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INFLUENCE OF POWER TRANSMITTER DYNAMIC LOAD ON PHYSICAL AND CHEMICAL PROPERTIES OF USED LUBRICANT

A. Ilić[1], D. Josifović[1], L. Ivanović[1], S. Savić[1]
[1]Faculty of Mechanical Engineering, University of Kragujevac, Kragujevac, Serbia,
gilic9@sbb.rs ; danaj@kg.ac.rs ; lozica@kg.ac.rs ; ssavic@kg.ac.rs

Abstract: *The tribologycal conditions within gear power transmitters as a real tribomechanical system are quite complex and are conditioned to a large extent with the characteristics of used lubricant. Complexities of the conditions are determined by temperature of the elements in contact, current properties of the used lubricant, external load in reference to specific pressures in contact zone, dynamic nature of contact creating, transfer of power and movement. The aim of this paper is to establish the influence of power transmitters' dynamic load to its lubricant degradation. Also, the basic elements of analytical approach to lubricant film behavior under the dynamic loaded conditions were given in this paper. Variations in exploitative conditions lead to variations in load of elements in contact and provoked variation of friction coefficient, so as temperature and pressure decrease. By the means of all listed, those variations lead to changes of lubricant characteristic and its degradations. Furthermore, the intensive wearing and damages of power transmitter elements are provoked. All of the listed facts imposed the great importance of lubricant's current chemical composition, real behavior and its acting mechanisms. Beside all, stability of lubricant's physical and chemical properties during working life is key element of power transmitters' safety and reliability. Experimental procedure shown in this paper refers to testing of power transmission properties and its lubricant properties subjected to dynamic load. Lubricant sampling in exploitation provide very important data of current lubricant condition through its properties testing. Experimentally obtained results point out the necessity of considering the lubricant's present properties as timely depended constructive element. Paper conclusions bring the proposals for reduction of the unwanted consequences due to lubricant degradation. In that way, minimal losses of material and energy, so as decrease of maintenance coasts and minimal ecological impact can be done.*

Keywords: *dynamic load, power transmitter, lubrication, pressure, temperature*

1. INTRODUCTION

Power transmitters and especially gear power transmitters are very dependent on properties of the lubricants for their lubrication. Distinctive close correlation of gear power transmitters properties with the characteristics and properties of lubricants, make this type of power transmitters the most interesting for examining the influence of dynamic load of power transmitters on the physical-chemical properties of its lubricants. In addition to this aspect, the complexity of tribological processes in the gear power transmitters represents one more reason for observing this type of power transmitter during the examination of the influence of dynamic loads of power transmitters on the physical-chemical properties of lubricants [1].

During exploitation, power transmitters are exposed to time variable, dynamic and unsteady loads which represent the functions of a range of factors. Operating regime changes lead to changes in working loads of elements, force and friction coefficient of contact surfaces, increase in operating temperature, and with all these, to changes of properties and lubricant degradation, intensive wear and damage to power transmitter elements. In order to reduce friction and wear, and thereby prevent damage and prolong the life of the power transmitter, various types of lubricants are used. Selection of lubrications for power transmitters depends on the type and construction of the transmitter, materials of which the elements are made, the type and level of loads, working conditions, lubrication method, operating regime and the like [2]. Lubricants should be seen as a constructural element and is therefore very important to know their composition, properties and mechanisms of action. This is illustrated by the fact that many analyses of failure causes of power transmitters have shown that they occurred as consequences of the use of lubricants of poor or inadequate properties [3]. Also, the stability of physical and chemical properties of used lubricant during exploitation is very important. Moreover, by lubricant sampling, very important information about the current condition of lubricants in the system can be obtained, and further, its physical and chemical properties can be examined and an assessment can be provided of whether it is necessary to replace it. The proactive system maintenance with a regular review of functional parameters has a significant role in it [4, 5 and 6].

2. THEORETICAL APROACH – HYDRODYNAMIC THEORY OF LUBRICATION

The usual considerations of some real problems refer to the approach that uses the approximate differential equations of viscous liquids flow that are obtained from the full differential equations by neglecting nonlinear inertial members while retaining the members who are conditioned by viscosity. Further improvement of development the approximate solving methods is based on differential equations that are obtained from the Navier - Stokes equations when some members who are conditioned by viscosity except the nonlinear inertial members are ignored. A very important technical problem of lubrication gave the impulse for the development of approximate method based on these differential equations [7].

