed an option to reduce fuel consumption for power generation. However, the studies carried out are devoted to the optimization of the architecture of the ship's hull and do not consider the energy losses directly in the diesel engine.

In studies [10, 11], a variant of reducing mechanical losses in one of the elements of a diesel engine, fuel equipment, has been proposed. However, the use of the proposed solutions for the lubrication system is impractical due to the different temperatures and pressures of these research objects.

The method proposed in [12] provides an increase in the effective power of a diesel engine. At the same time, its implementation requires significant changes in the engine cooling system.

Work [13] is devoted to improving the efficiency of gas turbines – one of the main elements of modern diesel engines. At the same time, the optimal thermal and dynamic modes of operation of the diesel engine have not been established.

The authors of works [14, 15] proposed a variant of reducing the friction coefficient in the case of translational movement of diesel engine parts. However, its use requires the application of special coatings on the surface, which is not always possible.

Analysis of the experience in the design and operation of ship propulsion systems that ensure the minimum level of mechanical losses shows that it is advisable to improve them in the following areas:

– increasing the stability of the parts of the crank mechanism and motion bearings;
– increasing the elastic damping properties of the lubricant;
– minimization of hydraulic losses and contact loads in the tribological system «shaft – lubricant – bearing shell»;
– improvement of methods to reduce thermal and dynamic loads on movable and immovable parts of a diesel engine and shaft line.

The solution to these problems can be ensured by controlling the structural characteristics of the boundary lubricating layers.

5. Methods of research

The research was carried out in two stages:

1) in a scientific laboratory, using optical methods, the structural characteristics of the boundary lubricating layers of various motor oils were studied;

2) on marine diesel engines, the effect of engine oils with different structures of the boundary layer on mechanical losses was studied.

During experimental studies by the optical method of absorption dichroism, the optical density of the lubricating layer D was studied from its thickness d – $D=f(d)$. This makes it possible to estimate the spatial boundary of the boundary layer – d_S and the degree of its orientational ordering, which is characterized by the value of the scalar order parameter S. The study was carried out on a device, the diagram of which is shown in Fig. 1 [16].

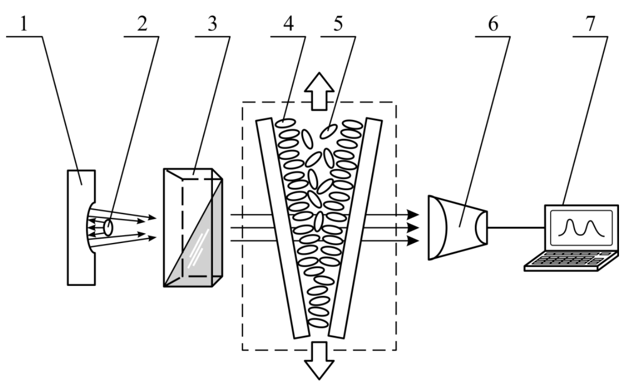

Fig. 1. Device diagram for determining the structural characteristics of boundary lubricating layers: 1 – lens; 2 – light source; 3 – polarizer; 4 – wedge-shaped cuvette; 5 – oil; 6 – photoelectronic device; 7 – computer

From the light source 2, the light beam was focused by the lens 1 and followed by a parallel beam through the polarizer 3 into the volume of the studied oil 5. To carry out the procedure for scanning the boundary layer through the thickness, a wedge-shaped cuvette 4 made of polished quartz glass was used. The volume of the cell was filled with oil, the molecules of which formed a boundary layer with an ordered molecular structure near the quartz surface. During the experiment, the cuvette was moved in a direction perpendicular to the direction of the incident light. The intensity of light passing through cuvette 4 was recorded using photoelectronic device 6 and transmitted to personal computer 7.

