

Maintaining Boundary and Hydrodynamic Lubrication Modes in Operating High-pressure Fuel Injection Pumps of Marine Diesel Engines

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Abstract

Background/Objectives: The effects of hydrodynamic and boundary lubrication occurring in the plunger-bushing friction pair of the high-pressure fuel injection pump in marine combustion engines have been studied. **Methods:** To determine thickness of the boundary lubrication layer of fuel, optical double refraction method has been suggested based on the optical anisotropy phenomenon. As an evaluation of tribotechnical characteristics of the plunger-fuel-bushing triad the electric impulse wear measuring technique has been suggested enabling to determine friction force and wear intensity. **Findings:** It has been proven that the fuel located in the gap between the plunger ram and the bushing performs lubricating functions. It has been shown that, owing to the elastic and damping properties and the disjoining pressure, the boundary layer of fuel helps reducing friction loss and wear of the contacting surfaces. The thickness of the fuel boundary layer affected by two-phase pressure of plane-parallel metallic surfaces has been determined. Marine fuels with viscosity value of 380...500 sSt at 40°C were used for the experiments; investigations were carried out in the temperature range of 30...60°C. It has been experimentally established that the thickness of the fuel boundary layer ranges within 4...12 micrometer, depending on operational conditions, which enables hydrodynamic and boundary (preventing direct contact between the surfaces) modes of lubrication. The ways for improving regularity of molecules in the boundary layer and for controlling its thickness have been suggested. **Applications/Improvements:** Liquid-crystalline properties of the boundary layers of fuel can be used in the precision pairs of high-pressure fuel injection pumps to reduce mechanical losses and to improve fuel efficiency.

Keywords: Bushing, High-pressure Fuel Injection Pump, Hydrodynamic and Boundary Lubrication, Marine Combustion Engine, Plunger Ram, Wear Intensity

1. Introduction

Ensuring the required modes of lubrication is one of the potential means for improving energy efficiency and operational reliability of marine combustion engines, inasmuch as in this case the amount of energy lost for overcoming the external friction and for compensating the oscillating processes occurring in the structure of an engine is reduced.

High-pressure fuel injection pumps are one of the elements securing the operation of the combustion engines and they are employed both in marine diesel engines and in diesel engines of stationary electric power plants¹⁻³.

The functional area of high-pressure fuel injection pumps is dozing and feeding, during the specified period, a required portion of fuel into the cylinder of a diesel engine^{4,5}. In modern marine diesel engines, the fuel injection pressure in the range of 1200...1300 bar has to be maintained⁶, which stipulates special requirements to the quality of the contacting friction surfaces in the high-pressure fuel injection pumps (namely, those of the plunger-bushing precision pair). Under such conditions, the plunger-bushing friction pair operates in the mode of boundary friction, and the fuel located in the gap of this precision pair performs lubricating functions⁷. Given the abovementioned facts, to secure reliable operation of the

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high-pressure fuel injection pumps, special requirements are to be set to the friction surfaces (of the bushing and of the plunger ram) and to the fuel. Furthermore, the fuel and the pressure surfaces of the plunger should be regarded as a complex tribological system operating in modes of hydrodynamic or boundary lubrication⁸.

2. Concept Headings

Injecting fuel with a high-pressure fuel injection pump (of either shear action type or valve type) occurs in the course of translational movements of the plunger within the bushing housing. Thereat, the quality of processing the adjoining surfaces should ensure minimum friction loss and prevent any leakages of fuel completely; moreover, the width of the diametric gap should affect the process of injection and the uniformity of the fuel feeding to the cylinder of the engine as little as possible⁹.

In the course of the diesel engine operation, the parts of the fuel injection equipment are worn continuously; this is especially true for such precision pairs as the needle – injector spray nozzle and the plunger–bushing of the fuel injection pump. Wear of those parts results in wider gaps between them and, consequently, in the loss of hydraulic density, in leakages and, accordingly, in reduced cyclical feed of fuel. This further leads to lower power of a separate cylinder and to the unevenly distributed loads on all cylinders¹⁰. Besides, the products of intensive wear in the plunger-bushing friction pair can lead to more intense adhesive contact and further destruct the geometry of the pressure surfaces.

