

LIQUID LUBRICANTS FOR SPACE ENGINEERING AND METHODS FOR THEIR TESTING

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Abstract

This paper presents the analysis of the world source letters [1-60] about liquid lubricants for lubrication of the tribological nodes in space engineering for instance: mineral oils, synthetic hydrocarbons, silicones, perfluoropolyethers (PEPEs), ionic liquids, silicic hydrocarbons. Requirements for liquid lubricants in space applications and research methods for their testing are characterized, among others: four-ball vacuum apparatus and pin-on-disk friction tester for tests in vacuum. The development trends of liquid lubricants for space applications are described, too, e.g. direction of development of lubricant substances, development of lubricating substances research and lubrication technologies for space engineering in the future (lubrication systems in inert atmosphere, mist lubrication, lubrication with fine grade powder, deposition of liquid lubricant vapours, gas bearings, magnetic bearings.

The existing research methods are imperfect. Till now it is impossible to simulate many factors occurring in space (eg. State of weightlessness, the atmosphere containing the atom oxygen). It is hard to determine precisely (predict) the tribological node wear. There fore the research works on improvement of the existing test stations and analytical, methods and creation of new methods of tests and analysis are necessary.

Keywords: tribology, lubrication, space engineering, test methods, liquid lubricants

1. Introduction

Space has been, for ages, the subject of human beings' interest. Together with development of science, people may explore the space objects more and more precisely. The space flights became possible in the 20th century. Sputnik 1, the Soviet spacecraft, went into orbit around the Earth in 1957. In 1969 the first man landed on the Moon during Apollo 11 mission. Neil Armstrong was the first person who set foot on the Moon [57].

Thanks to successful conquest of space it was possible to carry out more and more difficult and long-lasting missions. Desirable period of correct operation of equipment increased, and this time it often amounts 20 or even 30 years [55]. Poland more often takes part in such international space programmes and carries out various research with the use of Polish equipment sent into space. Movable elements of these devices often need lubrication with appropriate lubricating substances. It is not easy to select the appropriate substance all the more so because lubricant working conditions in space are different than those ones on the Earth. Main differences are first of all: no field of gravity, very low ambient pressure (10^{-13} - 10^{-16} Tr), extreme and changeable temperatures (-60-200°C), no oxygen and molecular nitrogen (only monoatomic, impermanently occurs). For the space engineering needs many lubricating substances were tested. The most popular liquid lubricants used in the space engineering are as follows: silicones, mineral oils, perfluoropolyethers (PFPE), polyalphaolephines (PAO), multiply-alkylated cyclopentanes (MACs-Multiply-Alkylated Cyclopentanes). Moreover other liquid lubricants are being tested: silahydrocarbons (SiHC - Silahydrocarbons) and ionic liquids. Ionic liquids, thanks to their properties, may turn out to be perfect liquid lubricants under hard working conditions, in vacuum

and at extreme temperatures. Therefore it is necessary to test the lubricating properties of the ionic liquids continuously. Such tests are being run, among others, at Department of Tribology, Surface Engineering and Service Fluids Logistics of Institute of Motor Vehicles and Transportation, Military University of Technology [34, 35]. It should be remembered that all lubricating substances have advantages and disadvantages. A substance ideal for some mechanism may not be necessarily appropriate for the other one. In some cases only slight change of material or processing type of interacting parts may be the reason that the lubricating substance used previously does not act as a suitable lubricant yet [2].

At the beginning of the 21st century people's return to the Moon is planned, and then expedition to Mars, i.e. human space flights to distant places [8]. The human space flight to Mars will be a great challenge, and, may be, current technologies will not be able to handle it.

2. Lubricating Liquids Used Currently in Space Engineering

2.1. Silicones

Silicones are polymers (polymers are compounds with very large particles with chain structure; their molecular weights are greater than 10,000 u in general) including mainly macromolecular compounds of organic silicone polysiloxanes. Their main chain is built from alternately placed oxygen and silicone atoms(...-Si-O-Si-O-...), also combined with the carbon atom.

The silicone oils kinematic viscosity increases together with degree of polymerization (i.e. with increase of the polymers molar mass). It is possible to obtain oil liquids [1] by means of polymerization ended at several or a dozen or so molecules.

Silicones, for their low vapour pressure and freezing point were often used as liquid lubricants during first space missions. Nowadays the silicone oils are not being used for lubrication in the space engineering for a tendency to the silicone oil layer tearing or its extrusion from the friction area under the influence of load [13]. Thanks to their compressibility and low viscosity changes within a wide temperature range silicones are being used, nowadays, in some hydraulic systems in the space engineering. Silicone oils compressibility is considerably greater in comparison with mineral oils. Attenuation of liquid shock absorbers with the silicone oils under temperature changes from -40°C to 70°C decreases only 3 times. In case of mineral oils decrease is equal to 2,000 times approximately. Fluorosilicone oil was used in the springs of the hydraulic legs of Surveyor VI lander. Owing to this fact it was possible to stretch the springs under extreme thermal conditions on the Moon during unmanned mission [3, 13].

