



Features of Interaction of Fullerene Compositions with Friction Surfaces of Tribosystems

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Abstract

The research on the formation of a lubricating film on the energetically active friction surfaces of tribosystems with a force field in the presence of fullerene compositions in the lubricant is performed in the work. It is shown that under the influence of the stress-deformed state of the surface layers, the friction surface acts as a "force field generator", which affects the formation of the electric field in the volume of the lubricating film. Expressions for calculating the intensity of the total force field of the "friction surface + lubricant" system have been obtained. Applying the method of dimensional analysis and experimental data, an expression is obtained for determining the thickness of the lubricating film that will be formed on the friction surface under the influence of the force electric fields of the friction surface and the liquid. The results of modeling the change in the thickness of the lubricating film, as well as the formation of clusters and micelles based on fullerene molecules from the intensity of force fields on the friction surface and in the volume of the lubricating film are presented.

Keywords: Tribosystem; Fullerene compositions; Dynamic viscosity; Force field; Electric field; Clusters; Micelles; Solvent; Lubricating film; Lubricating film thickness; Lubricating materials.

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1. Introduction

With the development of nanomaterials in tribology, which include fullerenes, it became possible to effectively use functional additives to lubricants in the form of geomodifiers. It was found that oils modified with nanomaterials, which form dispersed systems in the lubricant, increase the wear resistance of working surfaces of various types of tribosystems.^[1,2]

The use of fullerenes as additives to technical liquid lubricants raises a number of questions about their effectiveness, the degree of influence on antiwear and extreme pressure properties. An important feature of such additives is that fullerenes are highly soluble in a wide range of organic

and inorganic solvents. Another interesting phenomenon observed in fullerene solutions C60, are the processes of formation and growth of clusters, which indicates the proximity of many solutions C60 to the class of colloidal systems.

The presence of a dispersed phase in the lubricant in the form of clusters and micelles, which are formed around fullerene molecules, create wear-resistant structures on the friction surface that can perceive the load, reducing the wear rate and friction losses, which is noted by the authors of the works.^[3-5]

Widespread use of such materials in the form of a finely dispersed powder as lubricant additives or a fullerene composition preliminarily dispersed in a solvent is impossible without the development of the physical foundations for their interaction with the friction surfaces of tribosystems.

2. Analysis of literature data and statement of the problem

The authors of the works,^[6,7] based on theoretical studies and experimental material, the following conclusion is made. The use of lubricants with functional additives will provide a positive effect both in the manufacturing process and at the stage of operation of tribosystems of machines and mechanisms for various purposes. At the same time, the mechanisms of action of lubricant compositions containing

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nanomaterials on the performance of tribosystems were not analyzed by the authors and, in our opinion, require further development.

In work^[8] presents a review of the literature on lubricants with the addition of nanoparticles. It is noted that the use of nanoadditives leads to an increase in the viscosity of the base medium. According to the authors, this increases the bearing capacity of the interface, reduces the coefficient of friction, and increases wear resistance. From the analysis of this work, a conclusion follows about the prospects for the use of nanoadditives for liquid lubricants. However, the question of the optimal concentrations of nanoparticles in the base lubricant remains unresolved.

Similar conclusions are contained in the work.^[9] The authors argue that the characteristics of the lubricant can be improved by the use of nano-additives. The work is devoted to an information review of the application of nano-additives to liquid lubricants and the prospects for their use in the production of oils. However, the paper does not provide data on the mechanisms of the lubricating action during the formation of structures on friction surfaces.^[10-13]

Further development of the features of the use of nanoparticles as additives is given in the work.^[14] The authors consider various technologies and concentrations of nano-additives in lubricants. The following factors are analyzed in the work: the size of nanoparticles, the shape of nanoparticles, their structure, the modification of the friction surface, the concentration of nanoparticles, the physical and chemical properties of friction surfaces. Data are given on the reduction of friction coefficients and wear rate. In our opinion, this work is fundamental for the use of nanoparticles in lubricants, but the issues of the interaction of fine surface structures with friction surfaces are not considered by the authors.

Works^[15-17] dedicated to fullerenes as lubricant additives. The authors note that the use of fullerenes reduces the coefficient of friction and increases the wear resistance of tribosystems. The works contain experimental material without analyzing the mechanisms of interaction of fullerenes with friction surfaces. At the same time, at work^[17] noted that the concentration of fullerene additives should be in the range of 0.5 ... 2.0% of the mass. In this range, a positive effect was found from the use of.

The studies that are presented in^[18,19] focus on the use of fullerene C60. The authors note a positive effect, but conclude that the mechanism of interaction between fullerenes and base oil is unclear and requires further research. At the same time, the paper presents data that the reduction in the

friction coefficient with the addition of fullerenes to oils can reach 90% compared to the base oil.