At the contact areas of the elements of the high-pressure fuel injecting equipment in marine diesel engines, the following types of friction can be observed: dry friction (when the contact surfaces interact without any lubricant); hydrodynamic friction (in case when the thickness of the liquid located within the diametric gap does not exceed the thickness of molecular layer of this liquid more than 100 times); boundary friction (when the layer of liquid located within the gap can be regarded as monomolecular layer), and mixed friction (as a combination of dry and hydrodynamic, or of dry and boundary friction types). Given the complexity of physical, chemical and thermal processes, associated with partial mass transfer occurring in the course of friction, those processes cannot be described by the equations of classical mechanics. Periodic changes in the friction modes (from hydrodynamic to boundary and to mixed friction) make

it impossible to apply standard hydrodynamic theory of lubrication to describe them. Constantly changing thickness of the lubrication liquid layer located in the diametric gap of the plunger-bushing friction pair makes it impossible to apply the universal microscopic model to describe the friction process. Therefore, phenomenological models have been gaining wide application enabling the experimental explanation of the observed results¹¹.

Given all mentioned above, the purpose of this study is to develop the methodology for evaluating the modes of boundary and hydrodynamic lubrication by indirect indicators, such as the characteristics of the lubricating layer of the liquid located in the plunger-bushing pair of the high-pressure fuel injection pump, and wear intensity at the friction surfaces.

As a hypothesis for the undertaken investigation, it has been assumed that monomolecular layers of fuel, generated close to the friction surfaces of the fuel injection equipment (particularly, those of the plunger and of the bushing of the high-pressure fuel injection pump), make for additional elasticity of the fuel and ensure either hydrodynamic lubrication mode or the mode of boundary lubrication with no contact between the friction surfaces.

To confirm the suggested assumption, complex investigations have been carried out that included determining structural characteristics of thin layers of fuel that create the boundary layer at the surface of the plunger ram and at the surface of the bushing of the high-pressure fuel injection pump, and modeling wear of those surfaces. Molecular structures of boundary layers have been studied applying optical method of double refraction¹², and wear at the contacting surfaces was investigated applying the method of electric impulse measuring⁷.

Marine fuels used in marine diesel engines represent a mechanical mixture of different hydrocarbons (group C-H), sulfur and its compounds (group S-R), water and ash; they also include organic acids, tars, surface-active components and other elements.² Complex interaction between those components under conditions of catalytic effects produced by metallic surfaces changes the properties of the fuel that is in direct contact with the surfaces of the plunger-bushing friction pair and creates micron-thin inter-layers. Those inter-layers are characterized by orientation-ordered regularity of molecules, which results in anisotropy of some of their properties. In this regard, fuels, as well as the lubricating oils, create the boundary phase of quasi-crystalline structure at the

metallic surfaces; the thickness of this structure can make up to several microns. This boundary phase is characterized by stable bonds with the surface and by longitudinal cohesion.

3. Methods

Traditional experimental methods of studying structural regularity of a matter (such as radiographic analysis, nuclear magnetic resonance, as well as the methods based on magnetic susceptibility anisotropy or electric polarizability) can be applied to the investigating larger samples^{13,14} and cannot be used for studying thin wall layers of liquid generated at hard surfaces. For such objects, the most appropriate are the optical methods that are based on the fact that within the boundary layer, orientation-ordered regularity of molecules occurs which leads to optical anisotropy. One of the basic methods for obtaining information on the peculiar features of orientation-ordered regularity of organic liquids in the thin layers that adjoin metallic surfaces is the analysis of their optical anisotropy. Anisotropy of optical properties means that, in the wall layers, the effect of double refraction of light is observed; the description of this effect is given below.