The intensity of light I, passed through a layer of oil with a thickness d, is determined in accordance with Bouguer law by the expression:

$$\ln I = \ln I_0 - \mu d,$$

or

$$D = \mu d,$$

where I – intensity of light transmitted through a cuvette filled with oil; I_0 –intensity of light passing through the cuvette, air-filled (without oil); μ – coefficient of light absorption by the oil in the cuvette; $D = \ln I / \ln I_0$ – optical density of the oil in the cuvette.

Analysis of the dependence $D=f(d)$ makes it possible to determine the structural characteristics of the boundary lubricant layer – the degree of ordering of the molecules S and the thickness d_S.

The research was carried out for marine engine oils Castrol Vection 15W40 (Great Britain), Shell Rimula R4X 15W40 (Holland), which were used in the circulating lubrication system of the marine diesel Volvo Penta TMDA 163A (Sweden). The main characteristics of engine oils are given in Table 1.

Table 1

Main characteristics of engine oils used in the experiment

Parameter, dimension	Engine oil brand	
	Castrol Vection 15W40	Shell Rimula R4X 15W40
SAE class	15	15
Density at 15 °C, kg/m^3	910	906
Kinematic viscosity at 40 °C, cSt	96	95
Kinematic viscosity at 100 °C, cSt	13.66	12.93
Flash point, °C	222	218
Pour point, °C	–14	–18
Total Base Number, mgKOH/g	10.2	10.3

These oils are used in circulating lubrication systems for marine diesel engines of low and medium power (up to 3500 kW). The optical characteristics of oils (in particular, the refractive index of light) make it possible to use them for experiments on a setup, the diagram of which is shown in Fig. 1).

6. Research results

In the case of structural heterogeneity of the layer (the presence of an ordered structure of oil molecules near the surface), the dependence $D=f(d)$ is not linear and is characterized by the presence of a break point (Fig. 2, *a*). This makes it possible to calculate the value of the degree of ordering of the molecules of the boundary layer S and determine its thickness d_S.

The breakpoint of the dependence corresponds to the transition of the bulk phase into the boundary lubricant layer with an ordered molecular structure and determines the thickness of the boundary layer d_S.

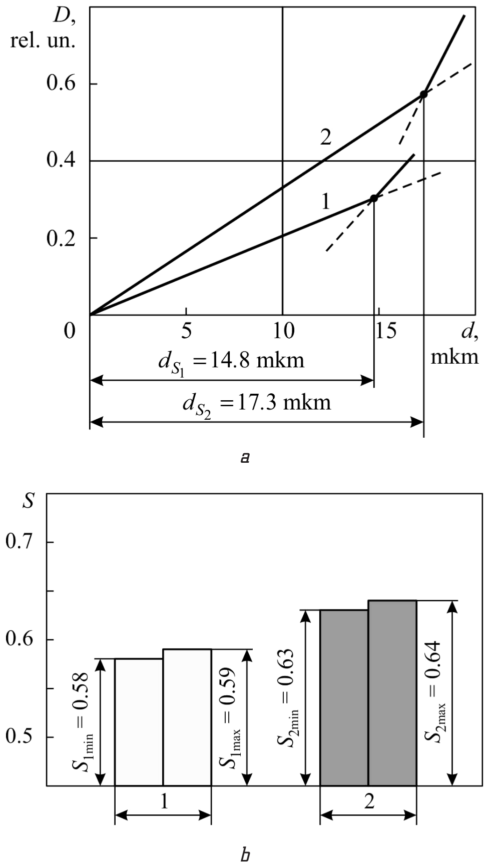

Fig. 2. Experimental results:
a – dependence of the optical density of the oil *D* (relative units) on the thickness of the oil layer *d* (μm); *b* – degree of ordering of molecules of the boundary layer *S*; 1 – Shell Rimula R4X 15W40 engine oil; 2 – Castrol Vection 15W40 engine oil

The higher the angle of inclination of the initial section of the dependence, the greater the value of the degree of ordering of the molecules of the boundary layer *S*. The determination of the value of d_S is shown in Fig. 2, *a*.