The authors of the works^[3-5] it has been experimentally established that the way to improve the tribological properties of lubricants by introducing a finely dispersed fullerene powder into base technical oils is ineffective. In these works, a variant of preliminary dispersion of fullerenes in vegetable high-oleic oils, such as rapeseed, and then adding this composition to industrial oils is proposed. This option improves the wear rate by 26.6%, increases the critical load by 40.9%. However, the anti-seize properties of such compositions do not improve, the load of the scuff does not change. The paper presents experimental studies on the change in the friction coefficient, which decreases by 86%.

As follows from the above analysis of works, the use of fullerene compositions in lubricants is a promising direction. Compositions are obtained by preliminary dispersion of a fine powder of fullerenes in vegetable high oleic oils. Such compositions, when added to technical oils, can act as a new generation of antifriction and antiwear additives that respond to the force field of the friction surface.

Similar results with the use of fullerenes were obtained in the works^[20-24] The authors provide data on the positive effect of the use of fullerenes as additives to lubricants and working fluids. However, in the presented works, no attention is paid to the features of the interaction of fullerene compositions with energetically active friction surfaces. The issues of the mechanisms of formation of fine structures on friction surfaces and their role in reducing friction and wear are not considered.

The presented analysis of the use of fullerenes in lubricants allows us to conclude that it is necessary to study the mechanisms of formation of fine structures in the form of films on friction surfaces containing fullerene molecules. At the same time, the way to improve the tribological characteristics of lubricants by introducing a finely dispersed fullerene powder into base technical oils is recognized as ineffective. The reason is the low solubility of fullerenes in industrial oils. To do this, it is necessary to first disperse fullerenes in vegetable high oleic oil, such as rapeseed, and then add this composition to technical oils.

The use of such materials as lubricating compositions is impossible without the development of the physical foundations for the interaction of clusters and micelles containing fullerenes with energetically active friction surfaces. One way to solve this problem is to develop mechanisms for the interaction of aggregates with friction surfaces and to model such processes in the force field of an active friction surface. The simulation results will allow to substantiate the composition and content of fullerene compositions for lubricants for various purposes.

3. Purpose and objectives of the study

The purpose of this work is to carry out theoretical studies of the formation of an oil film on the energy-active friction

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surfaces of tribosystems with a force field in the presence of fullerene compositions in the lubricant.

To achieve this goal, it is necessary to solve the following tasks:

- substantiation of the structure of the model of oil film formation on energy-active friction surfaces of tribosystems;
- modeling the formation of an oil film on the energy-active friction surfaces of tribosystems in the presence of fullerene compositions in the lubricant.

4. Purpose and objectives of the study

A structural approach to studying the formation of a lubricating film containing fullerene compositions on the friction surface of tribosystems with a force field is described in the work.^[25] Based on this work, we will make the following assumptions when developing a model for the formation of an oil film on energy-active friction surfaces:

- Intensity of the force field of the friction surface during the operation of the tribosystem, express as surface energy, dimension V/m;
- The electric field strength in the volume of the lubricant, which is under the influence of the force field of the friction surface and contains clusters and micelles of fullerenes and other molecules of surfactants, we express in terms of the dimension V/m;
- The thickness of the oil film on the friction surface of the tribosystem, which is formed due to the "crosslinking" of spatial aggregates - micelles and clusters into a three-dimensional structure near the friction surface (in the force field of the friction surface), resembling a honeycomb structure, is expressed in terms of the dimension m.

5. The results of the study of the formation of an oil film on the energy-active friction surfaces of tribosystems in the presence of fullerene compositions in the lubricant

5.1. Substantiation of the structure of the model of oil film formation on energy-active friction surfaces of tribosystems

The most convenient method for determining the electric field strength is the solution of the Poisson differential equation for the potential, which is presented in the work.^[25] The right side of the differential equation contains three terms.

The first term on the right side of the differential equation determines the intensity of the force field created by the friction surface during the operation of the tribosystem:

$$E_n = \frac{\sigma}{2\epsilon\epsilon_0}, V/m, \tag{1}$$

where σ – surface charge density, Cl/m², is determined based on the work;^[26]

ϵ – relative permittivity of the lubricating medium, dimensionless quantity;

ϵ_0 – dielectric constant, equal to 8.85 10⁻¹² Cl/(V•m) or F/m.

Surface charge density σ depends on the load, sliding speed and physical and mechanical characteristics of triboelement materials (modulus of elasticity and Poisson's ratio),

determined on the basis of works.^[25,26] The magnitude of the force field strength acts as a "force field generator" of the friction surface of tribosystems.

The second term on the right side of the differential equation determines the electric field strength in the volume of the lubricating film due to the formation of clusters of fullerenes:

$$E_c = \frac{n_c \cdot p_c}{4\pi\epsilon\epsilon_0 \cdot d_c^3}, V/m, \tag{2}$$

where n_c – number of clusters per volume unit of base lubricant, pcs;

p_c – dipole moment of a cluster of fullerenes, dimension Cl•m; d_c – average distance between clusters and the friction surface, equal to the average size (diameter) of a cluster of fullerenes, dimension m.

