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Estimation of Operational Properties of Lubricant Coolant Liquids by Optical Methods

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Abstract

Comprehensive tribotechnical and optical studies of lubricating-coolant liquids have been performed, which can be used when machining parts of marine diesel engines. Tribotechnical studies were carried out on a three-finger frictional testing machine; optical studies were performed on an original spectrophotometric installation that implements the method of dichroism in the absorption of impurity molecules. The article quotes results of the comprehensive studies which allowed determining qualitative characteristics of thin lubricating layers – the equilibrium thickness of the epitropic liquid crystal layer and the tribological characteristics of the contacting surfaces (normal load resistance force and torque). The thickness of the liquid crystal layer increases the elastic-damping properties of lubricating coolant liquids, which reduces the friction torque in tribocoupling. The effect of surfactants, being part of composition of lubricating coolant liquids, on the formation of wall-adjacent orientation-ordered layers is considered. The authors propose a lubricating coolant liquid, including potassium oleate as a surfactant. It is identified that the boundary layer thickness of lubricating coolant liquids can reach 13.5 ... 15.8 mcm, and the proposed optical method for impurity molecule absorption dichroism may be used to evaluate anti-friction properties of lubricating coolant liquids as an alternative to high-energy and long-lasting tribotechnical studies.

Keywords: Lubricating coolant liquids, surfactants, epitropic liquid crystal, tribotechnical studies, friction torque, optical studies, method of dichroism, absorption of impurity molecules, boundary layer thickness

INTRODUCTION

Ship power plants and their elements are large consumers not only of fuel and oil, but also of some other working agents, which include lubricating coolant liquids (LCL). They are used to compensate for the thermal and mechanical stresses while machining high-strength parts (primarily these include cylinder sleeves, pistons, engine connecting rods, as well as main and secondary shafts of auxiliary mechanisms) [1]. Similar operations can be carried on board a marine vessel or in the factory, and, in the latter case LCL consumption can measure tens or hundreds of liters per workpiece to be processed. LLC recycling is used to save them (with additional filtering after initial use) [2]. However, to do this, LCL components should have temperature resistance, and the filtering process should not alter their basic properties [3, 4]. When using LCL during the repair and renewal operations in the course of sea voyage, the stock of LCL on board the vessel is limited by the volumes of the relevant technical capacities, as well as the lack of ability to replenish it. Under such conditions those LCL are advantageous which have higher lubricity, and whose synthesis is possible with minimum use of water available on board the vessel, including desalinated water.

CONCEPT HEADINGS

LCL synthesis is complicated due to the fact that developed technological agent must possess not only sufficiently high lubricating, cooling, wetting, penetrating and detergent properties, but also meet other operational requirements [5]. The most important are nontoxicity, corrosion prevention, stability (which is especially important for long sea passages) bacteria resistance, hygiene [6]. Additionally, LCL should not be excessively foamed, destroy electric equipment insulation, cause seizing or jamming of the cutting tool and the machined workpiece [7]. At the same time LCL should be fire- and explosion-proof and meet the requirements of environmental safety [8, 9]. Basic requirements for the LCL, as well as the LCL properties, provided by these requirements, are given in Table 1.

Table 1: Basic requirements and properties of the LCLs

Requirements	Properties
Functional	1) lubricity – providing lubrication under boundary friction at the part-tool interface; 2) cooling ability – eliminating heat from the contact zone; 3) detergent ability – removing abrasive particles from the contact area.
Operational	1) disperse system stability during storage; 2) lack of corrosion effect on the tools and processed surface; 3) high antifoaming ability.
Sanitary	1) low toxicity or its full absence; 2) ability to regenerate and possibility to be used in the devices of biological or mechanical treatment; 3) incombustibility.

Depending on the composition, LCLs can be produced in the following versions:

1) pure mineral oils or oils with antifriction additives of fats and organic compounds (sulfur, chlorine, phosphorus) which have high lubricity, but low cooling ability and are prone to ignition;

2) oil-water emulsions (emulsols) with addition of surfactants which have high cooling ability, but are prone to delamination and impaired storage stability;

3) aqueous solutions of surfactants, which are characterized by high detergency, but do not provide the required lubricating effect.

Typically, aqueous emulsions are used as the LCLs that perform well the function of cooling the contacting elements, but have low lubricity [10].

Modern LCLs, doped with special chemical compounds, are capable of separating the contacting surfaces and their lower viscosity (in comparison with pure lubricants) facilitates LCL supply in the friction zone [11]. Low lubricity of lubricating coolant liquids is their negative characteristic as compared with conventional lubricants, which forces to feed LCL to the contact zone under increased pressure and in large volume. The former requires more power of the auxiliary equipment, the latter increases their consumption. Both factors restrict the LCL use in propulsion machinery of marine vessels, since it requires not only their increased stock, but also enhances the required performance of the treatment mechanisms, performing LCL regeneration [12].

LCL application is preceded by various tests, enabling to determine their basic properties, in addition, such studies allow to perform ranking of various LCLs according to the required characteristics [13]. Conducting such experiments requires energy-intensive equipment and long-term tests, associated with high consumption of the studied LCL samples. Therefore, the study was aimed at developing an alternative laboratory method which would make it possible to evaluate the basic operational properties of LCL with minimal time consumption and volume of the studied material – lubricity, thermal stability and ability to withstand normal loads.

METHODS

Recently, a large number of experimental studies are performed to investigate boundary friction mode [7, 14, 15]. This, in particular, is determined by the large number of failures and accidents occurring in these modes (for example, at start-up and sudden load increase, while machining parts), the necessity to operate shipboard power assets with overload and in the range of restrictive characteristics, and by exponential deterioration of properties of a lubricant that separates surfaces in the boundary friction mode [16, 17].