The founder of the hydrodynamic theory of lubrication is the Russian scientist Petrov who considered the possibility of direct application of Newton's hypothesis of stress and displayed the solution in case of shaft and bearing surfaces being coaxially cylindrical. In order to confirm the theoretical conclusions, Petrov has performed a large number of experiments which didn't only confirm the basic assumptions of his theory but also contributed to explanation of the problems related to the mineral oil use.

Circular flow of parts of viscous fluid between two cylinders that rotate around axes which correspond, Petrov has observed under conditions of partial fluid sliding along the walls, unlike the approach that includes complete liquid sticking to the walls. On the basis of experiments and further development of theories that deal with these problems, it was found that the basic links that Petrov obtained correspond to borderline case, of shaft rotation with a large number of revolutions, whereby the shaft carries a relatively small load. For this borderline case the shaft axis creates only a small deviation from the bearing axis, so that this deviation without loss of generality can be neglected. Under normal conditions of exploitation, however, the bearing axis does not correspond with the shaft axis. This kind of eccentric shaft position in the bearing leads to forces that balance the shaft load. Lubrication theory for the eccentric shaft position was developed by Zhukovsky and Chaplygin [7].

By comparison of the Reynolds differential equations for the lubricant film with the Navier - Stokes equations it is shown that for their production there is a need to disregard not only all the non-linear inertial members but also the members who are conditioned by viscosity. With the assumption of differential equations solutions in the form of rows and by comparison of the members with the same degrees, the row of differential equations systems is obtained, with the first system of this row being the Reynolds equation, while the other system contains Laybenson's equations for the lubricating film [7].

3. PROPERTIES OF THE USED LUBRICANT

The physical properties of lubricating oil are density, colour, viscosity, fire point, the point of hardening and flow, blurring point, specific heat and thermal conductivity, volatility, emulsivity and de-emulsivity, foaming, air separation ability (deaeration) and more. Viscosity is one of the most important properties of lubricants from the tribological aspect and it represents a measure of internal friction. Viscosity occurs as the result of action of the intermolecular forces in the lubricant and as forces grow stronger the viscosity grows higher. Viscosity shows its greatest impact during total lubrication, because film thickness, temperature increase and losses due to friction depend on it. Lubricants behave as Newtonian or non-Newtonian fluids, depending on whether the link between shear stress and velocity gradient is linear or not. Viscosity can be viewed through the dynamic and kinematic viscosity. Dynamic viscosity is obtained by applying Newton's law that connects the shear stress in the fluid and velocity gradient. Kinematic viscosity is the ratio of dynamic viscosity and fluid density. With lubricants that behave as Newtonian fluids, viscosity is a function of temperature and pressure. Oil viscosity decreases with temperature increase by a certain regularity that is increases with temperature drop. During the exploitation viscosity change tends to be as small as possible. Change of viscosity with temperature change is expressed through the dimensionless number - viscosity index. With non-Newtonian fluids, viscosity is not constant at the given temperature and pressure, but depends on the change of shear velocity. Emulsions, suspensions and multigrade oils are among the non-Newtonian fluids. Apparent viscosity is the measurement of viscosity at the specific shear gradient, while the structural viscosity represents the viscosity drop due to increase of shear velocity. Apparent viscosity describes the behaviour of oil at low temperatures. At the beginning of growth of shear velocity, multigrade oils retain their Newtonian character. Non-Newtonian area, which then follows, features a dramatic drop of viscosity. By continuing growth of shear velocity, oil re-enters the Newtonian area, which differs from the previous one. In this area, the present polymer molecules are no longer deformed. The relative viscosity drop increases with temperature lowering and pressure growth at amounts to 10-70 %. Typical example of a complex tribomechanical system with gear power transmitter operating in very changeable conditions of exploitation is the vehicle's gearbox transmission. Transmission of the vehicle consists of the elements of power transmission and motion (gears and grooved shafts), the elements of information transfer (leverage), elements of conduct (guides) and seals (gaskets). Each of these elements of the transmission can be analyzed as a set of special tribomechanical systems, such as gear pairs, bearings, etc. Also, each gear pair can be further analyzed as a single element which makes the contact. And finally each gear tooth flank or ball of roller bearing can be seen as a basic unit of tribomechanical system. This analysis suggests the fact that the tribological characteristics of a complex tribomechanical system can not be seen in a simple matter and that it is not possible to establish reliable methods and determine the diagnostic parameters for assessing the state of an observed system. Direct participation of lubricant in the contact processes of gear transmitter as tribomechanical system, with the main task to prevent the direct contact of surface elements, provides the lubricant with a special role from the aspect of testing. The lubricant is the carrier of information about the state of gear transmitter as a whole, with attention specially paid to the processes that affect the functionality and reliability. The importance of this information is expressed in monitoring and system diagnosis, because lubricant analysis can point to signs of potential problems that lead to failure, as well as to provide consideration of lubricant influence on the system operation [4, 5 and 6].