Number of clusters n_c , that can be formed in the basic lubricating medium can be determined by the Gibbs free energy or the Gibbs potential, the value of which indicates changes in the course of a chemical reaction. The change in the Gibbs energy is determined by the expression:^[27]

$$\Delta G_c = -RT \ln \left(\frac{C_f}{CCC} \right), J/mol, \tag{3}$$

where R – universal gas constant equal to 8.3144598 J/(mol °K);

T – lubricant temperature, °K;

C_f – concentration of fullerenes in the lubricating medium, mol/m³;

CCC – critical concentration of cluster formation from fullerene molecules, dimension mol/m³.

From formula (3), one can obtain an expression for determining the number of clusters:

$$n_c = \left(\frac{C_f}{CCC} \right) = \exp \left(\frac{\Delta G_c}{RT} \right), pcs. \tag{4}$$

Dipole moment of a cluster of fullerenes p_c define by the expression presented in the work^[23]:

$$p_c = \sum_{i=1}^{n_c} p_f \cdot L(b_c), Cl/m, \tag{5}$$

where p_f – the dipole moment of the fullerene molecule is equal to 3.34 10⁻³⁰ Cl•m;

$L(b_c)$ – Langevin function.

Langevin function based on work^[27] is determined by the expression:

$$L(b_c) = cthb_c - 1/b_c, \tag{6}$$

where b_c – dimensionless quantity that takes into account the strength of the force field of the friction surface E_n and temperature of the lubricating medium, which affects the orientation of the clusters relative to the intensity vector of the force field of the friction surface:

$$b_c = \frac{n_c \cdot p_f \cdot E_n}{kT}, \tag{7}$$

where k – Boltzmann constant equal to 1.380648 10⁻²³ J/°K.

By substituting the obtained expressions (4) - (7) into formula (2), it is possible to simulate changes in the electric field strength of the lubricating medium with a change in the concentration of fullerenes, temperature and strength of the force field of the friction surface.

The third term on the right side of the differential equation

determines the electric field strength in the volume of the lubricating film due to the formation of micelles, where a fullerene molecule or a cluster of fullerene molecules acts as a core, which is surrounded by attached macromolecular acid molecules (oleic, stearic, etc.). Such acids act as a "solvent" of fullerenes. The expression for determining the magnitude of the electric field due to the formation of micelles can be written as:

$$E_m = \frac{n_m \cdot p_m}{4\pi\epsilon_0 \cdot d_m^3} \cdot V/m, \quad (8)$$

where n_m – number of micelles per volume unit of base lubricant, pcs;

p_m – micelle dipole moment, Cl•m;

d_m - the average distance between the micelle and the friction surface, equal to the average size (diameter) of the micelles, dimension m.

When a certain concentration of fullerene molecules and a solvent, which is rapeseed vegetable oil, is reached, aggregates of the same type of micelle molecules are formed in the volume of the lubricant. This concentration is called the critical micelle concentration (CMC).

The number of micelles that can be formed in the basic lubricating medium is determined based on the change in the Gibbs energy²³:

$$\Delta G_m = -RT \ln \left(\frac{C_{f+ola}}{CMC} \right), J/mol, \quad (9)$$

where C_{f+ola} – concentration of fullerenes and "solvent" (vegetable oil containing oleic acid) in the basic lubricating medium, mol/m³;

CMC – critical micelle concentration, mol/m³.

Based on (9), the number of micelles is determined by the expression:

$$n_m = \left(\frac{C_{f+ola}}{CMC} \right) = \exp \left(\frac{\Delta G_m}{RT} \right), pcs. \quad (10)$$

The dipole moment of the micelle is determined from the work:¹²⁷

$$p_m = \sum_{i=1}^{n_m} p_{f+ola} \cdot L(b_{f+ola}), Cl \cdot m, \quad (11)$$

where p_{f+ola} – dipole moment of a macromolecular acid molecule, for example, for oleic acid in the presence of a fine powder of fullerenes $p_{f+ola} = 4.84 \cdot 10^{-30}$ Cl•m.

The Langevin function takes into account the orientation of micelles in the force field created by the friction surface, taking into account thermal vibrations of molecules:

$$L(b_m) = cthb_m - 1/b_m, \quad (12)$$

$$b_m = \frac{n_m \cdot p_{f+ola} \cdot E_n}{kT}. \quad (13)$$

By substituting the obtained expressions (10) - (13) into formula (8), it is possible to simulate changes in the electric field strength of the lubricating film with a change in the concentration of the fullerene solvent and fine fullerene powder, which leads to the formation of micelles. As follows from the obtained expressions, the micelle formation process, in addition to the concentration of the solvent of fullerenes, is affected by the temperature of the lubricating medium and the intensity of the force field of the friction surface.