2.2. Mineral oils

Mineral oils are mixtures of liquid hydrocarbons obtained from residues of the atmospheric distillation of petroleum plus some additives.

For good lubrication properties and viscosity-temperature characteristics, low freezing point, mineral oils, that contain liquid hydrocarbons with the long side paraffin chains, are the best.

In comparison to other liquid lubricants taken into consideration for the space engineering mineral oils have the highest vapour pressure. Mineral oils are liquid lubricants that operate well under conditions of boundary lubrication and elastohydrodynamic lubrication. However they become unfit for lubrication very quickly, and their quantity in a lubricated coupling decreases. For coming in synthetic oils and other liquid lubricants with significantly better properties, mineral oils are not being used very often. So far mineral oils are being used in fully sealed mechanisms, such as gyroscope stabilizer bearings, anti-vortex mechanisms [27 for 10].

2.3. Perfluoropolyethers (PFPEs)

Perfluoropolyethers are liquid compounds, polyether derivatives, obtained by means of polymerization of perfluorated monomers during reaction of fluoric alkyl oxides with compounds

containing active hydrogen (e.g. with water), alcohol fluoric derivatives or organic acids [58]. Liquids designated with K, created by means of polymerization of heksafluoropropene oxide in presence of a catalyst (CsF — cesium fluoride) were the ones of the first perfluoropolyethers [30 for 19]. The perfluoropolyethers designed with K and Z, and rarely D are being used in the space engineering [30].

Tab. 1. Molecular Formulas for Four Perfluoropolyethers, Where X Amounts from 10 to 60, and X/Y Proportion Amounts from 0.6 to 0.7 [30]

Perfluoropolyether Designation	Molecular Formula
D	$C_3F_7O(CF_2CF_2CF_2O)_X C_2F_5$
K	$C_3F_7O[CF(CF_3)CF_2O]_X C_2F_5$
Y	$C_3F_7O[CF(CF_3)CF_2O]_X (CF_2O)_Y C_2F_5$
Z	$CF_3O(CF_2CF_2O)_X (CF_2O)_Y CF_3$

Tab. 2. Selected Physical Properties of Four Perfluoropolyethers [30]

Liquid Lubricant	Average Molecular Weight	Kinematic Viscosity at 200°C, [cSt]	Viscosity Index	Freezing Point, [°C]	Vapour Pressure, [Pa]	
					at 20°C	at 100°C
Z (Z-25)	9500	255	355	-66	$3.9 \cdot 10^{-10}$	$1.3 \cdot 10^{-6}$
K(143AB)	3700	230	113	-40	$2.0 \cdot 10^{-4}$	$4.0 \cdot 10^{-2}$
K(143AC)	6250	800	134	-35	$2.7 \cdot 10^{-6}$	$1.1 \cdot 10^{-3}$
D (S-200)	8400	500	210	-53	$1.3 \cdot 10^{-8}$	$1.3 \cdot 10^{-5}$

Low freezing point and scanty vapour pressure of perfluoropolyethers (particularly Z grade) make it possible to use them in long-term applications (from 7 to 30 years) [30 for 22].

Low surface tension (from 18 to 24 $\frac{dyn}{cm}$ at 20°C) warrants that perfluoropolyether penetrates the smallest gaps of lubricated mechanisms, and provides great affinity of liquid lubricants with a lubricated surface [56].

High viscosity index, in comparison with other liquid lubricants, makes perfluoropolyethers the ones of the most appropriate liquid lubricants for the applications where minimal viscosity changes within a wide temperature range are needed [56]. It can be seen in the diagram (Fig.1) that shows kinematic viscosity versus temperature.

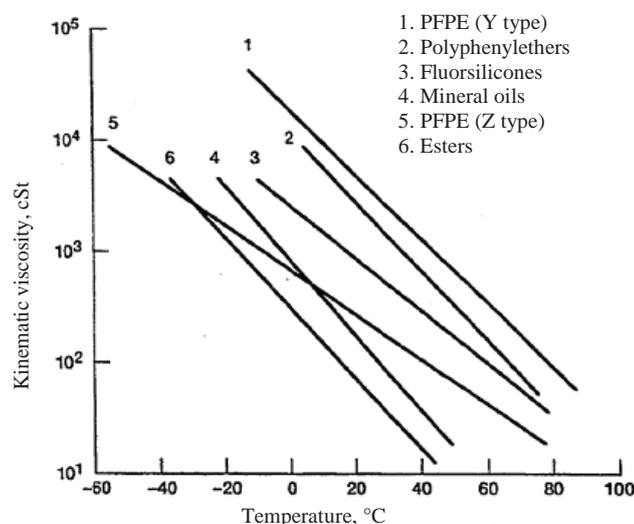


Fig. 1. Viscosity changes versus temperature for various liquid lubricants [13 for 49]

Perfluoropolyethers are good liquid lubricants under hydrodynamic and elastohydrodynamic lubrication conditions.