Linearly polarized light goes through the optically anisotropic orientation-ordered boundary lubrication layers of liquid (fuel) and then this light becomes elliptically polarized that leads to the shift of phases δ between the components of light that are polarized in parallel and perpendicularly to the plane of light incidence. The value of the phase shift is proportional to orientation-ordered regularity of the material under investigation and it can be measured by means of an experimental plant shown in Figure 1.

The lubricant under study is placed in the inner compartment of the light waveguide, formed by two parallel flat polished surfaces. To ensure maximum plausibility of the experiment, the material of the surfaces is the same as the material of the plunger of the high-pressure fuel injection pump. The width of the light waveguide is altered by means of micrometric calibrating screw within the range of 5...100 micron and is controlled by the microscope. The light from source 1 is made monochromatic by filter 2 (the wavelength of $\lambda=0.546$ mcm), is then polarized by polarizer 3 and goes to the adjustable inlet of the light waveguide 5, upon having preliminary passed the compensator 4. The light beams move within the light waveguide along zigzag path, being reflected

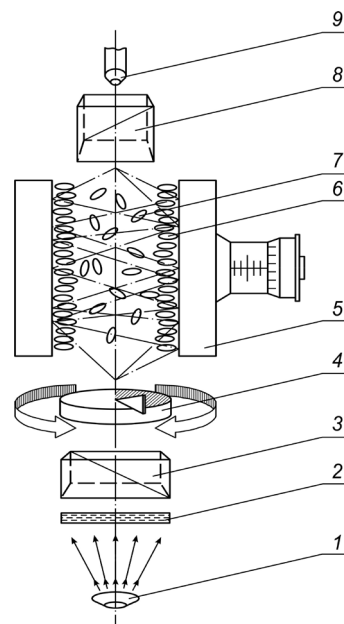


Figure 1. Scheme of experimental plant for defining optical anisotropy in wall layers: 1 – light source; 2 – filter; 3 – polarizer; 4 – compensator; 5 – light waveguide; 6 – wall layer; 7 – isotropic liquid; 8 – analyzer; 9 – microscope

from its walls, and afterwards they consequently pass the orientation-ordered wall layers 6 and isotropic liquid 7. To exclude any meniscus effects, the ends of the light waveguide are covered with glass. Upon leaving the light waveguide, the light comes to analyzer 8 and then proceeds to microscope 9. The side surfaces of the light waveguide and the glass are cleaned before every measurement.

To determine the shift of phases δ between the components of light E_p and E_s , that are polarized in parallel and perpendicularly to the plane of light incidence, for each fixed value of the light waveguide width, azimuth of extinction ϕ was found (the angle of slew of the compensator as compared to its rest position, when the intensity of light at the outlet is minimal). Then, value δ was found according to the equation as follows:

$$\delta = \arctg(2\sin 2\phi).$$

Dependency of phase shift δ on the inverse width l of the light waveguide $1/d$ is linear

$$\delta = \frac{2\pi}{\lambda} (2ld_s \Delta n) \frac{1}{d}$$

And it can be represented by the equations as follows¹²

$$\delta = k \frac{1}{2d} \text{ when } 2d > 2d_s, \text{ where } k = \frac{4\pi}{\lambda} l d_s \Delta n;$$

$$\delta = \delta_{\max} \text{ when } 2d \leq 2d_s, \text{ where } \delta_{\max} = \frac{2\pi}{\lambda} l \Delta n. \quad (1)$$

where, l is the length of the light waveguide, micrometer;

d is the width of the light waveguide, micrometer;

d_s is the width (thickness) of orientation-ordered boundary layer, micrometer;

Δn is the average value of optical anisotropy of the wall layer.

Determining value δ experimentally and then applying graphic-analytical solution to dependency $\delta=f(1/2d)$ makes it possible to find the thickness of the generated boundary layer of fuel.