During the functioning of the tribosystem, due to the

influence of temperature, as well as the load and sliding speed, the process of cluster and micellization, as well as their destruction, can occur simultaneously, therefore, the total electric field of the lubricating medium E_g defined as the sum:

$$E_g = E_c + E_m, V/m. \quad (14)$$

5.2 Modeling the formation of an oil film on energetically active friction surfaces of tribosystems in the presence of fullerene compositions in the lubricant

Applying the dimensional analysis method, which is widely used in the theory of similarity and simulation, as well as experimental data, it is possible to obtain an expression for determining the thickness of the lubricating film that will be formed on the friction surface under the influence of the force electric fields of the friction surface and liquid:

$$h = \frac{\mu(T_v) \cdot A_{fa} \cdot v_{sl}}{N} \left(\frac{E_n + E_g}{\sqrt{E_n^2 + E_g^2}} \right), m, \quad (15)$$

where h – lubricating film thickness, m;

$\mu(T_v)$ – function of dynamic viscosity change in the volume of the oil film as a function of temperature, Pa•s;

A_{fa} – the actual friction area, which is the sum of the friction areas of all actual contact patches, the dimension m², is determined based on the work;²⁸

v_{sl} - sliding speed, m/s;

N – tribosystem load, N.

Operating temperature in the volume of a thin oil film on the friction surface T_v , define by expression:

$$T_v = T \cdot \exp \left(\frac{\beta \cdot W_{TS}}{N \cdot v_{sl}} \right), ^\circ C, \quad (16)$$

where T – volumetric temperature of the lubricating medium, for example, in an oil bath, °C;

β - coefficient equal to 20, dimensionless quantity;

W_{TS} - the rate of dissipation work in the tribosystem, J/s, is determined on the basis of the work.²⁸

The function of changing the dynamic viscosity in the volume of the oil film on the friction surface is determined by the expression:

$$\mu(T_v) = \mu_0 \cdot \exp(-\alpha(T_v - T)), Pa \cdot s, \quad (17)$$

where μ_0 - dynamic viscosity of the lubricant at 100 °C, Pa•s;

α – piezoelectric coefficient equal to 0.013, dimension 1/°C.

Result of the change $\mu(T_v)$, which is obtained using formulas (16) and (17), is substituted into expression (15) to simulate a change in the thickness of the lubricating film h .

The solution of the Poisson differential equation, which is presented in the work²⁵ is a function:

$$E(z) = (E_n + E_g) \cdot \exp\left(-\frac{z}{h}\right), V/m, \quad (18)$$

where z – distance from the friction surface along the normal, dimension m.

Initial data for modeling the change in the thickness of the oil film on the friction surface of tribosystems depending on the intensity of the force field of the friction surface and the presence of aggregates in the form of clusters or micelles in the volume of the oil film. The “ring-ring” tribosystem

(friction machine UMT-1) was chosen as the objects of modeling. Movable triboelement - 40Kh steel, HRC 55 ... 58, (the analog of AISI 5135 and 5140 steels), fixed triboelement - bronze Br.AZh 9-4 HB 110, (analogous to C61900 AISI), $K=0,5$. Motor oil was used as the base lubricating medium M-10G2k (mineral oil, viscosity corresponds to SAE 30, according to performance characteristics API CC, oil analogue: ROTELLA SX 30 SHELL). The load varied within $N=400...1800$ N; sliding speed $v_{sl}=0,1...0,9$ m/s.

The dipole moment of a fullerene molecule is equal to $p_f = 3.34 \cdot 10^{-30}$ Cl·m; the dipole moment of an oleic acid molecule is $p_{ola} = 4,84 \cdot 10^{-30}$ Cl·m. The average diameter of a cluster formed from fullerenes is $d_c = 5 \cdot 10^{-7}$ m; The average diameter of a micelle of fullerenes and oleic acid is $d_m = 4 \cdot 10^{-6}$ m. The presented data are obtained on the basis of publications.^[17-19] The critical concentration of cluster formation varied within $CCC = 0.01...0.1$ mol/m³; critical micelle concentration $CMC = 0.01...0.1$ mol/m³.

The results of modeling the change in the thickness of the oil film on the friction surface from the strength of the force fields of the friction surface and the liquid are shown in Fig. 1. The degree of influence of operating temperature $T^\circ\text{C}$ on the thickness of the lubricating film depending on the total intensity of electric fields $E = E_n + E_g$, shown in Fig. 2.

The results of modeling the formation of the number of clusters and micelles in the volume of the lubricant, which were obtained on the basis of solving the differential equation in the form of a function (18), are shown in Fig. 3 and Fig. 4.