During boundary lubrication perfluoropolyethers react with the lubricated surfaces. Then corrosive gases arise and, consequently, metal fluorides. This way perfluoropolyethers are being degraded. Therefore using pure perfluoropolyethers under boundary lubrication conditions seems to be inadvisable. Under X radiation influence perfluoropolyethers are susceptible to degradation, too. The course of the perfluoropolyethers degradation depends strictly on working conditions for the given coupling.

Pilot survey run under boundary friction conditions for three perfluoropolyethers (designed with K (Krytox), Z (Fomblin), D (Demnum)) with the use of the four-ball vacuum apparatus (in the air, under pressure from 10^{-4} to 10^{-6} Pa, at 600 N load and 100 rpm rotational speed, at temperature about 23°C) showed that [44]: higher wear occurs in vacuum in comparison with the air. The lowest wear in the air was observed when Krytox was used, the lowest wear in vacuum was observed when Krytox and Demnum were used. Only when Krytox was used, wear similar to scuffing did not occur.

The following additives are used for perfluoropolyethers: β -diketone, tricresyl phosphate (TCP- for tricresyl phosphate), phosphane, triazine phosphate, carboxylic acid. It is possible to obtain a little improvement when synthetic hydrocarbons are used or when materials of the coupling are changed [32 for 50].

Perfluoropolyethers without additives are still appropriate for less demanding applications. For applications under severe conditions it is recommended to use perfluoropolyethers with additives.

2.4. Synthetic hydrocarbons

Nowadays two groups of synthetic hydrocarbons are available: polyalphaolephines (PAO) and multiply-alkylated cyclopentanes (MACs).

Polyalphaolephines (PAO) arise during oligomerization (oligomerization is a process of changing a monomer into an oligomer) of linear α -olefins which have six or more carbon atoms in a molecule, and then hydrogenation of oligomer (oligomers, similarly to polymers, are formed from some fragments - mers, but they consist of a small number of mers) to oligomer without double bonds [58]. This way a mixture of monomers, dimers and polymers arises. The mixture is being distilled into fractions with a desired kinematic viscosity.

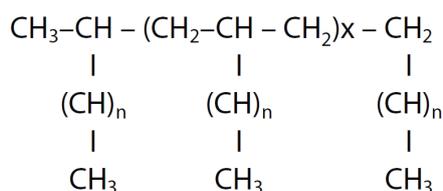


Fig. 2. Structure of the polyalphaolephine molecule, where $n \geq 7$, x amounts from 1 to 4 [58]

Polyalphaolephins freezing point is low. Their vapour pressure is less than the one for mineral oils. They have high viscosity index. Selected properties of lubricating liquid Nye 179, belonging to the group of polyalphaolephines, are shown in Table 3.

Tab. 3. Selected Properties of Nye 179 [13]

Name	Kinematic Viscosity at 40°C	Viscosity Index	Freezing Point	Vapour Pressure at 20°C
	[cSt]			[Pa]
Nye 179	30	139	<-60	$9.0 \cdot 10^{-7}$

Polyalphaolephines (PAO) served as materials for production of new synthesised hydrocarbons - multiply-alkylated cyclopentanes (MACs). Dicyclopentadiens and alifatic alcohols may be used for MACs creation. It is very important that MACs properties may be controlled by means of using another alcohol during the synthesis process. MACs arise during reaction of Cyclopenta-1,3-dien that was produced previously by means of dicyclopentadien decomposition, with various alcohols in the presence of a strong base. Next the reaction product is being hydrogenated to the final product, i.e. a mixture of di-, tri-, tetra-, penta-alkylated cyclopentanes. It is possible to determine a dominant cyclopentane by means of selection of the reaction conditions [52].

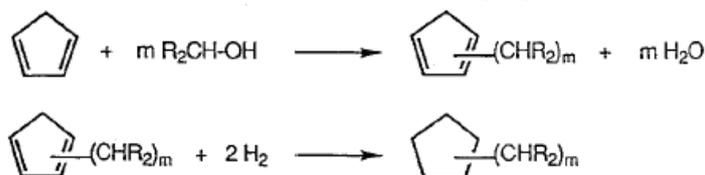


Fig. 2. Diagram of multiply-alkylated cyclopentanes (MACs) arise, where m amounts from 2 to 5 [52]

MACs kinematic viscosity at 100°C depends on their average molecular weight mainly. The kinematic viscosity may be controlled by means of: changing a number of carbon atoms in each alkyl group marked with “R” symbol in Figure 2, and changing a number of R alkyl groups attached to each cyclopentane. Values of kinematic viscosity for some selected MACs are shown, as an example, in Table 4.