The calculation of the order parameter *S* was carried out according to the formula:

$$S = 1 - \frac{\mu_s}{\mu_{iso}}, \quad (1)$$

where μ_s, μ_{iso} – linear coefficients of light absorption in the boundary layer and in the isotropic liquid phase. And also controlled by the expression:

$$S = \frac{R-1}{R+2}, \quad (2)$$

where *R* – dichronous ratio, which is determined by the ratio of optical density in two polarizations, which increased the accuracy of the results and confirmed the reliability of measurements.

The maximum S_{max} and minimum S_{min} values of the degree of ordering of the molecules of the boundary layer of the oils under study, calculated using expressions (1) and (2), are shown in Fig. 2, *b*.

Optical studies were carried out in the range of the wedge-shaped gap thickness of 0–60 μm (which corresponded to the technological gap in the tribological system «shaft – lubricant layer – bearing shell» of the marine diesel Volvo Penta TMDA 163A). The research results are shown in Fig. 3. This reflects the change in the order parameter *S* depending on the distance between the metal surfaces *d* for the studied oils. Curve 1 corresponds to the engine oil: Shell Rimula R4X 15W40 – Fig. 3, *a*; or Castrol Vection 15W40 – Fig. 3, *b*. Curve 2 – «reference» (vaseline), which does not form ordered boundary layers.

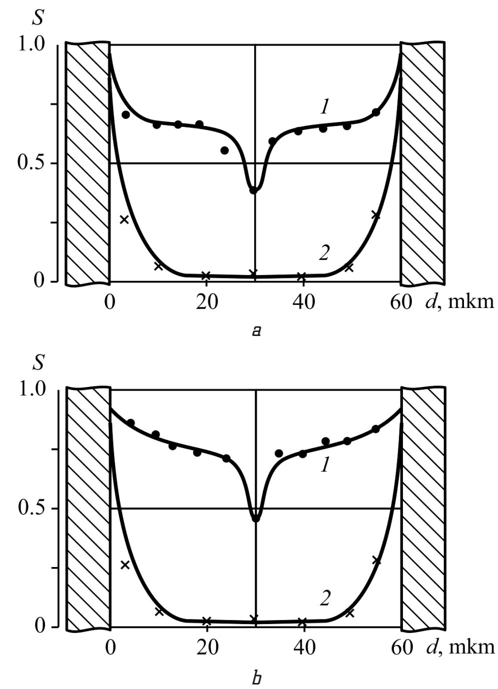

Fig. 3. Dependence of the order parameter on the distance to the surface for the investigated oil 1 and «reference» (vaseline) 2: *a* – Shell Rimula R4X 15W40 engine oil; *b* – Castrol Vection 15W40 engine oil

The central part of the dependence $S = f(d)$ on curves 1 corresponds to the isotropic phase (in which the ordering of molecules does not form), and the regions located near solid surfaces and characterized by higher values *S* correspond to an ordered boundary layer. The value of the order parameter *S* and the thickness of the boundary layer d_S of the engine oils studied are given in Table 2.

Table 2

Characteristics of the boundary lubricating layers of engine oils

Engine oil brand	Characteristic	
	Order parameter, *S*	Layer thickness, d_s, μm
Shell Rimula R4X 15W40	0.58–0.59	14.7–15.0
Castrol Vection 15W40	0.63–0.64	17.1–17.5

The results shown in Fig. 2, 3, as well as in Table 2 indicate that Castrol Vection 15W40 engine oil is characterized by a higher molecular order in the boundary lubricating layer compared to Shell Rimula R4X 15W40 engine oil.