4. EXPERIMENTAL TESTING OF OIL PROPERTIES AND THEIR CHANGES DURING THE EXPLOITATION

The subject of testing in this paper is the experimental determination of property changes of gear oil during operation depending on the dynamic properties of loads. The oil SAE 80W-90 of API GL-5 quality was tested which was used in gear group of working machines whose main properties are shown in Table 1. During the testing, the oil was tested that belonged to the gear group of working machines which were used in real conditions of exploitation [6].

Table 1. The values of basic physical - chemical properties of the new oil SAE 80W-90

Properties	**Value**
Appearance	clear
Color	ASTM 5.0
Density	0.902
Viscosity at 40^0C, $\frac{mm^2}{s}$	212.5
Viscosity at 100^0C, $\frac{mm^2}{s}$	18.27
Viscosity index, %	97
Level of combustion, ^{0}C	216
Level of solidification, ^{0}C	-18
Foaming (sequence I, II and III)	0/0
Corosity to Cu, 100^0C/3	1^a
TAN, mgKOH/gr	0.9
Humidity, %	0

Allowed quantities of certain elements in used gear oil and allowed values of deviations in physical - chemical properties of new and used oil are given in Tab.2.

Table 2. Allowed values of deviations in physical - chemical properties of oil

Physical-chemical properties of oil and wearing products	**Maximum deviation allowed**
Viscosity at 40^0C, $\frac{mm^2}{s}$	15%
Viscosity at 100^0C, $\frac{mm^2}{s}$	15%
Viscosity index, %	±5%
Total Acid Number (TAN), mgKOH/gr	3 mgKOH/gr
Insoluble residue in toluene, %	0.50%
Wearing products – Fe content, ppm	500 ppm

Table 3. Values of the tested physical and chemical properties of used gear oil SAE 80W-90, API classification GL – 5 during exploitation

Properties	**Value after period of exploitation, *h***												
	Sample	Gearbox 1				Gearbox 2				Gearbox 3			
		42	111	217	349	42	111	217	349	42	111	217	349
Color	ASTM 5.0	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black
Density	0,902	0,903	0,907	0,909	0,913	0,905	0,908	0,91	0,915	0,906	0,911	0,916	0,919
Fire point, ^0C	216	218	221	225	227	220	224	229	230	222	226	230	231
Level of solidification ^0C	-18												
Humidity, %	0	0	0	0	0	0	0	0	0	0	0	0	0
Foaming	0/0												
Viscosity at 40^0C, $\frac{mm^2}{s}$	212,5	215,2	223,8	226,1	229,6	216,3	224,7	226,6	230,3	223,6	224,9	227,2	231,1
Viscosity at 100^0C, $\frac{mm^2}{s}$	18,27	18,53	18,96	19,16	20,15	18,76	19,12	19,56	20,34	19,05	19,63	20,04	20,71
Viscosity index, %	97	97	96	96	96	98	95	96	96	98	97	96	96
TAN, mgKOH/gr	0,9	1	1,25	2	2,6	1,1	1,7	2,4	2,7	1,2	1,9	2,5	2,75
Insoluble residue in toluene, %	0	0,03	0,06	0,08	0,15	0,05	0,07	0,1	0,17	0,09	0,13	0,19	0,25
Fe content, ppm	0	25	41	270	349	76	260	375	670,5	112	335	536,5	873,4

Experimental testing included determining the color, density, viscosity at 40^0C and 100^0C, determining viscosity index, fire point and compressibility, TAN, foaming control, humidity content control, control of the insoluble residue in toluene and content control of wear products - iron. The oil of three gearboxes after various intervals of exploitation was tested out [6]. The results of experimental testing are presented in Table 3. Experimental testing was carried out in accordance with manufacturer specifications and proper standards by using the necessary equipment.