Tab. 4. Properties of Multiply-Alkylated Cyclopentanes (MACs) in Dependence of Alkyl Group Contained in MACs Molecule [52]

R Alkyl Group	A Number of Groups Marked with m	Kinematic Viscosity at 100°C	Viscosity Index	Freezing Point
	-	[mm ² /s]	-	[°C]
Octyl	2	2.18	135	-24
Dodecyl	4, 5	11.91	153	-9
Izotridecyl	3, 4, 5	20.09	71	-27
2-Octyldodecyl	2, 3	14.56	137	-57

The viscosity index for MACs changes in a predictable way in dependence of the molecule structure. MACs viscosity index mainly depends on R alkyl groups. The more average molecular weight and the less number of m groups in the molecule, the higher viscosity index. It is possible to obtain a liquid lubricant with a desired viscosity index and other demanded properties by means of mixing various MACs [52].

Freezing point of multiply-alkylated cyclopentanes (MACs) depends on their molecule structure, precisely [52]:

- a number of carbon atoms for the given alkyl group — the greater number, the lower freezing point;
- a number of substituents — the greater number, the lower freezing point;
- occurrence of branched alkyl groups that cause freezing point decrease, in contrast with linear alkyl groups.

Synthetic hydrocarbons make it possible to select physical properties within a wide range of values. It is possible to obtain desired parameters by means of appropriate selection of substituents. In case of MACs viscosity index and freezing point increase with the molecule chain length. Polyalphaolephines (PAO) and MACs are liquids with very low freezing point. Low volatility and tribological tests performed with the use of the SOT four-ball apparatus (§4) prove that multiply-alkylated cyclopentanes (MACs) meet demands for liquid lubricants designed for long-lasting space missions [11, 25, 29].

2.5. Ionic liquids

Salts with melting point lower than 100°C are called ionic liquids and are often described with IIs (Ionic Liquids) abbreviation [4]. Salts with melting point lower than 25°C are called room temperature ionic liquids (RTILs). Room temperature ionic liquids were initially used as the battery electrolytes. At present RTILs form the newest group of substances taken into account as the lubricants for space applications.

Ionic liquids usually consist of an organic cation that includes nitrogen or phosphorus, and an anion. The most popular cations are: phosphonium, imidazolium, pyridinium, ammonium. The most frequently used anions are those ones with a large number of fluorine atoms (BF_4^- , PF_6^- , CF_3SO_3^- , $\text{N}(\text{CF}_3\text{SO}_2)_2^-$). It is possible to form ionic liquids with desired properties, so-called Task Specific Ionic Liquids (TSILs) by means of changing cations and anions combinations [4].

Ionic liquids form during a synthesis reaction. An appropriate anion is being entered during ion exchange. The reaction should be under control because it is inadvisable to leave free ions. Free ions may influence negatively the ionic liquids properties and a synthesis reaction as itself.

Ionic liquids forming will be described on the example of synthesis of 1-Butyl-3-methylimidazolium chloride. In this case ionic liquids form during reaction of n-alkylimidazolium salt in the presence of a solvent. It is necessary to put in chlorobutane and 1-methylimidazole, in equal amounts, into a flask and steer them at constant temperature of 70°C for 24 to 72 hours until two phases are obtained. Then it is necessary to decant the upper phase that contains the substrates which will not have reacted (decantation means pouring off the liquid from above deposit). It is necessary to rinse out the rest with ethyl acetate until all remaining components are removed, and vaporize the solvent residue (i.e. ethyl acetate) in a vacuum evaporator at 70°C temperature. This way it is possible to obtain a light yellow ionic liquid with melting point of 70°C [23].

Ionic liquids, from the point of view of the space engineering applications, have many desirable properties, among other things: very low volatility, high temperature stability, low melting point, and ability of good mixing with other organic compounds (for some ionic liquids) [53]. Ionic liquids are potentially capable of replacing liquid lubricants used till now in the space engineering that have some disadvantages (e.g. perfluoropolyethers may decompose under boundary friction conditions).

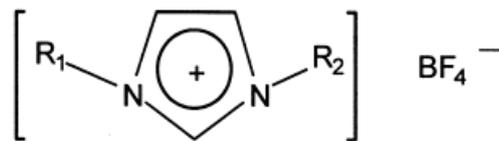


Fig. 4. Structure of the ionic liquid molecule, where R_1 and R_2 are various alkyl groups [54]

The friction factor and wear in the presence of some ionic liquids, in the atmospheric air and in vacuum, for various materials, were measured with the use of the SVR apparatus (an oscillating tribotester made in Germany) [7]. The working principle of the apparatus is shown in Fig. 5.