Mathematical description and physical explanation for phenomena occurring in the lubricating layer under the boundary lubrication differ from the hydrodynamic theory and have their own peculiarities. On the one hand, extreme fineness of the lubricant in the boundary friction mode prevents applying standard hydrodynamic ideology for description and on the other hand, the complexity and diversity of this process makes it difficult to construct a universal microscopic model In this regard, the processes occurring in the contact area in the boundary lubrication mode are described by the multi-molecular theory of boundary friction and confirmed by the experimental results [18].

TRIBOTECHNICAL STUDIES

Among the experimental methods that determine the lubricant characteristics in the boundary friction mode, the studies performed using rheometers [17, 19] and friction machines [20] are most common.

With this in mind, tribotechnical tests were carried out in a plant shown schematically in Figure 1. It is based on the three-finger frictional testing machine. Friction couple of the machine was comprised of a rotating polished plate 13 and three-fingered cam 10 pressed thereto. The cam fingers had needles 12 of the investigated material, which interacted with plate 13. Lever device 7 allowed changing the load transmitted by the needles to the friction couple. Plate 13 was placed in bath 14 and rotated by electric motor 16. Motor shaft rotation speed was controlled using transformer device 17, enabling to produce both rough (to set speed operating mode), and precise (to adapt the rotation frequency to the desired value) adjustment. The rotational speed was measured with counting device 20. The friction torque occurring during rotation of the friction couple turned the cam pivotally coupled to disc 8. Disk 8 turned load 21 of the rotary transformer 3 by means of thread 9. LCL was continuously fed to the needle-plate interface via line 11; the LCL amount was metered using needle valve 6. The wear intensity during friction of the plate and the needle was recorded continuously by means of device 2, which implemented the electric pulse measurement method. The principle of this method is based on the fixation of contacts of two metal bodies, separated by a layer of lubricant in the process of friction. Amalgamated copper pin 18 was attached on the underside of plate 13. Voltage of 10 mV was supplied to pin 12 and the needle 18 with mercury current collector 19. In case of a break in the LCL lubricating layer needles 12 and plate 13 got into contact with each other by protruding rough edges, resulting in a pulse change in the voltage across the load resistance.

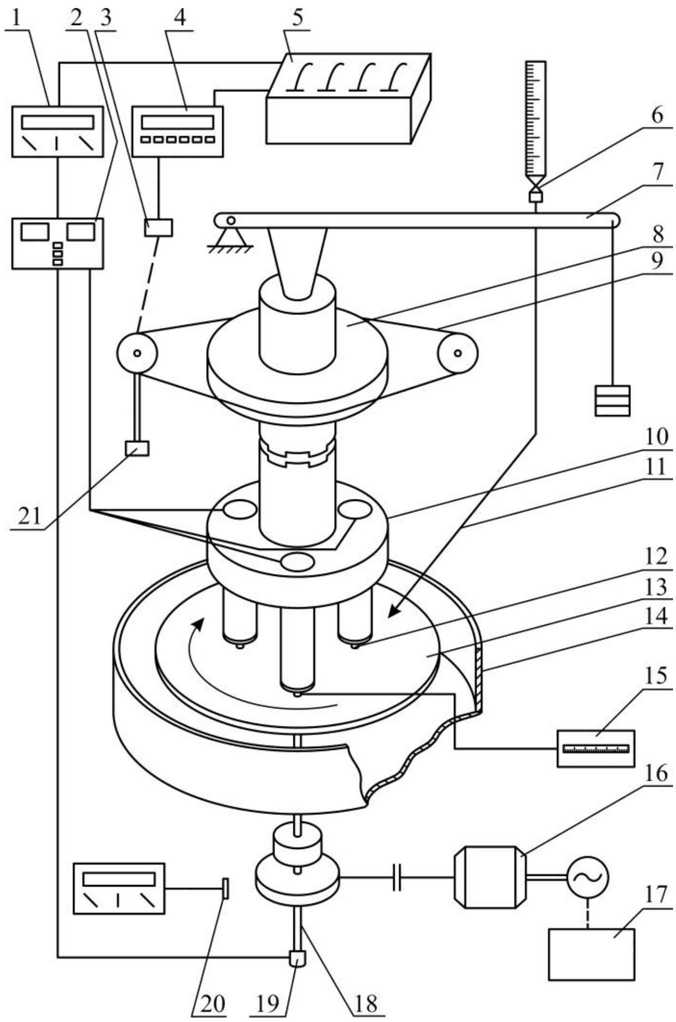


Figure 1: Scheme of a pilot plant for studying the LCL tribotechnical characteristics:
1 – pulse counter; 2 – wear meter; 3 – rotating transformer; 4 – millivoltmeter; 5 – self-recording apparatus; 6 – valve; 7 – lever device; 8 – disk; 9 – thread; 10 – three-finger cam; 11 – lubricant supply line; 12 – needle; 13 – plate; 14 – bath 15 – thermocouple element; 16 – electric motor; 17 – transformer device; 18 –amalgamated copper pin; 19 – mercury current collector; 20 – revolution meter; 21 – load

The number of electrical pulses per unit time was recorded by counter 1. In the course of operation, by switching the respective measuring relay contacts (not shown in the figure), it was possible to measure the wear intensity values and the actual contact area for a single needle-plate pair, and for the entire system as a whole. Under conditions of boundary friction wear of the contacting surfaces is observed at the boundary lubricating film breaks, and therefore frequency of electrical pulse repetition can be regarded as proportional to the wear intensity rate. In one of the cam fingers thermocouple 15 was installed and connected to recording device, enabling to continuously record the temperature of the friction zone in operation.

Measurements were made at a constant rotational speed of output shaft, with variable temperatures and contact pressures occurring in the friction zone. In the measurements values of friction torque (via millivoltmeter 4) and wear intensity rate (via pulse counter 1) were recorded. Pressure varied within 10...30 MPa in the contact zone. Provision was made in the pilot plant for analog recording of the obtained results using self-recorder 5.