6. Discussion of the results of studies of the formation of an oil film on energy-active friction surfaces of tribosystems in the presence of fullerene compositions in the lubricant

An analysis of the dependences presented in Fig. 1 allows us to state that the magnitude of the force field strength of the surface E_n is a more significant factor than the magnitude of the electric field strength of the liquid E_g . As follows from Fig. 1, for small values $E_n = 2,5 \cdot 10^6$ V/m film thickness is one molecule of oleic acid $h = (1 - 7) \cdot 10^{-11}$ m. When increased to $E_n = 7,5 \cdot 10^6$ V/m, film thickness increases to $h = 1 \cdot 10^{-6}$ m. The obtained simulation results confirm that the friction surface, as a "force field generator", is a more significant factor in the formation of an oil film on the friction surface.

From the analysis of dependences of the influence of operating temperature $T^\circ\text{C}$ on the thickness of the lubricating film depending on the total intensity of electric fields $E = E_n + E_g$, Fig. 2, we can conclude that the change in temperature from $T = 80^\circ\text{C}$ to $T = 120^\circ\text{C}$ leads to a decrease in film thickness from $h = 4,5 \cdot 10^{-7}$ m to $h = 2,5 \cdot 10^{-7}$ m.

An increase in the number of aggregates (clusters and micelles) in the volume of the lubricant, Fig. 3, increases the total electric field strength of the lubricating film E_g , which is formed under the action of the force field of the friction surface E_n . At the same time, using a "solvent" for fullerenes in the form of macromolecular acids, it is possible to achieve an increase in the number of aggregates by more than an order

of magnitude. This is explained by the fact that when using a "solvent", fullerene molecules form clusters in the lubricant to a lesser extent, and begin to actively form micelles, which was proved in the work.^[15] The micelle core is a single fullerene molecule or a cluster of several fullerene molecules with polar molecules of a high molecular weight acid, such as oleic acid, attached to the core.

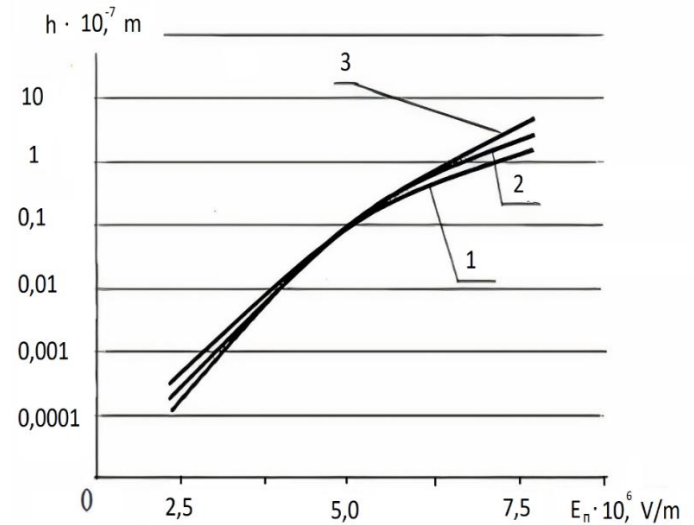


Fig. 1 Results of modeling: dependences of the change in the thickness of the oil film on the strength of the force fields of the friction surface and liquid: 1 – $E_g = 1,6 \cdot 10^6$ V/m; 2 – $E_g = 3,2 \cdot 10^6$ V/m; 3 – $E_g = 7,2 \cdot 10^6$ V/m.

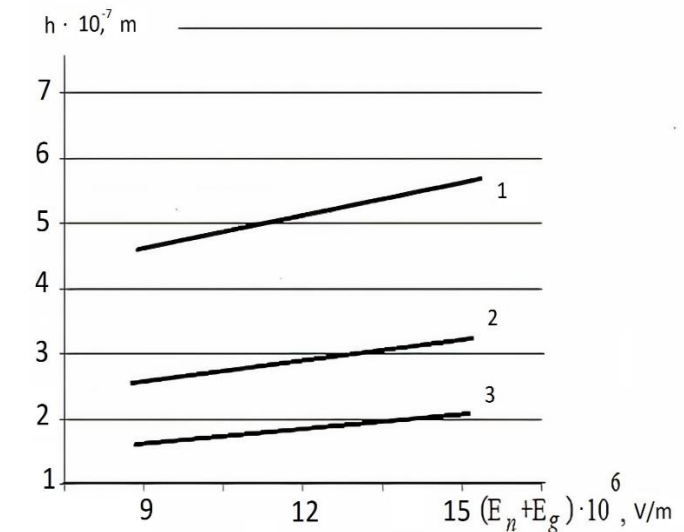


Fig. 2 Results of modeling: dependences of the change in the thickness of the lubricating film on the magnitude of the total electric field strength and operating temperature: 1 – $T = 80^\circ\text{C}$; 2 – $T = 120^\circ\text{C}$; 3 – $T = 160^\circ\text{C}$.