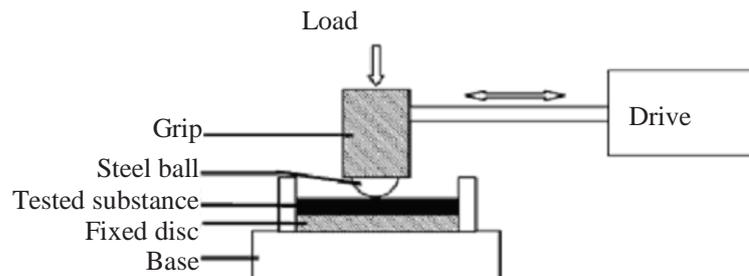


Fig. 5. Scheme of the SVR apparatus [7]

A small ball 10 mm in diameter was sliding on a disc with 1 mm amplitude, under load of 50 N. The test was performed at frequency of 25 Hz and lasted 30 minutes. Two drops of a lubricating liquid were given to a place of contact of the ball and the disc. The tests were performed for various materials the ball and the disc were made of. For comparison the results the same tests were performed for perfluoropolyether and fosfazen (X-1P), that is liquid lubricants universally used in the space engineering. Selected properties of the tested liquids are shown in Table 5.

Tab. 5. Selected Properties of the Liquid Lubricants Used for the Tests [39]

Liquid Lubricant	Average Molecular Weight	Density	Freezing Point	Kinematic Viscosity [$\frac{mm^2}{s}$]	
		[$\frac{kg}{m^3}$]	[°C]	at 40°C	at 100°C
X-1P	1002	1500	-15	224.0	11.2
PFPE	5000	1900	-50	176.2	19.7
L106	254	1150	-50	82.5	10.9
L206	268	1128	-50	88.0	11.8
L208	296	1088	-35	138.1	15.5

The ionic liquid designed with L106 is 1-Methyl-3-hexylimidazolium tetrafluoroborate, and L208 is 1-Ethyl-3-octylimidazolium tetrafluoroborate.

Selected results of the test performed in the atmospheric air for various materials the ball and the disc were made of, are shown in Table 6. It may be observed that the ionic liquid under test demonstrated perfect properties for the three material couples described below (SAE-52100 steel, Al20204 aluminium, and copper) and the friction factor for L106 is less than the one for X-1P and PFPE.

Tab. 6. Friction Factor Measured During the Tests Performed with the use of the SRV Tester [54]

Liquid Lubricant	Friction Factor (for the Ball / Disc Couple) in the Atmospheric Air		
	Steel / Steel	Steel / Aluminium	Steel / Copper
X-1P	0.098	0.128	0.117
PFPE	0.145	-	0.145
L106	0.065	0.040	0.025

The friction factor values for the ionic liquids under test (L106 and L206) versus the friction factor determined for perfluoropolyether (PFPE) were measured with the use of the CZM vacuum friction tester of the ball-on-disc type [7]. The test was performed under pressure of 10^{-3} Pa and load of 9.0 N, the ball and the disc were made of SAE52100, steel, and the disc rotated with speed of 500 rpm. The both ionic liquids demonstrated the friction factors two times less than the one for PFPE (Table 7).

Tab. 7. The Friction Factor for Selected Liquid Lubricants Determined with the use of the CZM Tester [39]

Liquid Lubricant	L106	L206	PFPE
Friction Factor	0.070	0.067	0.142

Thermogravimetric analysis (TGA) with the use of the Perkin-Elmer 7 apparatus was performed in order to evaluate ionic liquids volatility. The percentage loss in mass was determined in steps of 10°C. It appears from the analysis that the ionic liquid L106 does not show any mass loss at temperatures less than 320°C, while X-1P i PFPE demonstrated the mass losses 65.9% and 13.2% respectively. The test confirmed very low vapour pressure for the ionic liquid under test (Fig. 6).

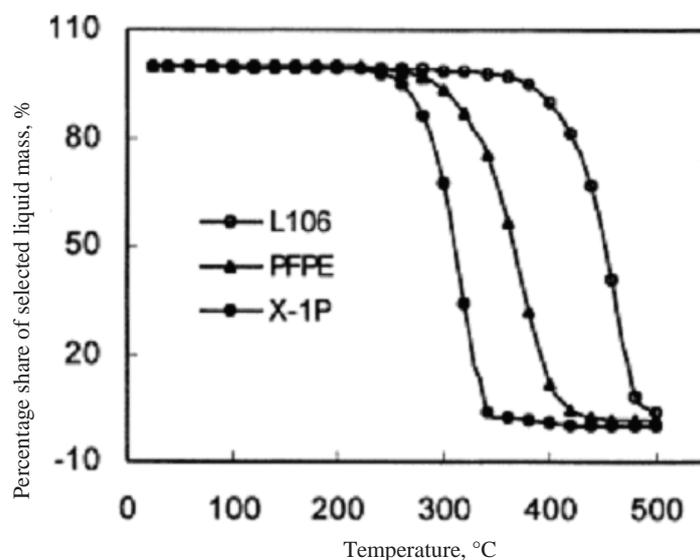


Fig. 6. Chart of the mass loss versus temperature for selected liquid lubricants [39]

The spectroscopy of photoelectrons excited with X-rays (XPS) was a basis for evaluation of a chemical composition of the layers during the friction process. The test was performed with the use of the PHI-5702 spectroscope. The test results confirmed the thesis that anions decompose during the friction process into fluorides, nitrogen oxides, B_2O_3 boron oxide, BN boron nitride and $FePO_4$ [53]. The phenomenon takes place in the atmospheric air and in vacuum, which is more important from the point of view of the space missions. These substances protect the surfaces against wear and decrease the friction factor.