The LCL tribotechnical characteristics were evaluated to determine their ability to provide maximum contact stresses and temperature in the friction triad: metal – the LCL layer – metal. The magnitude of friction torque, which arose in tribocoupling, was assumed as a criterion characterizing the contact stresses.

OPTICAL RESEARCH

In the process of polymolecular adsorption of a number of liquids relatively large magnitude of the intermolecular forces provides for possible change in characteristics of the subsurface layer on the surface of a solid body [21]. In this case, asymmetric field of the surface forces acting from the side of the metallic surface leads to orientational ordering of the liquid-crystal type in the boundary layers. Therefore, such orientationally ordered boundary layers possess special physicochemical properties (thermal capacity, anisotropy of optical characteristics, the presence of the structural component of disjoining pressure) [22]. These properties are so different from the bulk ones that the orientationally ordered boundary layers can be regarded as a special boundary phase – the epitropic liquid crystal (ELC) [23]. The structure of such a layer formed near a metal substrate is shown in Figure 2.

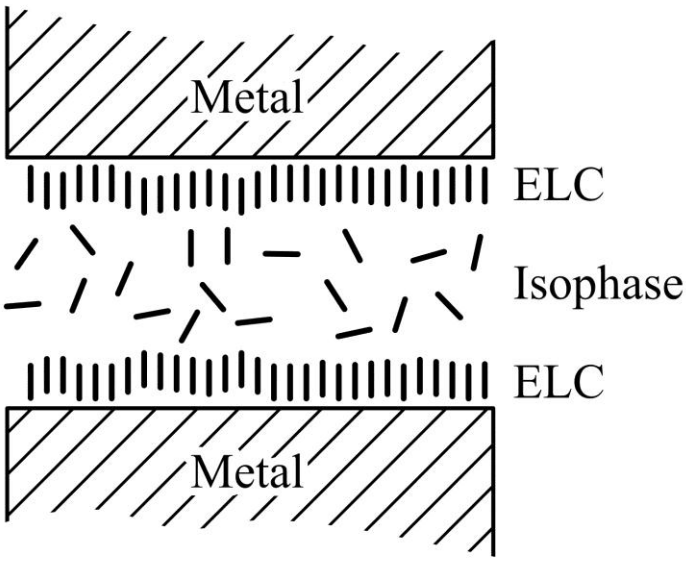


Figure 2: The structure of the narrow symmetric hetero-phase intermediate layer

The method of studying the dichroism in absorption of impurity molecules (the guest-host method) was used as a basic optical method for determining the structural characteristics of orientationally ordered wall-adjacent layers of LCL (which can be considered as ELC). In this case, molecular ordering of the basic matrix ('host', LCL being considered in this capacity) can be judged by the nature of absorption of dissolved impurity molecules ('guest'). Sudan black dye (absorption band maximum ν_m=17,500 cm^{-1}) was used as absorbing impurities with high extinction value; the structural formula of this dye is shown in Figure 3.

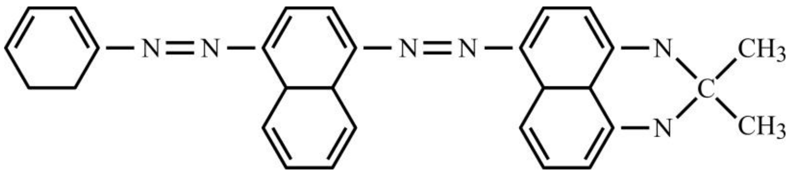


Figure 3: Structural formula of Sudan black molecules

Available coupled benzene rings provide for high extinction of the impurity and allows investigating sufficiently thin (0.2...5 microns) layers at low impurity concentration (1...3wt %) which practically exerts no effect on the structure of the matrix of the tested product. The choice of the type of absorbing impurity was determined by the degree of its solubility in the matrix. To improve the homogeneity the mixture of the LCL and impurity component was subjected to ultrasound exposure. UZG-5-M modular generator of multiphase ultrasonic field with a phase correction and magnetostriction radiator was used as an ultrasonic generator. In case of in-phase operation, the generator allows gaining modularly any power in the range of 20...5000 W, and also provides an output frequency of the ultrasonic signal in the range of 7...30 kHz with the accuracy of setting the frequency up to 1 Hz. While conducting the experiment, the ultrasonic generator power was varied in the range of 1...5 kW, and frequency in the range of 20...30 kHz. This made it possible to achieve a high degree of homogenization of the guest-host system under investigation and to destroy the nanotube agglomerations that usually form in such a mixture.

In a homeotropic orientation of the molecules in the boundary layer LCL (such orientation was assumed proceeding from the previous studies concerning characterization of mineral and engineering oils [17, 18, 19, 20] and the normal direction of the light wave incidence relative to the substrate, the absorption coefficient of the ordered liquid crystal systems will be less than that of the bulk liquid. Moreover, in this experimental geometry, the average light absorption coefficient should decrease regardless of light polarization state, as well as for the natural non-polarized light.

Optical experiments were performed with the Specord M40 Carl Zeiss spectrophotometer directly connected with a personal computer (Figure 4). The light beam from the light source 2 was focused by the lens 1 and as a parallel flux it was directed through polarizer 3 to volume of sample liquid 5. To implement the boundary layer scanning procedure by thickness the wedge-shaped cuvette 4 was used, it was made of polished quartz glass. The volume of the cuvette was filled with the investigated LCL, whose molecules formed boundary layer with an ordered structure of molecules near the quartz surface. During the experiment the cuvette was moved in the direction perpendicular to the incident light direction. The transmitted light intensity was recorded using photoelectronic device 6 and transmitted to personal computer 7.