It should be noted that the depth of penetration of the force field into the lubricant z does not exceed $0,2 \mu\text{m}$. According to the results of the numerical analysis for $z = 0,2 \mu\text{m}$ the value of the total force field decreases from 100% to 13%.

The dependences of the change in the total electric field strength in the lubricating film on the value of the dipole

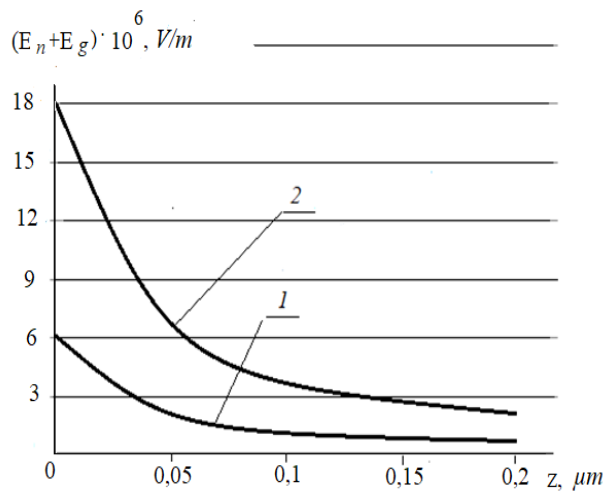


Fig. 3 Results of modeling: dependences of the change in the total strength of the force field of the friction surface and the electric field in the lubricating film on the number of aggregates (clusters and micelles) and the distance from the friction surface: 1 – number of clusters $n_c = 1 \cdot 10^3$ pcs; 2 – number of micelles $n_m = 50 \cdot 10^3$ pcs.

moment of the aggregates and the distance from the friction surface are shown in Fig. 4. It follows from the presented dependences that the higher the dipole moment of the aggregates, the greater the total electric field strength in the volume of the oil film. This effect will have a positive effect on the formation of the structure of the lubricating film on the friction surface and on the wear resistance of the tribosystem. An increase in the dipole moment of aggregates is facilitated by the formation of micelles.

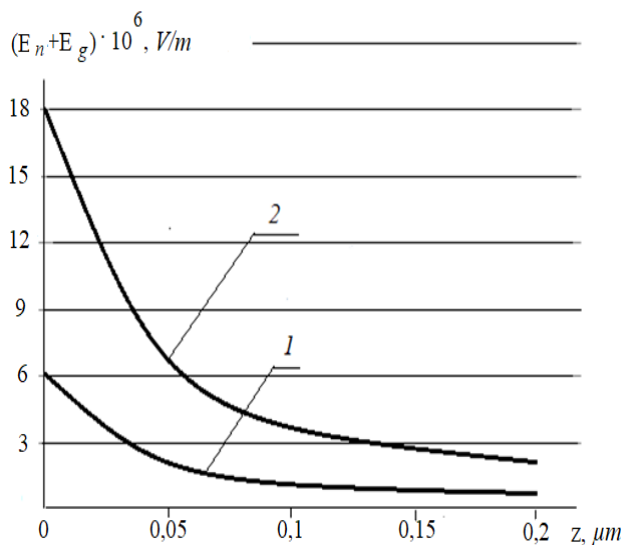


Fig. 4 Results of modeling: dependences of the change in the total strength of the force field of the friction surface and the electric field in the lubricating film on the magnitude of the dipole moment of aggregates (clusters and micelles) and the distance from the friction surface: 1 – dipole moment of clusters $p_c = 3,31 \cdot 10^{-27}$ Cl•m; 2 – dipole moment of micelles $p_m = 9,04 \cdot 10^{-26}$ Cl•m

Experimental studies were carried out using the laboratory equipment, materials, and structures of tribosystems described above for modeling. The error between the results of modeling and experiment was calculated by the formula:

$$e_I = \left| \frac{I_{ex} - I_m}{I_m} \right| \cdot 100\%, \quad (19)$$

where I_{ex} , I_m , are the values of the wear rate measured during the experiment and obtained during modeling.

The results of experimental studies of the change in the volumetric wear rate I , m^3/h , for the tribosystem: movable triboelement steel AISI 5135, fixed triboelement - bronze C61900 AISI, with a change in the load N , N , and sliding speed v_s , m/s , are shown in Fig. 5 and Fig. 6. The "base oil" curve corresponds to the volumetric wear rate of a tribosystem where the lubricant (mineral oil, viscosity corresponds to SAE 30, according to API CC performance characteristics) does not contain fullerene additives. The lower curves correspond to the following concentrations of fullerene compositions: 50 g/kg = 0.5 g/kg of fullerenes + 49.5 g/kg of vegetable rapeseed oil; 100 g/kg = 0.75 g/kg of fullerenes + 99.25 g/kg of vegetable rapeseed oil; 150 g/kg = 1 g/kg of fullerenes + 149 g/kg of vegetable rapeseed oil.