It is interesting that some ionic liquids, used as additives for liquid lubricants, may be very effective in the wear and friction factor decrease, because only 1% of an ionic liquid added to the lubricating substance is enough to create the mentioned above compounds forming a layer protecting the surfaces [4].

Benzotriazole additive to a ionic liquid improves lubricating properties and serves as a corrosion inhibitor. Tricresyl phosphate (TCP) and dibenzyl disulfide additives improve anti-wear properties [4].

Ionic liquids have perfect anti-wear properties, decrease friction factor, are capable of transferring large loads, and have very low volatility and vapour pressure. Those properties are being kept either in the atmospheric air or in vacuum. Owing to this fact ionic liquids are perfect lubricating substances for the space applications. However, more thorough tests of interaction of tribological nodes and ionic liquids are needed before ionic liquids are used.

2.6. Silicic hydrocarbons

Silicic hydrocarbons (SiHC) are liquid lubricants the molecules of them contain only silicon, carbon and hydrogen atoms. It is a relatively new group of liquid lubricants that may be used within a wide range of application in the space engineering in the future. They do not show poor properties under boundary friction conditions, just like silicones. Silicic hydrocarbons have low volatility and very wide viscosity range.

Accurate values of the tested liquids viscosity and the structure of selected silicic hydrocarbons are shown in Table 8 [26, 27].

Measurement of volatility with the use of the thermogravimetric analysis at pressure of 33 Pa proved that the SiHC-1 liquid under test loss is less than the one for P2001A, and slightly greater than the one for Fomblin Z25. In the chart shown in Fig. 10 temperature at which the mass loss amounts half of the liquid initial mass is marked with "T" [26 for 18].

Tab. 8. Values of Kinematic Viscosity for Selected Liquid Lubricants and Structure of Selected Silicic Hydrocarbons [26, 27]

Designator	Kinematic Viscosity [cSt]		Molecular Formula	Type
	at 40°C	at 100°C		
2-94-96	133	20	$(n-C_{12}H_{25})_2Si[C_8H_{16}Si(n-C_{12}H_{25})_3]_2$	Tri
MJD990405	206	31	$Si[C_3H_6Si(n-C_{12}H_{25})_3]_4$	Penta
MJD991029	77	13	$Si[C_3H_6Si(n-C_6H_{13})_3]_4$	Penta
SiHC-3	57	10	$CH_3Si[CH_2CH_2Si-(C_6H_{13})_3]_3$	Tetra
SiHC-2	71	12	$CH_3Si[CH_2CH_2Si-(C_8H_{17})_3]_3$	Tetra
SiHC-1	94	15	$CH_3Si[CH_2CH_2Si-(C_{10}H_{21})_3]_3$	Tetra
6-88-134	105	18	$n-C_8H_{17}Si[C_3H_6Si(n-C_{12}H_{25})_3]_3$	Tetra
Pennzane 2001A	108	15	-	-

In order to determine tribological durability of liquid lubricants under test the SOT apparatus was used (§4.1). Before the test about 50 μg of the substance under test was placed on the ball only. The test was being conducted until the lubricating substance run out or the friction factor increased rapidly. Durability is determined by a number of turns until damage divided by quantity of the lubricating liquid on the ball. The test was performed under 1.5 GPa load, at temperature of about 23°C, under pressure lower than 1.3·10⁻⁶ Pa, and at rotational speed of 200 rpm. The test proved (Fig. 8) that the lifetime of silicic hydrocarbons is much longer than the one for perfluoropolyethers used in the space engineering [26].

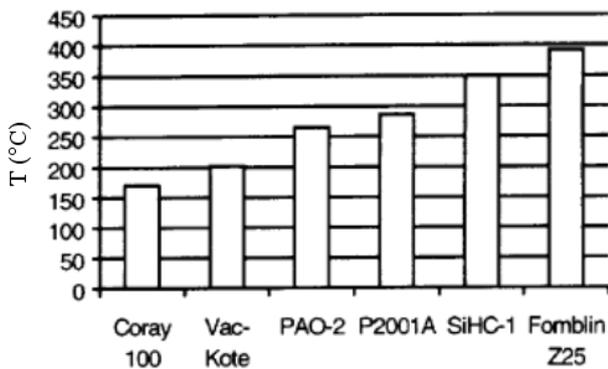


Fig. 7. Chart of volatility, where T is the temperature at which the mass loss for each liquid amounts half of the total mass loss for the given liquid [26 for 18]