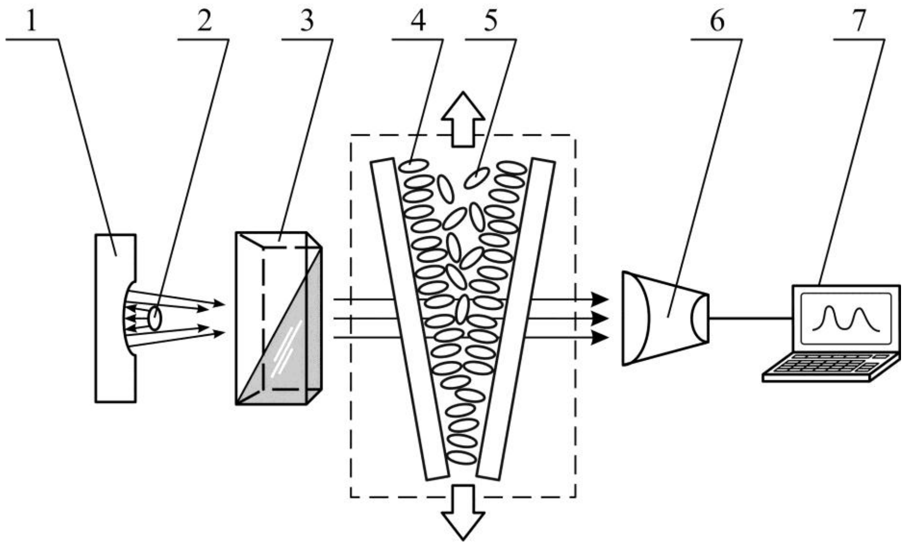


Figure 4: Scheme of scanning with the light probe of the wedge-shaped liquid layer:

1- a focusing lens; *2* - a light source; *3* - a polarizer; *4* - a wedge-shaped cuvette;

5 - tested liquid; *6* - photoelectronic device; *7* - PC

Scanning was performed using a mechanical device that allows moving the cuvette without opening cuvette chamber and recording the movement with an accuracy of 0.1 mm, which corresponded to a change in the cuvette gap thickness of 1...2 nm. The layer thickness was scanned in the range of 3...20 mm at the wavelength of maximum absorption of impurity molecules. The temperature was maintained in the experiments in the range of (20±2)°C.

Using polarizer 2 it is possible to obtain two incident light polarizations: electrical vector of the light wave is parallel to the lateral surface of the cuvette (*p*-polarization), or is normal thereto (*n*-polarization).

For ELC phase properties defined in the optical experiment to correspond characteristics of the LCL lubricating layer in contact friction area, the cuvette surfaces must be made of metal. However, metal opacity does not allow taking measurements in the 'peek-a-boo' experimental mode. To solve this contradiction, a metal layer was pre-deposited on the optically polished quartz glasses by thermal spraying, which was close by characteristics to metals used in the friction elements of seaborne machinery. The thickness of the sprayed layer (h~0.15 micrometers) was large enough, on the one hand, which provided practically the same influence on the boundary layer molecules as a usual metal surface, and on the other hand, it was small enough which provided semitransparency of the test sample. The conditions of vacuum deposition on the preheated (up to 180°C) quartz surface provided high adhesion of the layer and its homogeneity, which was checked by preliminary electron-microscopic observation of deposited substrates.

When light passes through an optical light guide, filled with absorbing medium, the light intensity I decreases according to the Lambert-Bouguer-Beer law:

$$I = I_o e^{-D},$$

which can be represented in the form of expression:

$$D = ln\frac{I_o}{I}$$

Where I_o and I are intensity values of light transmitted through the light guide with clean liquid and with liquid containing impurity molecules, respectively, for the same values of its width;

D is optical density of the absorbing material, which, in turn, is determined by the expression:

$$D = l\mu_i + 2ld_s(\mu_s - \mu_i)\frac{1}{d},$$

where l and d are the length and width of the wedge-shaped cuvette;

μ_s and μ_i – absorption coefficients of the wall-adjacent layers and the bulk liquid in the cuvette;

d_s – thickness of the wall-adjacent (boundary) layer of fluid.

The latter expression shows that in the isotropic phase $\mu_s=\mu_i$ and dependence of $D=f(d)$ is linear in accordance with Lambert-Bouguer-Beer law. The available structural heterogeneity of the liquid interlayer (molecular ordering in the wall-adjacent layer) determines the difference in the values of the absorption coefficients $\mu_s \neq \mu_i$ and leads to the deviation from linearity of the $D=f(d)$ dependence, whose curve in this case is approximated by two straight lines $D=D_i+D_s$, corresponding to the isotropic one:

$$D_i = l\mu_i,$$

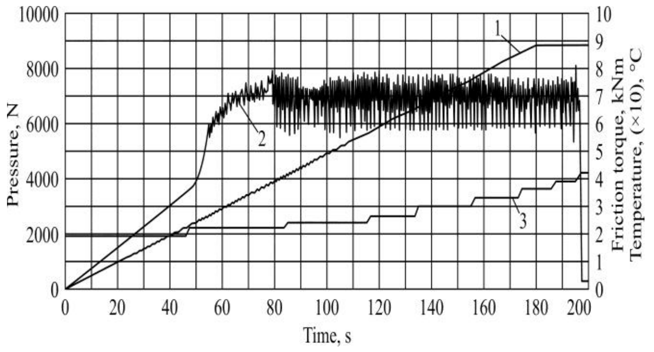
and the bulk phase:

$$D_s = 2ld_s(\mu_s - \mu_i)\frac{1}{d}.$$

By the of nature the $D=f(d)$ dependence one can judge on a number of facts: the degree of the wall-adjacent layer uniformity, on the orientational order parameter therein, on the wall-adjacent layer thickness, on the nature of the boundary between the wall-adjacent layer and the bulk liquid, on the orientation of molecules in the wall-adjacent layer, as well it is possible to draw certain conclusions about the properties of the first fluid monolayers directly adjacent to the substrate. However, for practical engineering problems it is possible to be limited only to the value of the boundary layer thickness d_s – as a basic parameter of the orientational ordering.