Hypergolic properties and combustibility of fuel in the cylinder of a diesel engine are the only traditionally distinguished characteristics of fuels, while another feature, namely, lubricating capacity, is seldom mentioned at all. In addition, it is exactly this lubrication capacity that secures quality and reliable operation of the fuel injecting equipment of a diesel engine, which represents one of the most important units of every engine. The idea of "lubricating capacity" is of small current importance for "larger areas" of a fuel system (fuel pumping pipelines, filters, separators, etc.), save, probably, screw-type and gear-type fuel pumps. However, for the elements of high-pressure fuel injecting equipment, where the gap between the contacting surfaces makes just several micrometers, the idea of "lubrication capacity of fuel" is one of the most crucial. Moreover, an important role in the process of friction is now played by orientation-ordered regularity of molecules in the boundary lubrication layer that predetermines its mechanical properties (including antifriction properties and wear resistance). Higher degree of orientation-ordered regularity in the boundary lubrication layer results in lower friction losses and lower deterioration¹⁵. Besides, in orientation-ordered boundary layers, positive disjunctive pressure occurs, whose value is defined by the degree of orientation-ordered regularity of molecules and by the layer thickness; the very presence of this pressure prevents surfaces from direct contact^{16,17}.

A distinguishing feature of marine fuels (as compared to the fuels used in automotive transport) is their higher viscosity¹⁸, moreover, given the fact that the fuel also performs lubricating functions, its viscosity value can be different depending on the conditions required to maintain the established mode of friction, similar to the

changing viscosity values of oil¹⁹. Here, higher viscosity of fuel improves the lubrication capacity of oil.

Analysis of the operational conditions of a typical friction unit of the fuel injecting equipment shows that the position of the plunger ram in the high-pressure fuel injection pump is unstable. Deflection trajectory of the plunger can take different shapes depending on the length of the plunger and on its robustness. The whole gap, filled with fuel, can be represented as a system consisting of many areas, within which three uniform tribotechnical processes run:

- 1) the process of direct adhesive contact between operational surfaces of a pump element;
- 2) the process of shear in isotropic layer of fuel (whose thickness ensures hydrodynamic mode of friction and lubrication);
- 3) the process of shear in anisotropic layer of fuel (within which the orientation-ordered regularity of fuel molecules is observed and the boundary friction and lubrication occur).

Inasmuch as all these three areas, in their linear dimensions, make up 1...100 micrometer, and their distribution within the gap over the length of the plunger ram is of random character, the task of analyzing the effective forces in the plunger-bushing precision pair can well be reduced to a simplified two-dimensional problem.

Tribotechnical model of the plunger pair of the high-pressure fuel injection pump is represented in Figure 2.

Consider the forces affecting the plunger: P_{com} is the force caused by compression of the fuel; P_w is the force caused by the weight of the pump element; P_d is the moving force of the plunger; P_r is the off-center radial force; e is the eccentricity, the distance between the moving force axis P_d and the geometrical axis of the plunger; a is the technological gap.

As the pump element moves, the following friction forces occur between the plunger and the bushing: F_a is the shear resistance force, occurring at adhesive contacts in the area of friction; F_{bl} is the shear resistance force in the boundary layer of the fuel, characterized by the regularity of molecules; F_{liq} is the force of viscous (liquid) friction in the layer of the fuel with volumetric properties; N_{liq} is the hydrodynamic lift force occurring at micro-burrs at the rough areas of the surface; N_{bl} is the force caused by the disjoining pressure in the wall boundary layer of the

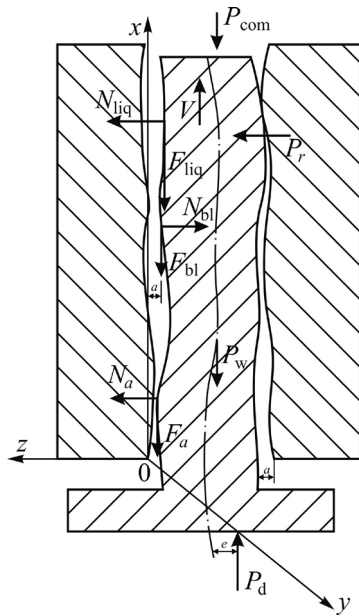


Figure 2. Tribotechnical model of plunger-bushing pair of high-pressure fuel injection pump

fuel; N_a is the force, caused by molecular interactions at adhesive contacts.