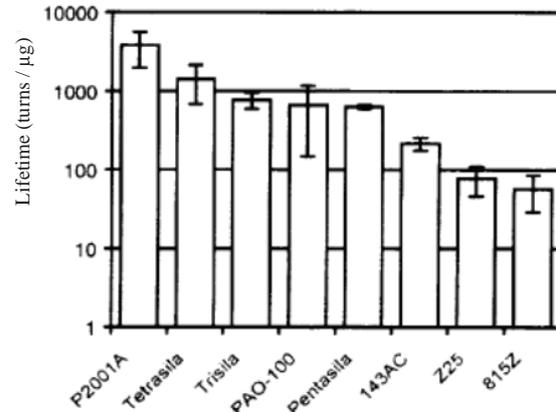


Fig. 8. Lifetime of selected liquid lubricants tested with the use of the SOT apparatus [26]

A gradual evolution of manufacturing and using liquid lubricants in the space engineering is shown in Fig. 9. At present some of presented liquid lubricants play a small role in the space applications, some are being used frequently, and some will be probably used widely in the future.

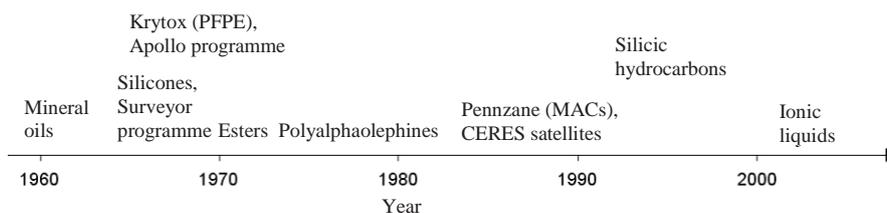


Fig. 9. A historical outline of the tests being performed and attempts to implement subsequent liquid lubricants in the space engineering [3, 13, 27, 55, 59, 60]

3. Requirements for liquid lubricants used in space engineering

3.1. Viscosity

Viscosity is one of the most important parameters of liquid lubricants. Viscosity, in general, relates to the liquid molecular weight. It significantly influences the other parameters values. The viscosity change versus temperature in one of more important relationships. The lubricating liquid viscosity decreases when temperature increases. This relationship is described by means of viscosity index, too. The higher viscosity index, the viscosity depends on temperature to a smaller extent, and the angle of inclination of the straight line showing relationship between viscosity and temperature in the logarithmic graph is lesser (Fig. 10).

The next important characteristics is relationship between viscosity and pressure. In general, viscosity increases when pressure increases. Up to 25 MPa the increase is small. Above this value viscosity increases significantly. Viscosity is namely the resultant of temperature and pressure. In various space applications the rotational speed of different mechanisms is very small because they have to operate with very large precision. Under such conditions the boundary lubrication appears. It is necessary to take it into consideration while selecting liquid lubricants [36]. It is about optimization, viscosity and temperature properties, and lubrication and surface properties.

3.2. Volatility

Volatility is a property of liquid lubricants that depends on a molecule structure and a type of a lubricating substance. For the given homologous series the higher molecular weight, the lower volatility. Volatility increases when temperature increases. The mixture volatility is equal to the volatility of the most volatile component [47].

In vacuum, a problem of the molecules missed as a result of evaporation appears. In the atmospheric air the molecules that had vaporized partially return to the surface they had left as a result of rebounding with other molecules, while in vacuum the molecules that vaporized do not rebound and are lost forever. Therefore it is necessary to select the lubricating liquid with the lowest vapour pressure, because — by means of appropriate selection — it is possible to limit the lubricating liquid loss [13].

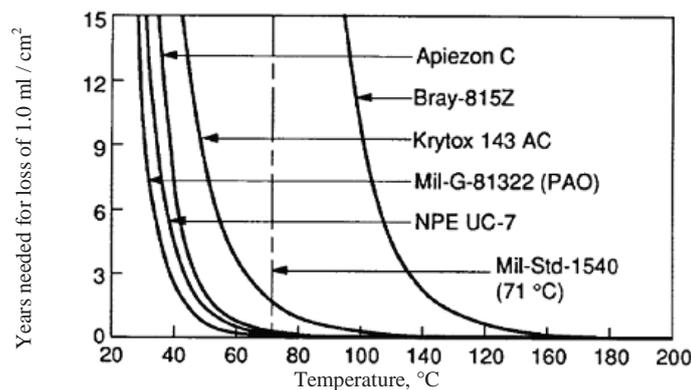


Fig. 10. Loss of selected liquid lubricants as a result of evaporation [13]

3.3. Condensation of Lubricating Liquid Vapours

The lubricating liquid that was vaporized has a tendency to form a cloud around a satellite. The formed vapours condense on colder surfaces. Some very important devices (e.g. lenses, mirrors, windows) may be polluted and, as a result, become useless. For the devices that have to operate reliable for many years it is necessary to minimize the effect of slow evaporation of liquid lubricants [13].