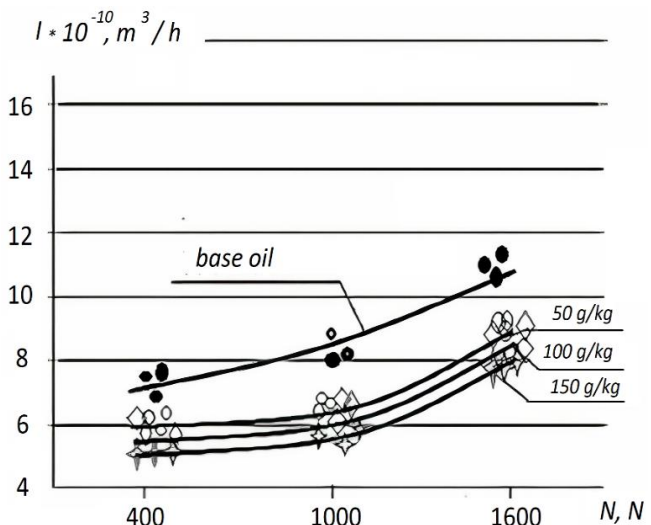


Fig. 5 Experimental and theoretical dependences of the change in the volumetric wear rate on the load and the concentration of the fullerene composition in the base oil.

This range of changes in the concentration of fullerene compositions was selected on the basis of experimental studies that were analyzed on the basis of publications, for example [3]. The result of these studies is the conclusion that an increase in the fullerene composition of more than 150 g/kg does not have a positive effect.

The analysis of the obtained experimental dependences (points on the field of graphs, Fig. 5 and Fig. 6) and their

comparison with theoretical curves (solid lines) allows us to conclude that the error in modeling the volumetric wear rate of the tribosystem is 8.9-14.0%. A higher error value corresponds to higher loads. This can be explained by an increase in temperature in the friction zone during tests at higher loads. When changing the sliding speed, on the contrary, a large error corresponds to a lower sliding speed.

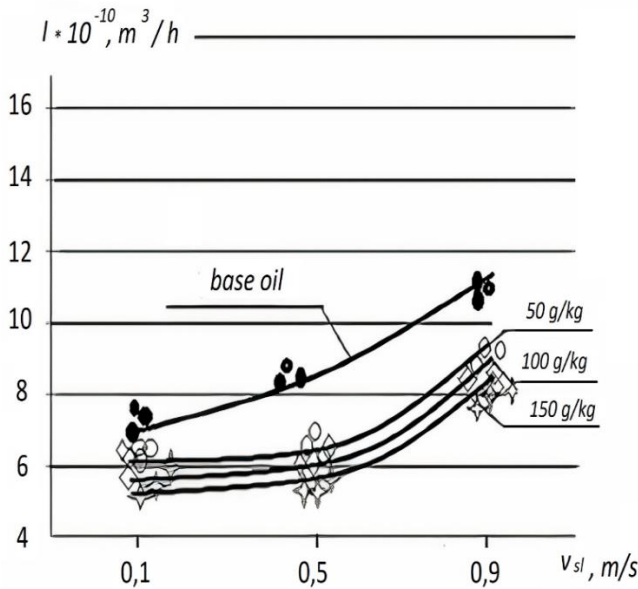


Fig. 6 Experimental and theoretical dependences of the change in the volumetric wear rate on the sliding speed and the concentration of the fullerene composition in the base oil.

The reproducibility of the results of wear rate measurements was evaluated using the Cochran criterion:

$$G_p = \frac{S^2_{max}}{\sum_{i=1}^N S^2_i} \tag{20}$$

where S^2_{max} - is the maximum value of the standard deviation for the volumetric wear rate, m^3/h ;

S^2_i - are the values of the standard deviation of the i -th experiment for the volumetric wear rate, respectively.

The hypothesis is being tested:

$$G_c < G_{tabl} \tag{21}$$

where G_{tabl} is the tabulated value of the Cochran criterion at a given confidence level $q = 0.90$.

The values of the standard deviation of the wear rate, which was determined using the method of artificial bases at different load values, are presented in Table 1, for different values of the sliding speed, in Table 2.

The analysis of the calculated values of the Cochran criterion – G_c and tabulated values - G_{tabl} at a given significance level of 0.9 (the number of evaluated parameters is 2, the number of repetitions is 4) allows us to conclude that condition (21) is met, *i.e.*, the measurement results are homogeneous and reproducible.

From the analysis of the presented experimental values and

their comparison with theoretical dependences, it follows that the mathematical model of the formation of a lubricating film on the friction surface of triboelement adequately reflects the wear process and is in a functional relationship with the wear rate.

Table 1. Values of the standard deviation of the wear rate and the Cochran criterion at different loads, concentration of fullerene composition 100 g/kg.