Forces F_a and F_{bl} act along the axis of the plunger ram; and forces N_a and F_{bl} act along its radius.

The shift of the plunger in radial direction occurs under the effect of force P_r , resulting in adhesion contacts N_a and F_a in the plunger-bushing precision pair. They are counteracted by the resistance forces in the boundary layer of fuel N_{bl} and F_{bl} , acting axially and radially. Thus, the boundary layer helps activating the elastic and damping properties of the fuel, reducing the number of adhesive contacts and decreasing the energy losses due to friction. In turn, the adhesive contacts increase friction forces and energy losses to ensure the plunger movement.

In case when the distance between the parts in the plunger-bushing pair is within the range of the technological gap a , the process of “fuel” lubrication of those surfaces occurs in the mode of hydrodynamic lubrication and the fuel injection equipment operates as usual. However, in real situations, the conditions of liquid friction are often not observed, affected by the shift and the displacement of the plunger ram in the gap, by changing viscosity of the fuel, by reversal pressures, by changing velocity of relative movements of the contacting surfaces, by fuel contamination with abrasive impurities²⁰. As a consequence, hydrodynamic friction and lubrication become boundary or mixed, and thus the plunger-bushing

operation reliability is affected by anisotropic layer of the fuel, characterized by regularity of molecules.

The presence of the boundary layer or the boundary film reduces the friction force by 2...10 times, as compared to the case of friction without any lubrication, and it also reduces wear of contacting surfaces by $10^2...10^4$ times. This can be explained by the emerging forces of disjoining pressure acting between the surfaces that helps minimize the contact areas of the surfaces²¹. The strength of the boundary film of fuel mostly depends on the nature of the fuel and on the presence of active molecular impurities within it. The boundary layers of the fuels at the contacting surfaces of the pump elements in the fuel injection equipment possess an ordered structure. Today, there are no universal and commonly accepted methods for investigating quasi-crystalline properties of lubrication materials or, in particular, fuels for marine diesel engines. Among the existing methods for evaluating these properties the method of measuring wear intensity at the friction units operating in the mode of boundary lubrication can be noted. This method can be practiced at the plant shown in Figure 3.

The plant includes the following parts: 1 - fuel injection pump; 2 - temperature sensor; 3 - flat sample; 4 - cylindrical sample; 5 - loading device; 6 - friction force meter; 7 - actual contact area meter; 8 - wear intensity meter; 9 - sliding velocity meter; 10 - thermometer; 11 - multimedia detector; 12 - oscillograph; 13 - heater; 14 - power supply unit for the heater; 15 - power supply unit for the electric motor; 16 - electric drive motor; 17 - device for fuel injection control; 18 - friction force encoder.

Between elements 3-4 a normal load N was generated that simulated the changes in the modes of lubrication in

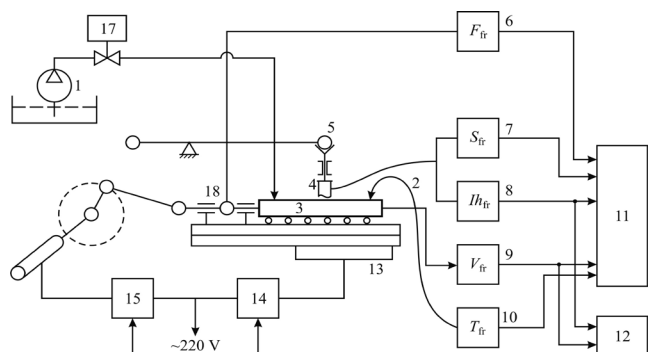


Figure 3. Schematic diagram of the plant for studying friction and wear processes occurring in plunger pairs of high-pressure fuel injection equipment of marine diesel engines

the high-pressure fuel injection pump between the plunger and the bushing. To detect and to analyze the processes occurring in pair 3-4, a controller was used to measure the parameters as follows: contact area (block S_{fr}), wear intensity (block Ih_{fr}), slip velocity (block V_{fr}), temperature of the contact area (block T_{fr}). Wear in friction pair 3-4 was measured applying the electric impulse method,¹⁵ illustrated by the flow diagram shown in Figure 4.