RESULT

The results of tribological tests were obtained proceeding from the criteria for determining the critical conditions on the friction surface [24]. At the same time the seizure pressure and time of steady operation of the steel-steel friction couple (as the most characteristic of marine diesel engine components) was estimated as a function of the normal load when applying different LCLs to the interface to ensure constant velocity movement of the samples. Before tests control samples were ground both manually and in the friction machine. Measured input (normal pressure, spindle revolutions per minute, contact zone temperature) and output (friction torque, operation time) parameters of the engine component operation were recorded synchronously by the computer in the real time mode. The test results were printed out; they are shown in Figures 5, 6 and Table 2. Seizure moment corresponds to a sharp change in the character of the appropriate curve (line 2 in Figure 5, *a*, *b*, *c*). The LCLs of various brands and manufacturers were tested (which are designated as "1", "2", "3" for business reasons), as well as LCL Greterol.



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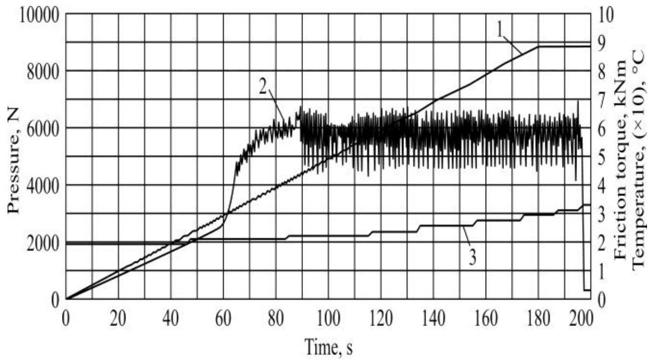

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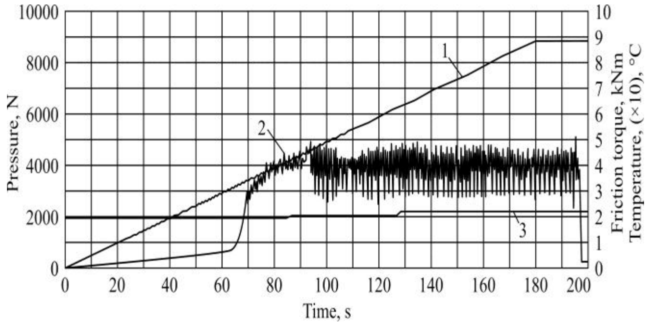

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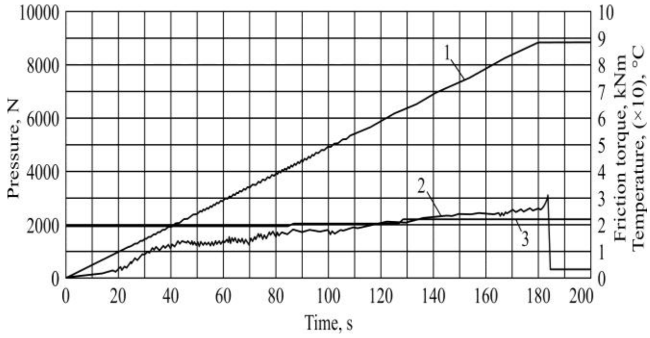
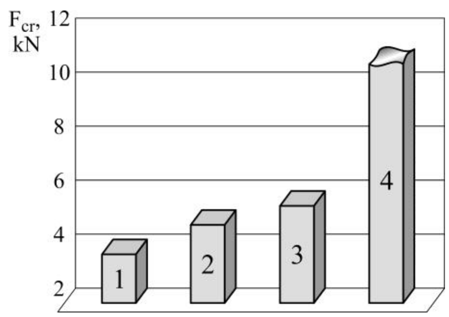


d)

Figure 5: Friction machine test results for various LCLs
a – “1”; *b* – “2”; *c* – “3”; *d* – Greterol;
1 - applied force, 2 - friction torque, 3 - temperature in the contact zone

Seizure pressure was 3.0...5,0 kN for the majority of the test materials, and the operating time prior to seizure made 75...95 s. Maximum compression strength of the samples produced by the friction machine was 7.0 kN. When working with LCL Greterol (in the wide range of variation of its concentration in water), this force was not enough to destroy the lubricating film, so the seizure time was not recorded (Figure 5, *d*).

Sinusoidal section on the oscillograph record corresponds to the destruction of the LCL boundary layer and direct contact of surfaces. Step-shaped increase in temperature corresponds to the increase in the number of direct contact surfaces (which was recorded with pulse counter – position 1 in Figure 1) and the increase in their wear intensity. It should be noted that the sinusoidal variation of the friction torque and the abrupt temperature rise in the friction zone were observed only for LCL “1”, “2” and “3”. When studying the LCL Greterol, these phenomena were not recorded.



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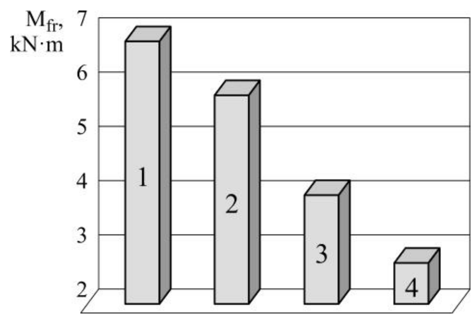

b)

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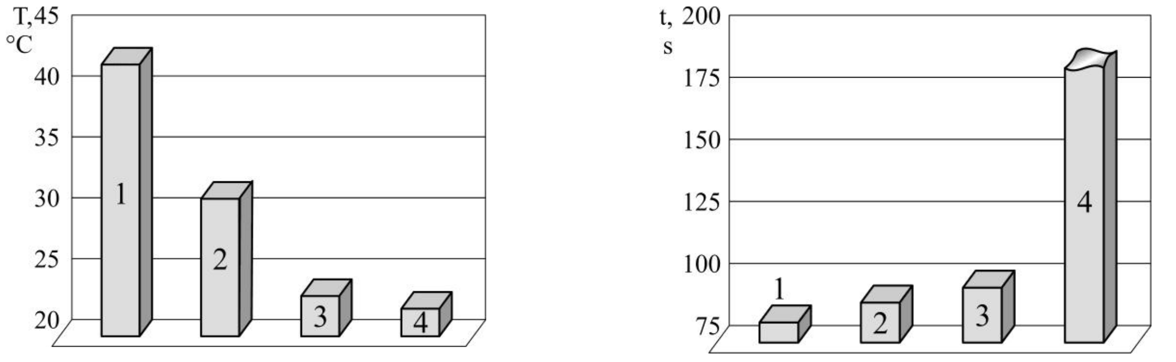

c) *d*)