In parallel with laboratory studies to determine the characteristics of boundary lubricating layers, experiments were carried out on marine diesel engines Volvo Penta TMDA 163A, the operation of which was carried out using Castrol Vection 15W40 and Shell Rimula R4X 15W40 engine oils. Both grades of engine oils are recommended by the manufacturer for the operation of diesel engines. The ship's power plant included two named diesel engines, each of which was equipped with an autonomous lubrication system, which made it possible to use various engine oils in them (for one – Castrol Vection 15W40, for the second – Shell Rimula R4X 15W40). Diesel engines before the start of the experiment had a commensurate period of operation, the same technical condition of the main contact assemblies (crankshaft, bearing shells, fuel equipment) and were operated at the same loads (with an inconsistency of no more than ±2.5 %). This made it possible to draw a conclusion about their identity to each other both before the start of the experiment and during it [17, 18].

As a criterion by which the mechanical losses of diesel engines were estimated when they operate on engine oils characterized by different structural characteristics (the degree of ordering of molecules and the thickness of the boundary layer), the overshoot of the rotational speed with a change in load was taken. The rotational speed measurements were carried out using an electronic tachometer (installed on the diesel control unit), which was additionally connected to a portable oscilloscope. The measurements were carried out for the starting mode (as the most dynamically loaded) and for various modes of load variation. The results shown in Fig. 4, indicate that an increase in the structural ordering of the boundary lubricant layer helps to reduce the overshoot of the rotational speed when starting the diesel engine and to reduce vibration in the «shaft – bearing shell» friction pair, which provides a lower level of mechanical losses.

The performance of any dynamic system (including the «shaft – lubricant layer – bearing shell») is determined by its stability [19, 20]. The assessment of the dynamic stability of the diesel engine, as well as the quality of transient processes when the external load changes, can be performed by overshoot of the rotational speed. For this purpose, on two diesels Volvo Penta TMDA 163A measurements were carried out (using the above tachometer and a portable oscilloscope) the rotational speed with the same load changes. One of the diesel engines was operated on Castrol Vection 15W40 engine oil (order parameter S=0.63–0.64, boundary layer thickness d_S=17.1–17.5 μm), the other – on Shell Rimula R4X 15W40 engine oil (order parameter S=0.58–0.59, the thickness of the boundary layer is d_S=14.7–15.0 μm). As the criterion by which the level of dynamic stability was determined, the overshoot of the engine shaft speed Δω and the time to reach a stable operating mode t were taken. The calculation results are summarized in the form of a Table 3 and are shown in Fig. 5, 6.

Table 3

Performance characteristics of the marine diesel engine Volvo Penta TMDA 163A when working with various engine oils

Parameter	Engine oil brand	
	Shell Rimula R4X 15W40	Castrol Vection 15W40
Load increase by 20 %		
Engine speed overshoot, Δω, rpm	119	101
Time to reach steady state, τ, s	2.4	1.7
Load decrease by 20 %		
Engine speed overshoot, Δω, rpm	118	103
Time to reach steady state, τ, s	2.4	1.8
Load increase by 35 %		
Engine speed overshoot, Δω, rpm	119	112
Time to reach steady state, τ, s	2.8	1.8
Load decrease by 35 %		
Engine speed overshoot, Δω, rpm	123	114
Time to reach steady state, τ, s	2.9	1.9

Removing such diagrams is a mandatory technical procedure and is carried out daily. Thus, the ship mechanic constantly monitors the load on diesel engines and controls its misalignment.