To the friction pair Fr , direct current voltage $U \approx 20$ mV is fed from the power supply unit with internal resistance of less than 0.1 ohm that is achieved by means of divider $R_1 R_2$. While the elements of the friction unit are moving, the boundary lubrication layer containing structural defects is destructed at the tips of the burrs on the rough areas of the metallic surfaces of the friction pair, and then the adhesive contact occurs accompanied by the event of wear. The current in the measuring electric circuit rises drastically. The voltage drop at resistor R_3 is of impulse nature. Selecting the voltage impulses at R_3 by their amplitude and counting their frequency or their total number within a specified period, it is possible, upon proper calibration, to determine the rate of wear, the intensity of wear and the absolute value of wear in the friction pair. Friction force was measured by integrating the momentary value of the friction force, applying inertia sensors, or by integrating the signal at simple RC circuits upon transforming it into an electrical signal.

4. Results

The results of the complex study of optic and tribotechnical characteristics of the boundary layers of fuel generated on metallic surfaces are described below.

The principal parameter determined applying the optic method of double beam refraction was the thickness of the boundary layer of fuel d_s . This value can be found by applying graphic solution to equation (1) based on introducing experimental values.

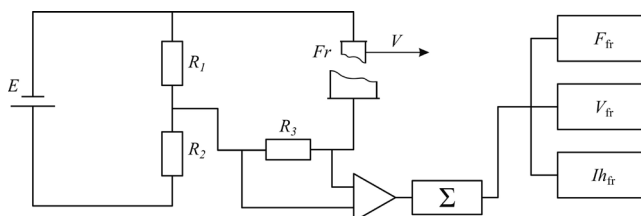


Figure 4. Flow diagram for wear measurement of friction units applying electric impulse method

For the purposes of the investigation, the following types of fuel used in marine combustion engines have been selected: RMK380, RMK420, RMK460, RMK500 with viscosity values of 380, 420, 460, 500 sSt at 40°C, accordingly. The measurements were taken at constantly maintained temperature in the light waveguide in the range of $30 \pm 1^\circ\text{C}$. The results of optical measurements in the boundary layers of fuel are represented in Figure 5 as a dependency of phase shift δ on the inverse width l of the light waveguide $1/2d$.

In all cases, the shift of phases in the area of volumetric liquid phase increases linearly, then it reaches its maximum and does not change in the range of the width of the light waveguide d that corresponds to the double thickness of the boundary layer of the fuel (at the moment when the light waveguide is filled with orientation-ordered boundary layer of fuel at both sides). Thus, the point of intersection of those two lines determines the double thickness of layer d_s and characterizes the liquid-crystalline properties of the boundary layer of the fuel.

For the purposes of determining thermal resistance of the boundary layers of different types of fuel, similar measurements were taken at different temperatures in the contact area. To this end, the thermostat control was introduced in the area of the light waveguide that made it possible to maintain the temperature there within the range of $25 \dots 70^\circ\text{C}$. The results of measuring optical anisotropy for this case are shown in Figure 6.

In the course of the parallel tribotechnical investigations of the processes occurring in the plunger-bushing friction pair of the high-pressure fuel injection pump friction force F_{fr} and wear intensity I_h were determined.