Figure 1. shows the change in density of the tested oils during exploitation.

Besides determining the impact of dynamic load characteristics on changes in the physical and chemical properties of oil, the goal of experimental testing was also the checking of the oil replacement intervals, checking the choice of lubricant and monitoring the oil quality.

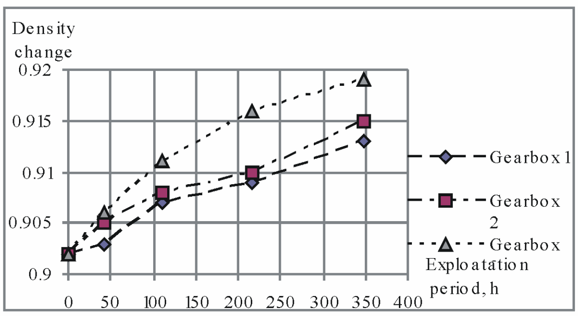

Figure 1. Density change of sampled gear oils

Besides determining the impact of dynamic load characteristics on changes in the physical and chemical properties of oil, the goal of experimental testing was also the checking of the oil replacement intervals, checking the choice of lubricant and monitoring the oil quality. Density change has a trend of slight growth expressed during whole period of exploitation [6]. Figure 2. presents the change of temperature of fire of the tested oil.

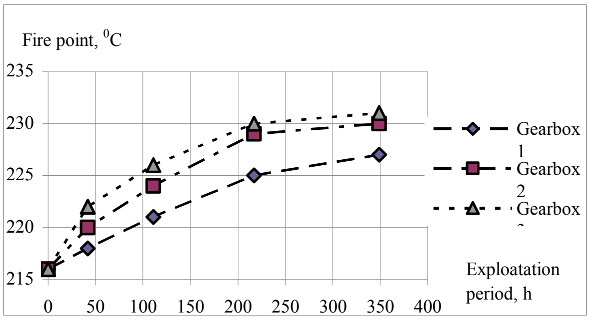

Fig.2. Change of fire point of sampled oil

The growth of fire point indicates the oxidation (aging) of oil or evaporation of easily volatile components. Oil on which sampling was conducted, has a trend of continuous growth (Figure 2.) of fire point, which is another inevitable indicator of oil oxidation due to dynamic load characteristics. Figure 3 shows viscosity change of the tested oil at temperature of 40^{0}C, while figure 4 shows viscosity change at temperature of 100^{0}C.