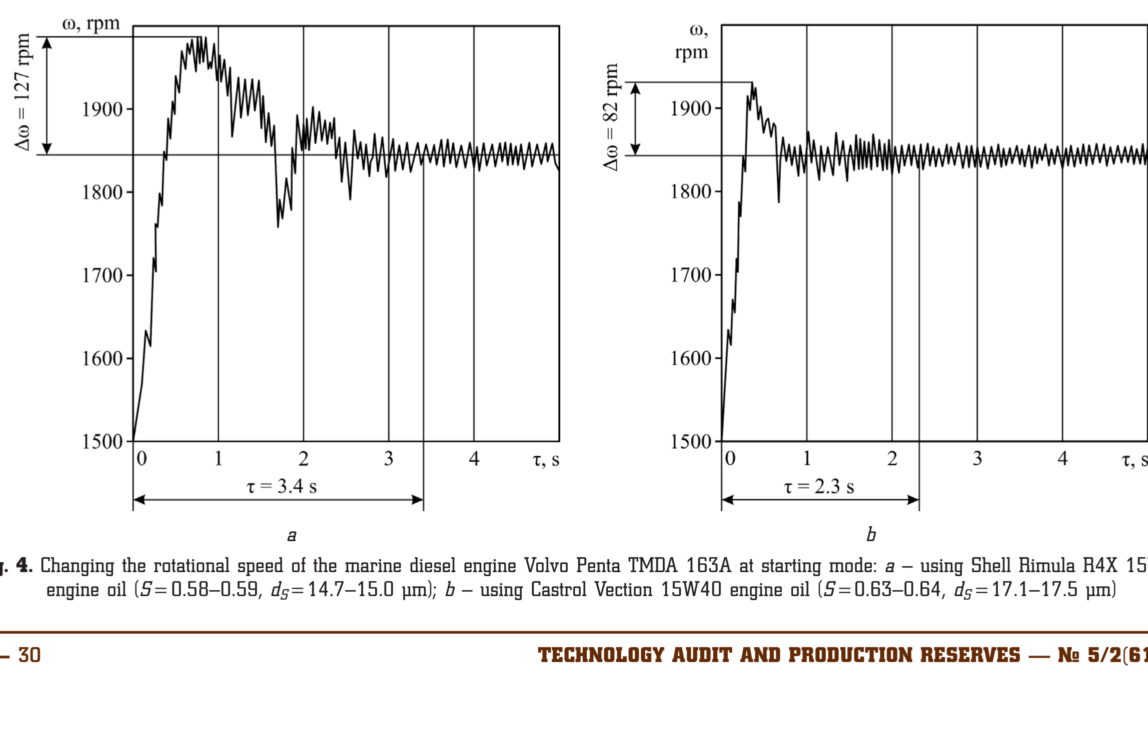

Fig. 4. Changing the rotational speed of the marine diesel engine Volvo Penta TMDA 163A at starting mode: *a* – using Shell Rimula R4X 15W40 engine oil (S=0.58–0.59, d_S=14.7–15.0 μm); *b* – using Castrol Vection 15W40 engine oil (S=0.63–0.64, d_S=17.1–17.5 μm)