Figure 6: Dependences of Critical force (*a*), Friction torque (*b*), Temperature (*c*), time prior to the initial seizure (*d*) for various LCLs:

a – "1"; *b* – "2"; *c* – "3"; *d* – Greterol;

Studies carried out on the Specord M40 Carl Zeiss spectrophotometer allowed experimentally determining the dependencies of the optical density of different LCL *D* (relative units) on their multi-molecular layer thickness *d* (mcm). These dependencies for different LCLs are shown in Figure 7.

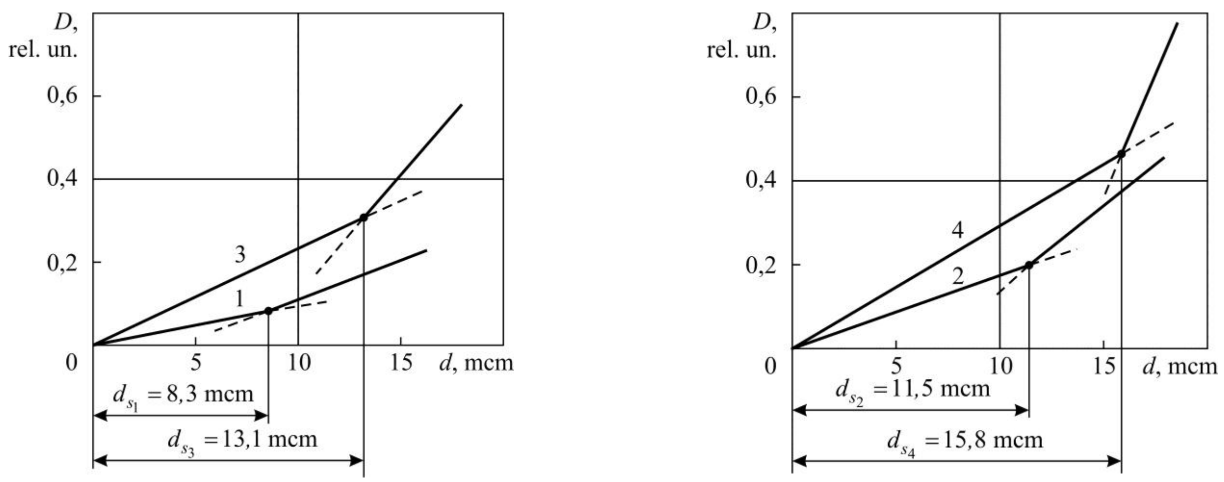

Figure 7: The LCL absorbance *D* versus thickness *d*:

a – "1"; *b* – "2"; *c* – "3"; *d* – Greterol

The obtained dependencies are characterized by two sections – corresponding to optical density of the LCL in the bulk phase and in the boundary layer. The inflection point of dependency *D*=*f*(*d*) corresponds to the thickness of the boundary layer d_s, and the initial section corresponds to the degree of ordering of LCL molecules in the boundary layer which can be determined as the order parameter *S*:

$$S = 1 - \frac{\mu_s}{\mu_i},$$

or

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

where *R* is a dichroic ratio defined by the ratio of optical densities in two polarizations *p* and *n*: $R = D_p / D_n$.

The results of the comprehensive studies are given in Table 2.

Table 2: LCL test results

LCL type	Tribological study		Optical study	
	Seizure load, kN	**Time before seizure, s**	**The boundary layer thickness, d_s, mcm**	**The order parameter, *S***
Water + LCL «1»	3.2	77	8.0...8.3	0.22±0.025
Water + LCL «2»	4.3	84	11.0...11.5	0.24±0.03
Water + LCL «3»	5.1	94	11.2...13.1	0.25±0.025
Water + LCL Greterol (0.5...4%)	7,000	more than 185	13.5...15.8	0.34±0.03

DISCUSSION

The above results indicate that different LCLs exhibit different tribotechnical characteristics, the main ones being the load at which the seizure of surfaces occurs and time before seizure. In our opinion this is explained by different molecular structure of the LCLs. There are LCLs consisting of long molecular chains with branched groups, which promote the formation of oriented molecular structure in the boundary layers. Ordered boundary layers of LCL (like any lubricant) are characterized by thickness and degree of order. The conducted studies show that the LCLs, which have a more ordered structure of the multi-molecular boundary layer, provide better tribotechnical characteristics of the contacting surfaces. The conducted spectrophotometric studies are consistent with the methodology of such investigations [25, 26].

To provide lubricating functions surfactants are included into the composition of the LCL. In this case, additional wedge forces occur in the triad ‘metal-lubricating fluid-metal’ that are caused by the orientational ordering of the molecules in the fluid boundary layers. These forces increase the bearing capacity of the LCL multi-molecular layer and hinder the contact of surfaces [27]. And the characteristics of these layers have a pronounced ‘non-Newtonian’ character and, under certain conditions, acquire properties of liquid crystals. First of all, this is associated with the increase in the ordering of molecules in the boundary layers of the LCL – the properties which is completely absent in the bulk phase and ineffective in terms of hydrodynamic lubrication.

Using the phenomenon of orientational ordering of the molecules in the boundary lubricating layers, as well as enhancing their liquid crystal properties can to the fullest promote the manifestation of such characteristics of the LCL as thermal stability and contact stress resistance. It is possible to activate the liquid crystal properties of the LCL most effectively using the well-known surfactants (perfluoroacids, amidofen, efren and others), and some modern organometallic compounds.