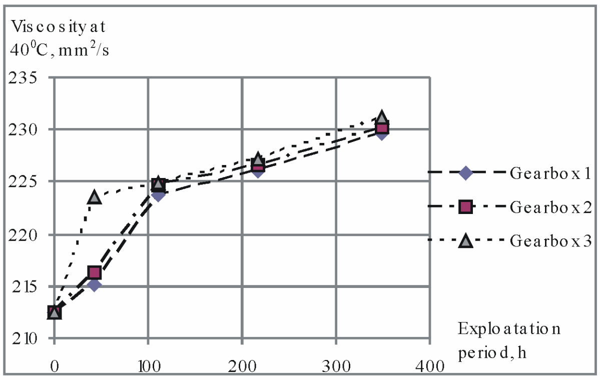

Figure 3. Viscosity change at 40^{0}C of tested oils

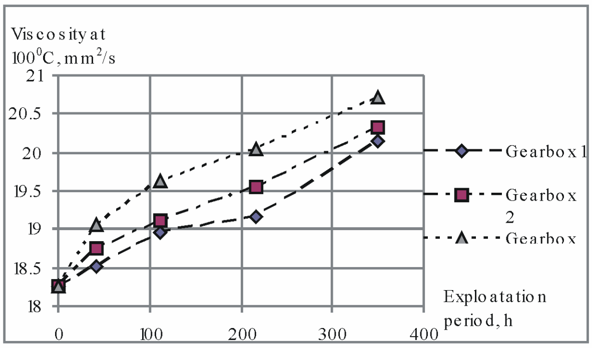

Figure 4. Viscosity change at 100^{0}C of tested oils

In the figure 3. and figure 4. there is an evident trend of constant viscosity growth during exploitation. This increase in viscosity is a consequence of properties change of tested oils due to dynamic loads during exploitation. The increase in viscosity indicates the process of oil oxidation as well or oil contamination with water and dirt, as well as wears products. In the analyzed oil there was no oil contamination with water, because during the analysis of the tested samples water did not show. This conclusion is suggested by the fact that in the examined samples there was no foaming, given that one of the reasons for foaming is the presence of water. It is concluded that one of the main reasons for the increase of viscosity oil oxidation, and contamination of oil by wear products. Water is an undesirable contaminant in the oil, and it is the most present liquid contaminant of lubricating oil and originates from the environment or it is the result of condensation. Water was not the cause of oil degradation in terms of oxidation, the destruction of the oil film, causing corrosion, deposit formation and hydrolysis of certain additives. Particles that got into the oil caused an increase in the intensity of oxidation processes in which process acidic compounds and insoluble products are formed that are internal contaminants. Also, these products neutralize the additive polar molecules in the oil, particularly anti-wear and EP additives, corrosion inhibitors and dispersants. Furthermore, very fine solid particles in stable oil suspension cause an increase in oil viscosity. In regard to the fact that allowed deviations of viscosity at 40^{0}C and 100^{0}C amount to a maximum of 15% to initial values it can be concluded that tested oils meet this criterion. Viscosity drop may be due to mixing with the oil of lower viscosity or due to lower concentration of viscosity improver. Causes of this process can also be high temperature, load, long exploitation interval, insufficient quantity of oil, inefficient cooling and the like. As shown in the figure 5. TAN have trend of increase which indicates oil degradation.

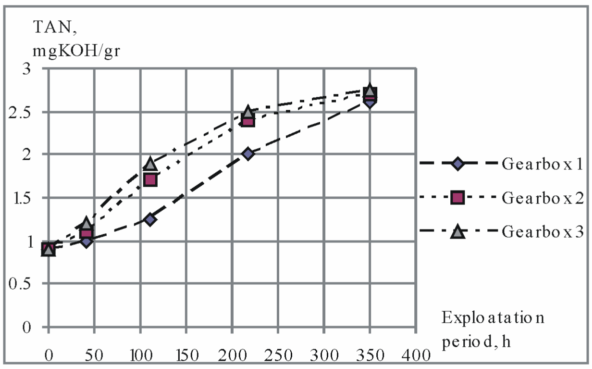

Figure 5. Change of TAN for sampled gear oils

During the exploitation testing of the change in TAN the values were reached which were in within the permissible range of values according to an appropriate standard and specifications of manufacturers. With mineral oils with fewer additives TAN grows rapidly, while with oils that has high additive content, in the initial period of exploitation it decreases, and then receives a growing character. By degradation of oil during exploitation, certain types of polymeric insoluble residues are formed. The content change of these insoluble residues during exploitation is shown in Figure 6 [6].

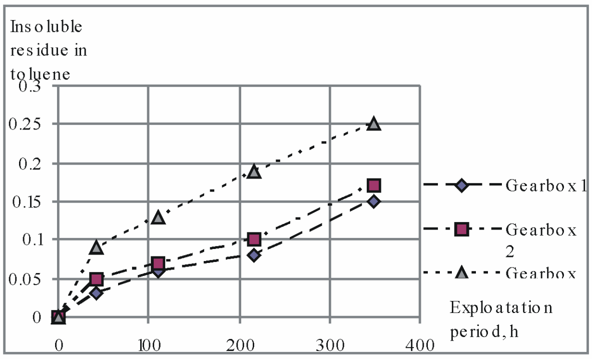

Figure 6. Insoluble residues in toluene of the sampled oils

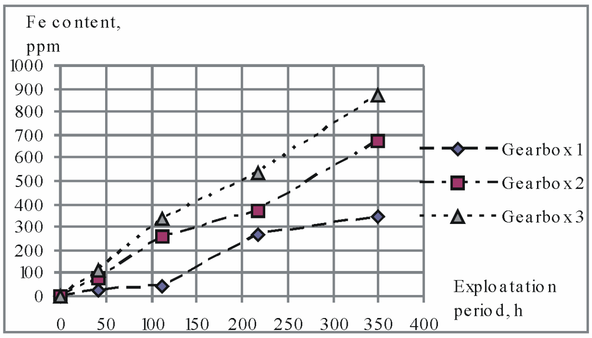

Figure 7. Content changes of wear products of sampled oils

During the testing, observed oils are considered to meet the criterion change of the insoluble residue amount in toluene. Wear products caused the contamination of oil well above the permissible limit and now an intensive degradation of oil starts that will be more intense due to their catalytic action. Also, it can be concluded that this strong growth of the concentration of iron, as wear products, leads to failure of gearbox elements which are mutually located in relative motion.