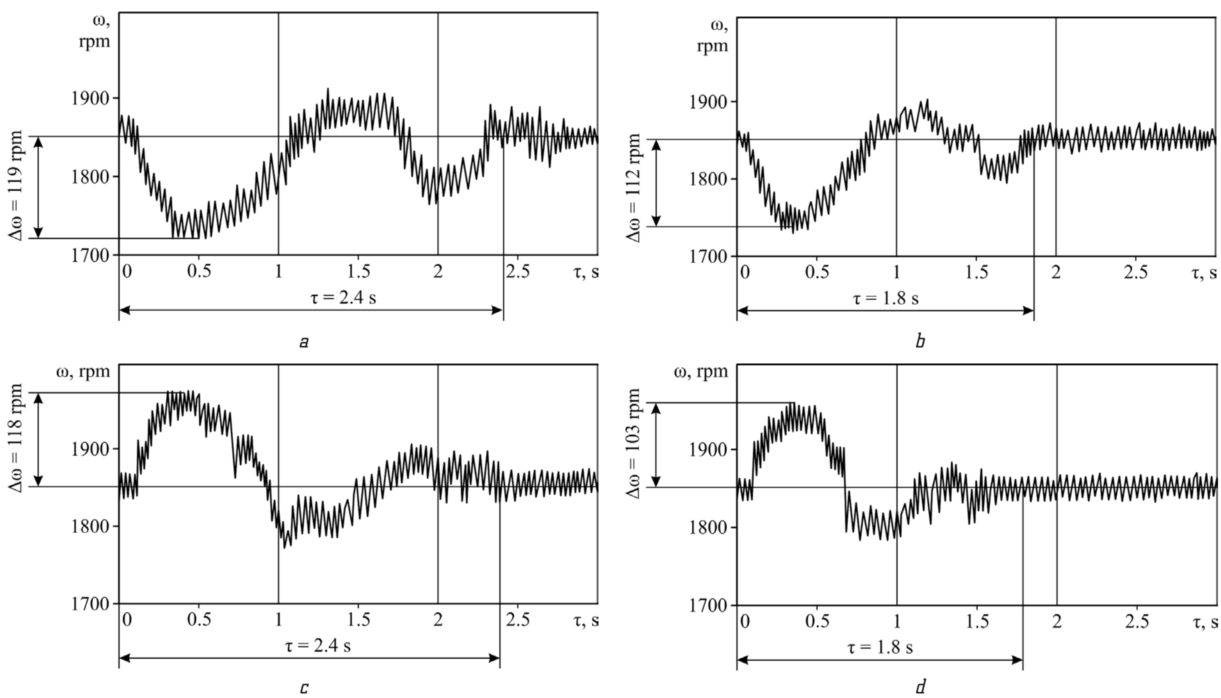

Fig. 5. Dependence of the rotational speed of the Volvo Penta TMDA 163A diesel engine on time when changing the load and using engine oils with different characteristics of the boundary lubricating layers: *a*, *c* – Shell Rimula R4X 15W40; *b*, *d* – Castrol Vection 15W-40; *a*, *b* – load increase by 20 %; *c*, *d* – load decrease by 20 %