N, N	$S^2_{I_{max}}$	$\sum S^2_{I_i}$	G_c	G_{tabl}
400	$(0,605 \cdot 10^{-10})^2$	$(0,770 \cdot 10^{-10})^2$	0,785	0,853
1000	$(0,689 \cdot 10^{-10})^2$	$(0,877 \cdot 10^{-10})^2$	0,785	0,853
1600	$(1,093 \cdot 10^{-10})^2$	$(1,385 \cdot 10^{-10})^2$	0,789	0,853

Table 2. The values of the standard deviation of the wear rate and the Cochran criterion at different values of the sliding speed, the concentration of the fullerene composition is 100 g/kg.

$V_{sl}, m/s$	$S^2_{I_{max}}$	$\sum S^2_{I_i}$	G_c	G_{tabl}
0,1	$(0,628 \cdot 10^{-10})^2$	$(0,778 \cdot 10^{-10})^2$	0,807	0,853
0,5	$(0,636 \cdot 10^{-10})^2$	$(0,795 \cdot 10^{-10})^2$	0,800	0,853
0,9	$(1,000 \cdot 10^{-10})^2$	$(1,259 \cdot 10^{-10})^2$	0,794	0,853

Experimental studies have made it possible to confirm the theoretically obtained result that the use of a fullerene composition consisting of a solvent and finely dispersed fullerene powder reduces the wear rate when the load and sliding speed change by 21.2...24.9%. The modeling error is 6.5...9.2%.

Experimental studies have confirmed that an increase in the concentration of the fullerene composition in the base oil from 50 g/kg to 150 g/kg can reduce the volumetric wear rate by 7.8% (theoretical result is 6.4%). Therefore, the direction of reducing the volumetric wear rate by increasing the concentration of the fullerene composition above 100 g/kg can be recognized as ineffective and experimentally confirmed.

The result obtained differs from the known ones, which are given in the literature review, in that it allows us to expand the methods of using fullerenes in lubricants. Based on the above conclusions about the effect of the number of aggregates and their dipole moments on the magnitude of the total electric field, it is possible to justify the need to use a "solvent" of fullerenes, which will "start" the formation of micelles with a core of one fullerene molecule.

Based on work^[3] it can be concluded that macromolecular acids can act as "solvents". However, in the works of Academician P.A. Rebinder proved that there is a limiting solubility of macromolecular acids in lubricants, not more than 0.2% of the mass. This problem can be solved by using high-oleic varieties of vegetable oils, for example, rapeseed, which contains 76 - 82% of the mass. oleic acid. These vegetable oils are infinitely soluble in mineral and synthetic technical oils (motor, transmission, hydraulic).

The presented results are a continuation of the studies that are presented in the work³. Using the obtained theoretical

studies of the formation of an oil film on energy-active friction surfaces, it is possible to substantiate the content (% mass) of fullerene compositions in the lubricant, taking into account the load-speed range of operation of tribosystems.

As follows from the presented studies, fullerene compositions have rational modes of application. As shown by the experimental studies presented in the work^[3] adding a finely dispersed fullerene powder to a lubricant does not give a great effect. Dispersing fullerenes in a solvent, and then adding such a composition to the lubricant increases the effect of the application. In our work, rapeseed vegetable oil is used as a solvent. It should be noted that there is a wide class of fullerene solvents. Research on the use of various solvents is a promising area for further research.

The undertaken topic has a big potential for further research in the future. When it comes to further direction of research, in our opinion, it lies in the formation of "crosslinked" structures on the friction surface. Such structures lead to a change in the arithmetic mean deviation of the profile points Ra, μm and the average step of irregularities along the center line of the profile Sm, mm of newly formed friction surfaces. Defining decrease constraints Ra while increasing Sm when changing the thickness of the oil film h, will allow to obtain a decrease in the wear rate and a decrease in the coefficient of friction during the operation of tribosystems. The purpose of such studies is to predict the resource of tribosystems.

7. Conclusions

Theoretical studies have been carried out on the formation of an oil film on the energy-active friction surfaces of tribosystems with a force field in the presence of fullerene compositions in the lubricant. The role of the friction surface on the formation of clusters and micelles from fullerene molecules in a lubricant film has been established. It is shown that under the action of the stress-strain state of the surface layers, the friction surface acts as a "force field generator", which affects the formation of an electric field in the volume of the oil film. Expressions are obtained for calculating the intensity of the total force field of the system "friction surface + lubricant".

The results of modeling the change in the thickness of the oil film, as well as the formation of clusters and micelles based on fullerene molecules on the strength of the force fields of the friction surface and in the volume of the oil film, are presented. It is shown that the formation of micelles, in comparison with clusters, significantly increases the total strength of the force fields and causes an increase in the film thickness. It has been theoretically established that the use of "solvents" of fullerenes, which can be high oleic vegetable oils, can "start" the process of micellization, where the micelle core is a fullerene molecule surrounded by oleic acid molecules.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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