5. ANALYSE OF EXPERIMENTALLY OBTAINED RESULTS

During the exploitation, the analyzed oil has achieved its primary function and meets the intended replacement interval, which was determined by analysis of characteristic physical - chemical properties and concentration of wear products during exploitation. The increase in viscosity occurred during the examination period of exploitation. Maximum viscosity growth during the oil exploitation is less than 15% of allowed value. Degradation of oil during the testing was analyzed by an increase in TAN and the increase of insoluble residues (in toluene). Both features showed changes that are within the maximum permitted levels. Oil fire point has a trend of constant growth pointing to the process of oil oxidation (aging). The content of wear products in oil came out of the limits of maximum value allowed, indicating the need for check of functional characteristics and oil change interval. In the tested samples of oil there has been no occurrence of water or foaming. By conducted experimental analysis of changes of oil properties during exploitation, a great influence of dynamic load characteristics was proved [4, 5, 6].

6. CONCLUSION

Testing of physical and chemical properties of oil in the function of determining the state of gearbox group as a complex tribomechanical system aims to identify mechanisms of change in the system elements. By appropriate sampling and testing during exploitation, based on the model presented it is possible to identify the state of system elements and predict its future behaviour in exploitation [7]. The conditions in which the of gearbox group elements are found as the real tribomechanical system are complex and are determined to a large extent by oil properties. Complexity of the conditions is determined by temperature of elements in contact, temperature and properties of oil, external load, that is the specific pressure in the contact zone, the dynamic character of contact and transfer of power and movement, etc. During exploitation the gearbox group is exposed to time variable, dynamic and unsteady loads that represent the function of a range of factors. Dynamic loads conditioned complex physical-chemical processes that cause changes in oil. The amplitude as well as frequency of load primarily affect the change in pressure and temperature in the contact zone and thus cause a change in physical-chemical structure of oil. Processes created this way are manifested through unwanted effects that can be identified through the loss of material, energy, movement, functionality and reliability, reduced life cycle and increase in maintenance costs. Gearbox group is a set of very complex tribomechanical systems composed of series of subsystems that are also complex tribomechanical systems. Requirements regarding the oil properties, the type of use and their replacement interval are becoming stricter because designers of gearbox groups continually put before oil manufacturers new and more difficult conditions in terms of improving performance and efficiency [8, 9 and 10]. This inevitably leads to reformulating existing and creating new kinds of oils that are different in chemical composition, exploitation properties and viscosity grading. Direct participation of oil in the contact processes in tribomechanical systems with the main task to prevent direct contact of surfaces of elements gives it a special role in terms of maintenance. This role becomes more important since the oil is carrier of information about the state of the whole system in which process the particular attention is paid to the processes that affect the functionality, reliability and durability. The importance of this information comes into play in monitoring and system diagnosis, because oil analysis can point out to signs of potential problems that lead to failure, as well as to provide an insight into the influence of oil on the functioning of the gearbox group. The current state of the gearbox group system can be analyzed by examining oil without disrupting exploitation. Also, the conditions of exploitation, especially the dynamic characteristics of the load gearbox groups can be analyzed [11, 12 and 13]. Full understanding of the theoretical basis of the oil dynamics of oil and lubricants as a viscous incompressible fluid with the experimental testing of properties allows an adequate evaluation and application of results obtained by modern software packages such as Ansys, Fluent, FlowTech, PowerFlow, Flovent and the like, that use this kind of numerical algorithms for solving the adequate system of equations. Usage of these software packages for Computational Fluid Dynamics provides relevant information about the oil behaviour that can be used in the design, improvement and optimization of complex tribological systems within the gearbox group [14 and 15]. Numerical approach to oil dynamics includes consideration of the global geometry of elements, establishment of finite elements and establishment of shapes and sizes of oil particles and their conditions, as well as global boundary conditions so that the results obtained by analysis of numerical models created in this way, verified experimentally, are the important parameter that must be taken into consideration for solving the problems of lubrication of modern gearbox group.

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