Surfactants added to the LCLs enhance short-range forces of the intermolecular interaction. In this way intermolecular structural organization is increased and anisotropy of some physical properties occurs in the boundary lubricating layer. In particular, such ordered phases have optical anisotropy and absorption dichroism. The value of these magnitudes depends on the type of orientation of the molecules, which can be located perpendicular to the solid surface (homeotropic orientation) and parallel to it (planar orientation).

Greterol is one of the LCLs whose surfactant – Potassium oleate – is a typical lyotropic liquid crystal and when its micellae are adsorbed a relatively thick (about 13.0...16.5 mcm) orientationally ordered boundary layer is formed on the metal surface, this layer blocks the metal surface and protects it from the counterface influence. Similar results and similar conclusions were obtained in the studies of identical design [28, 29]. Additionally, it should be noted that the thickness of the boundary layer of LCL Greterol exceeds similar parameter of other LCLs, which were also studied in the research. The degree of orientational ordering (the order parameter *S*) did not differ in their values from one another for all tested LCLs and made about ~0.23...0.24, while for LCL Greterol its value reached S=0.34). That is why this LCL provides better tribological characteristics of friction units, especially thermal stability of the lubricant cooling layer, which is correlated with the similar studies [30].

The value of the boundary ELC layer for various kinds of LCLs markedly differs from each other (Table 2). The LCL consisting of water and Greterol has the greatest thickness of the ELC layer. Moreover, the increase in the concentration of the latter from 0.5 to 4% increases only the layer thickness, whereas the tribotechnical characteristics of the friction unit do not vary practically at such concentration changes (in all cases the time of seizure was not recorded while testing on the friction machine).

Also lower concentration of LCL Greterol should be noted relative to water (the recommended concentration of LCL Greterol amounts to 0.5...4%, while for the other examined LCLs it was 10...25%) that, in particular, is reflected on its economic characteristics. Rational use of LCL contributes both to improve the reliability during the machining and increase the efficiency of the ship power plant, just as it happens when using technical oils and fuel [31].

CONCLUSION

The following conclusions should be pointed out as the main ones.

1. Some chemicals (metal salts of fatty acids), added in the composition of LCLs as surfactants, promote the formation of an orientationally ordered multi-molecular ELC structure in thin lubricant films of these substances.

2. Appearance ELC structure in the LCLs contributes to improvement of their tribotechnical characteristics, in particular it increases the ability to resist normal loads and time of stable operation with a gradual increase of these loads.

3. Conducting of the LCL tribological studies is associated with energy consuming equipment and time-consuming to carry out the experiment in order to obtain the necessary array of experimental data. Therefore, the optical method for analyzing the results of the impurity light absorption in the wedge-shaped sample is one of the methods for determining the LCL characteristics in the thin submicron lubricating layer, which can be successfully used to solve technical tasks. Parameters determined in this case – the boundary layer thickness d_s and the order parameter S (characterizing the degree of molecular ordering in the layer) – are interconnected with the ability of the LCL to resist normal loads. Thickness of the liquid crystal layer d_s, as one of its qualitative characteristics, contributes to increase in elastically-damping properties of the LCLs, which reduces the friction torque in the tribocoupling.

4. Optimal concentration of the LCL in the water mixture is in the range of 0.5...4%, which in principle does not affect the performance of auxiliary equipment providing the LCL feed to the operated engineering tools.

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REFERENCES

[1] Sagin, S. W., Ablaev, A. A., Grebenyuk, M. N., 2013, “Reduction of energy costs when machining motion parts of the internal combustion engines”, Problems of Engineering, 4, pp. 75-87.

[2] Turkovskaya, O. V., Muratova, A. Y., Pleshakova, E. V., 1997, “Utilization of spent detergent solutions and lubricating cooling liquids”, Studies in Environmental Science, 66, pp. 781-787. DOI: 10.1016/S0166-1116(97)80090-8

[3] Golubkov, Yu. V., and Ermolaeva, N. V., 2012, “Isoprenoids in oil-based lubricating-cooling liquids”, Chemistry and Technology of Fuels and Oils, 48, pp. 59-61. DOI: 10.1007/s10553-012-0337-0

[4] Lei, S., Devarajan, S., Chang, Z., 2009, “A study of micropool lubricated cutting tool in machining of mild steel”, Journal of Materials Processing Technology, 3, pp. 1612-1620. DOI: 10.1016/j.jmatprotec.2008.04.024

[5] Zenkin, N. V., Varichkin, I. A., Sorokin, S. P., 2016, “Analysis of lubricating-cooling liquids”, Scientific Almanac, 4-3(18), pp. 82-85. DOI: 10.17117/na.2016.04.03.082

[6] Wyrwas, B., Dymaczewski, Z., Zgoła-Grzeskowiak, A., 2013, “Biodegradation of Triton X-100 and its primary metabolites by a bacterial community isolated from activated sludge”, Journal of Environmental Management, 128, pp. 292-299. DOI: 10.1016/j.jenvman.2013.05.028

[7] Del Giacco, M., Weisenburger, A., Spieler, P., 2012, “Experimental equipment for fretting corrosion simulation in heavy liquid metals for nuclear applications”, Wear, 280-281, pp. 46-53. DOI: 10.1016/j.wear.2012.01.018

[8] Ermolaeva, N. V., and Golubkov, Yu. V., 2010, “Environmental problems when working with oil cutting fluids”, Bulletin of the MSTU “STANKIN”, 3, pp. 71-74.

[9] Ermolaeva, N. V., Golubkov, Yu. V., Aung, K. P., 2013, “Minimizing the impact of lubricating coolant

liquids on the environment and human by automation tools", Bulletin of the MSTU "STANKIN", 1(24), pp. 70-75.