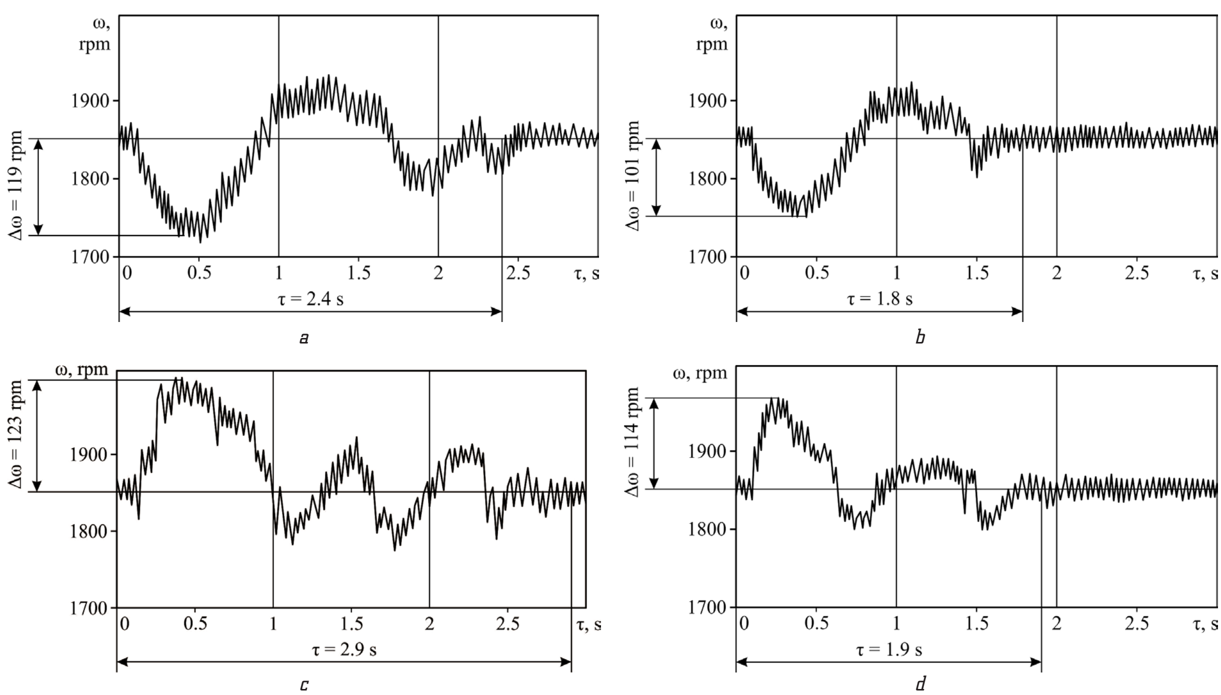

Fig. 6. Dependence of the rotational speed of the Volvo Penta TMDA 163A diesel engine on time when changing the load and using engine oils with different characteristics of the boundary lubricating layers: *a*, *c* – Shell Rimula R4X 15W40; *b*, *d* – Castrol Vection 15W-40; *a*, *b* – load increase by 35 %; *c*, *d* – load decrease by 35 %

7. SWOT analysis of research results

Strengths. The strengths of this research are that the established relationship between the structural characteristics of engine oils and the mechanical losses of marine diesel engines makes it possible to select engine oils. And also to carry out a preliminary assessment of the possibility of their use to ensure the processes of lubrication of diesel engine parts.

Weaknesses. The weaknesses of this research are related to the fact that engine oils intended for use in marine diesel engines must undergo preliminary tests, which may not always be possible on board.

Opportunities. Application of the proposed technology for determining the structural characteristics of engine oils can be used for any type and grade of oil (mineral or synthetic, high and low viscosity, used both in circulating and cylinder lubrication systems). The proposed method for indirect assessment of mechanical losses of marine diesel engines (by overshoot of the speed and the time to reach steady state operation in the event of a change in load)

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can be used for any types of internal combustion engines (low-, medium- and high-speed; as well as performing the functions of both main and auxiliary engines).

Threats. The option of maintaining the rheological characteristics of technical fluids proposed in this work is of an applied nature and is based on experimental studies. For the analytical calculation of the level of mechanical losses arising in marine diesel engines, it is necessary to solve a system of equations describing the following processes:
– energy dissipation in internal combustion engines;
– laminar and turbulent movement of engine oil in the lubrication system of a marine diesel engine;
– transformation of the calorific value of fuel into the useful work of internal combustion engines used on ships of sea and river transport.

8. Conclusions

1. As the main structural characteristics of engine oil, it is advisable to consider the degree of orientational ordering of molecules in the boundary lubricating layer S and the thickness of the boundary layer d_S. It is advisable to experimentally determine these indicators using optical methods, taking into account the anisometry of the light absorption coefficient in the boundary layer and the isotropic liquid phase. For engine oils used in marine internal combustion engines, the thickness of the boundary layer can be 15–17.5 μm, which corresponds to the technological gap between the diesel shaft and the bearing shell, and provides a boundary lubrication regime without contact interactions. This ensures the level of minimal mechanical losses occurring in marine diesel engines.

2. It is shown that the assessment of the level of mechanical losses arising in marine diesel engines can be carried out by indirect indicators – the overshoot of the rotational speed and the time to reach the steady state of operation in the event of a change in load. Motor oils, which are characterized by a higher ordering of the S molecules and the thickness of the boundary lubricant layer d_S, ensure the flow of transient dynamic processes with a lower overshoot of the speed of rotation and a shorter transient time. This helps to reduce contact interactions in the tribological system «shaft – engine oil – bearing shell» and to reduce mechanical losses of the diesel engine. Let's believe that this is due to the fact that such engine oils have a higher level of free energy of the boundary lubricating layer, which contributes to an increase in the elastic damping properties of the engine oil and an increase in the dynamic stability of the crankshaft.

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