Analysis of tribological processes running in the high-pressure fuel injection equipment shows that wear resistance of the friction surfaces is considerably affected by the changes of such operational factors as velocity,

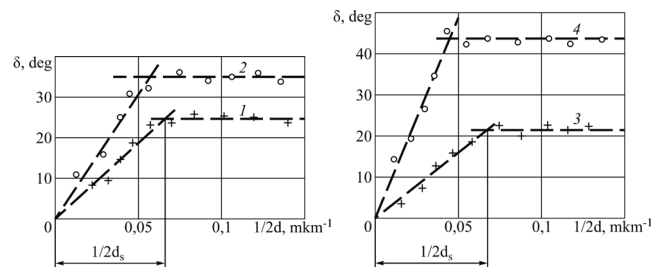


Figure 5. Experimental dependencies of phase shift δ on inverse width of light waveguide $1/2d$ for marine fuels: 1 – RMK420; 2 – RMK460; 3 – RMK380; 4 – RMK500

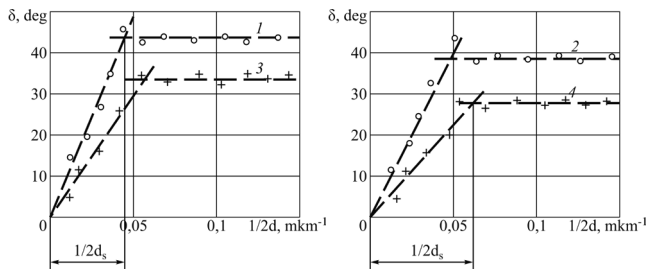


Figure 6. Experimental dependencies of phase shift δ on inverse width of light waveguide $1/2d$ for marine fuel RMK500 at different temperatures: 1 – 30 °C; 2 – 40 °C; 3 – 50 °C; 4 – 60 °C.

load, presence of water in the fuel, mechanical impurities and other additives mixed with the fuel. The boundary films of the fuel protect the friction elements of the fuel injection equipment from direct contact. Resistance to destruction of the lubrication film of the fuel depends on the nature of the metallic surface, on the load, velocity, temperature of friction, on the state of the surface, on the thickness of the film and on its composition²².

Figure 7 shows the results of measuring the dependency of friction force F_{fr} and wear intensity I_h on normal load N (generated between elements 3 and 4 from Figure 3) for the model of the plunger-bushing pair at velocity $V = 0.8$ m/s. The material of the pair is steel, the same as the material of the pump plunger ram. Lubricating material is fuel RMK500. Figure 7 shows that, as the normal load increases, friction force and wear intensity are also increasing in monotone. On reaching some particular load value, the structured boundary layer is destructed, and this leads to drastic increase in friction force and wear intensity.

Figure 8 shows the results of measuring the dependency of wear intensity and friction force on sliding velocity. The figure illustrates that, in dependency $F_{fr} = f(V)$, the minimum is observed, while dependency $I_h = f(V)$ is of falling character that is stipulated by the growth of hydrodynamic lift force at micro-burrs at the rough areas of the surface.

The process of preparing fuels for the engines includes gravitational sedimentation, cleaning (filtration and separation) and preheating to a required temperature. However, water and mechanical impurities remain in the fuel and they interfere with the structure of the fuel, changing, among other things, its lubricating capability. Water and other mechanical impurities in the fuel detrimentally affect the orientation-ordered regularity of the boundary lubrication layer of the fuel and result in higher friction force in the plunger-bushing friction pair (Figure 9).

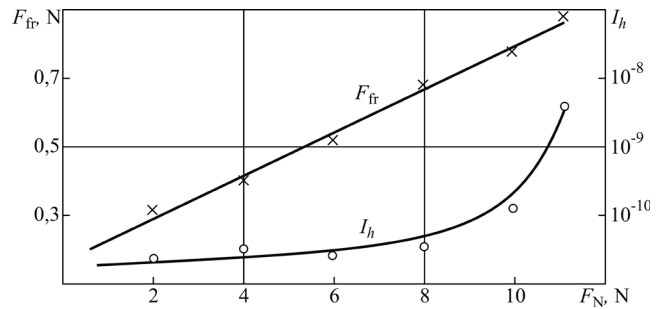


Figure 7. Dependency of friction force F_{fr} and wear intensity I_h on normal load.

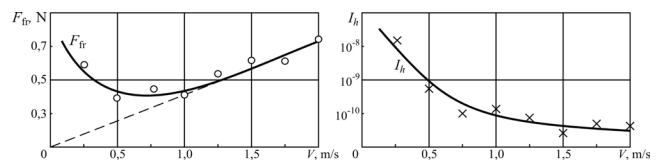


Figure 8. Dependency of friction force F_{fr} and wear intensity I_h on sliding velocity V .