[10] Takahashi, K., Shitara, Y., Kaimai, T., 2010, "Lubricating properties of TR Gel-lube-Influence of chemical structure and content of gel agent", Tribology International, 9, pp. 1577-1583. DOI: 10.1016/j.triboint.2010.01.016

[11] Pedisic, L. J., Saric, M., Bielen, S., 2003, "Application possibilities of new AW/EP additive types in watermiscible metalworking fluids", Industrial Lubrication and Tribology, 1, pp. 23-31. DOI: 10.1108/00368790310457106

[12] Varga, M., Alpar, T. L., Nemeth, G., 2004, "General waste handling and recycling in particleboard production", Management of Environmental Quality: An International Journal, 15(5), pp. 509-520. DOI: 10.1108/14777830410553951

[13] Kuznetsov, S. A., Belyaeva, N. A., Kol'tsov, N. I., 2009, "Making anticorrosion additives from self-emulsifying esters", Chemistry and Technology of Fuels and Oils, 3, pp. 208-210. DOI: 10.1007/s10553-009-0128-4

[14] Naumov, A. G., Latyshev, V. N., Radnyuk, V. S., 2015, "Tribological properties of iodine as a cutting-fluid component during metal cutting", Journal of Friction and Wear, 36(2), pp. 184-188. DOI: 10.3103/S1068366615020129

[15] Kannan, S., and Kishawy, H. A., 2008, "Tribological aspects of machining aluminum metal matrix composites", Journal of Materials Processing Technology, 1-3, pp. 399-406. DOI: 10.1016/j.jmatprotec.2007.07.021

[16] Sagin, S. V., and Semenov, O. V., 2016, "Marine Slow-Speed Diesel Engine Diagnosis with View to Cylinder Oil Specification", American Journal of Applied Sciences, 13(5), pp. 618-627. DOI: 10.3844/ajassp.2016.618.627

[17] Sagin, S. V., and Semenov, O. V., 2016, "Motor Oil Viscosity Stratification in Friction Units of Marine Diesel Motors", American Journal of Applied Sciences, 13(2), pp. 200-208. DOI: 10.3844/ajassp.2016.200.208

[18] Zablotsky, Yu. V., and Sagin, S. V., 2016, "Maintaining Boundary and Hydrodynamic Lubrication Modes in Operating High-pressure Fuel Injection Pumps of Marine Diesel", Indian Journal of Science and Technology, 9(20), pp. 208-216. DOI: 10.17485/ijst/2016/v9i20/94490

[19] Kiriyan, S. V., and Altois, B. A., 2010, "Rheology of motor oils with quasi-liquid crystalline layers in friction triad", Friction and Wear, 31(3), pp. 312-318.

[20] Popovskii, A. Yu, and Sagin, S. V., 2015, "Comprehensive evaluation of performance characteristics of lubricating hydrocarbon liquids", Automation of Marine Technical Facilities, 20, pp. 74-83.

[21] Azizov, A. H., Aliyeva, R. V., Kalbaliyeva, E. S., 2010, "Selective synthesis and the mechanism of formation of the oligoalkylnaphthenic oils by oligocyclization of 1-hexene in the presence of ionic-liquid catalysts", Applied Catalysis A: General, 375(1), pp. 70-77. DOI: 10.1016/j.apcata.2009.12.019

[22] Shishkin, Y. L., Kushcheva, M. E., Schwarzburg, L. E., 2009, "Determination of fraction and the component composition of lubricating coolant liquids (LCL) and thermal stability of the components by scanning calorimetry", Equipment and Techniques for Oil and Gas Industry, 4, pp. 37-40.

[23] Popovskii, A. Y, and Sagin, S. V., 2016, "Evaluation of operational properties of lubricating coolant liquids of the marine facilities", Automation of Marine Technical Facilities: science and technology collection, 22, pp. 66-74.

[24] Costa, A., and Macedonio, G., 2005, "Viscous heating effects in fluids with temperature-dependent viscosity: triggering of secondary flows", Journal of Fluid Mechanics, 540, pp. 21-38. DOI: 10.1017/S0022112005006075

[25] Fisher, A., Goodall, P. S., Hinds, M. W., 2003, "Atomic spectrometry update. Industrial analysis: metals, chemicals and advanced materials", Journal of Analytical Atomic Spectrometry, 18(12), pp. 1497-1528. DOI: 10.1039/b314153p

[26] Hsieh, T. T., Tiu, C., Simon, G. P., 1999, "Rheology and miscibility of thermotropic liquid crystalline polymer blends", Journal of Non-Newtonian Fluid Mechanics, 86(1-2), pp. 15-35.

[27] Izer, A., Kahyaoglu, T. N., Balkose, D., 2014, "Calcium soap lubricants", Bulletin of Kazan Technological University, 17(4), pp. 59-63.

[28] Chang, H., Li, Z. Y., Kao, M. J., 2010, "Tribological property of TiO_2 nanolubricant on piston and cylinder surfaces", Journal of Alloys and Compounds, 495(2), pp. 481-484. DOI: 10.1016/j.jallcom.2009.10.017

[29] Chentsov, V. P., Shevchenko, V. G., Mozgovoi, A. G., 2011, "Density and surface tension of heavy liquid-metal coolants: Gallium and Indium", Inorganic

Materials: Applied Research, 2(5), pp. 468-473. DOI: 10.1134/S2075113311050108

[30] Beznosov, A. V., Bokova, T. A., Antonenkov, M. A., 2010, “Wear of frictional surfaces in high-temperature lead and lead–bismuth coolants”, Russian Engineering Research, 30(2), pp. 128-132. DOI: 10.3103/S1068798X10020073

[31] Zablotsky, Yu. V., and Sagin, S. V., 2016, “Enhancing Fuel Efficiency and Environmental Specifications of a Marine Diesel when Using Fuel Additives”, Indian Journal of Science and Technology, 9(46), pp. 312-326. DOI: 10.17485/ijst/2016/v9i46/107516