5. Discussion

The obtained results are in line with the studies undertaken in similar areas of research^{23,24}, which confirms the relevance of the suggested model and the correctness of the pronounced hypothesis. Thereat, it should be noted that the fuels that represent complex disperse systems, create, on the metallic surfaces, the boundary layers whose thickness exceeds the thickness of the layers of “chemically pure” hydrocarbon liquids²⁵. Thus, it is possible to maintain that the plunger-bushing friction pair in the high-pressure fuel injection pump operates in the mode of boundary lubrication; moreover, the film of the fuel (acting as lubricant) can be up to 12 micrometer thick, ensuring not just monolayer but multilayer cover of the surface. It also has to be noted that the investigations have been carried out for the plane-parallel friction triad: metal - lubricant of the fuel - metal. In addition, the fuel in this triad, in contrast to a number of other similar studies²⁶, has been subjected to double effect of van der Waal forces of the metallic surfaces that facilitated the formation of thicker boundary layers. At the same time, the undertaken investigations deal with the fuels used in marine combustion engines, which predetermines their demand-driven nature.

Tribotechnical investigations are correlated with the scientific studies dedicated to potential reduction of

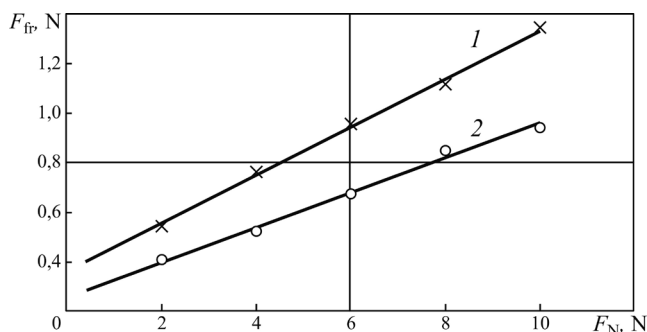


Figure 9. Dependency of friction force on normal load at different contents of water and mechanical impurities in fuel RMK500: 1 – fuel RMK500; 2 – fuel RMK500, containing 1 % of water and 0.3% of mechanical impurities.

energy losses in high-pressure fuel injection pumps²⁷, and the obtained results can secure this reduction of the fuel loss and can improve operational efficiency by making use of the effects produced by the higher hydraulic density in the plunger-bushing friction pair.

6. Conclusion

The complex of the undertaken investigations confirmed the fact that regular multi-molecular layers are formed in thin films of marine fuels on metallic surfaces in the plunger-bushing friction pair of high-pressure fuel injection pumps. Formation of these layers can be regarded as boundary phase that maintains hydrodynamic lubrication mode and the mode of boundary lubrication that prevents any adhesive contacts. The thickness of the boundary layers of the fuels used in marine diesel engines is within the range of 4...12 micrometer and it depends on the temperature at the friction area. However, even the smallest values are comparable to the technological gap in the plunger-bushing friction pair. Considering all this, the elastic and damping properties of the boundary layers of the fuel can be used for preventing direct contacts between the friction surfaces.

As one of the options for making van der Waal effects stronger, the use of the surface-active additives can be considered as well as the profile grinding and regular micro-relief patterning on the surfaces of the bushing and of the plunger ram of the high-pressure fuel injection pump. The former will improve the orientation of the molecules of fuel in the boundary layer and the thickness of this boundary layer; the latter will lead to generating additional hydrodynamic forces between the surfaces. Both options will

facilitate maintaining sustainable mode of hydrodynamic lubrication, or of boundary lubrication without direct contacts between surfaces. Such methods will reduce energy losses at the drives of the high-pressure fuel injection pumps, ensure the required pressure for fuel injection and minimize fuel losses at the diametric gap in the plunger-bushing friction pair in the course of fuel injection.

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