3.4. Thermal stability

Thermal stability is a substance resistance to the mass loss as a result of heating. It is a basic parameter of pure lubricating substances. While thermal stability evaluating it is necessary to take into consideration if a liquid lubricant operates within the sealed space or in vacuum, and when if some gases (oxygen, air, others) capable of triggering a reaction are present, the presence of an inert gas is provided.

Generally straight-chain hydrocarbons with a short alkyl chain are the most stable. The longer chain, the worse thermal stability. For synthetic hydrocarbons it is not possible to determine their parameters influencing thermal stability in an easy way. It is only possible to connect thermal stability with the bond strength between atoms [47].

3.5. Thermal conductivity

In situations where the state of weightlessness takes place, cooling by means of heat transfer through matter is impossible. It negatively influence the interaction of the surfaces in contact because there are difficulties with the generated heat removal. The phenomenon is very dangerous when solids are lubricants. It does not change the fact that the lubricating liquid should remove heat very well.

3.6. Resistance to oxidizing

The lubricant oxidizing is usually one of the most important factors that causes the lubricating substances not to act as lubricants. The lubricant is being stored on the Earth before it is used in space. During this period it may be in contact with molecular oxygen.

Many factors may influence the lubricant oxidizing. One of them is e.g. the temperature change. The lubricant stops playing its part when such soluble and insoluble compounds like sediments and acid compounds occur. Oxidizing is the reason. It is possible to recognise the phenomenon by the following signs: the lubricating liquid viscosity increase, acid value increase, general dirt, and occurrence of insoluble compounds.

The liquids with oxygen atoms within their molecules are more susceptible to oxidizing. Hydrocarbons with single bonds with straight chains are more susceptible to oxidizing than the ones with double and triple bonds. The more reactive hydrocarbon is, the worse its resistance to oxidizing is [47].

3.7. State of weightlessness

There is no gravity in space. The gravity phenomenon occurs on planets, moons and other celestial bodies. Gravitational acceleration amounts about $9.81 \frac{m}{s^2}$. Compared with the Earth, the acceleration on the Moon is 6 times smaller and 3 times smaller for Mars. Such differences cause that landing on Mars and the Moon is more difficult than the one on the Earth. All hydraulic and lubricating systems that use the gravity phenomenon for operation on the Earth, do not play their part in the state of weightlessness because there is no force causing attraction of the liquid to its destination place (e.g. a pump inlet or a tank for the lubricating liquid). It is possible to control a lubricating liquid in the state of weightlessness only by means of selection of the lubricating liquid with the appropriate surface tension [13].

3.8. Absence of Reactive Substances in Space

There are no reactive gases in space; first of all there is no molecular oxygen. Therefore no layers of oxides are being formed on the metal surfaces, what significantly increases the friction factor. In the moment when the layer still formed on the Earth is wiped, the friction factor

increases and failure is possible. The lack of the oxide layers protecting the surface is especially perceptible when the lubricating liquid quantity is limited.

No reaction with the lubricated surface is not the only important factor. It is necessary to take into consideration the lack of oxygen influence on the lubricating liquid, compounds and additives contained in it. The issue has not been examined accurately yet.

3.9. Influence of Pieces, Dust and Major Celestial Bodies

It is necessary not to allow for any pollution of the liquid lubricant and the lubricating system by dust or outside ashes. So it is necessary to design sealings and joints in an appropriate way. The sealings should be resistant to dust and ashes. Also large pieces and meteoroids should not cause any damages. Strong impact of a foreign body into the liquid lubricant tank may cause leakage and failure of the lubricated mechanism [13].

3.10. Lubricating Liquid Migration

The viscosity of a liquid lubricant has a fundamental influence on its migration. The liquid with a high viscosity migrates considerably slower than the one with a low viscosity. The temperature differences influence the liquids migration, too. The oil relocates from warmer zones to the colder ones. A tendency of liquid lubricants to the migration along the bearing surfaces is higher for the liquids with a lower surface tension [13, 30, 49].

3.11. Presence of Atomic Oxygen

At a height from about 200 km to 650 km over the Earth's surface the atomic oxygen occurs predominantly. The atomic oxygen is an oxygen radical. It has a single unpaired electron, thus it quickly reacts with various molecules. Simultaneously the excited electron does not allow for forming a stable compound, breaks free and is ready for the next reaction. Exposure of the lubricants to the influence of the atom oxygen may lead to their degradation. It is possible to cause the oxidizing reaction with a combination of extremely high temperatures [37].

3.12. Radiation

Ultraviolet (UV) and X radiation may damage plastics and elastomers. The damages are mainly caused by the ionization and the electron exciting. The changes are irreversible. Free radicals are being formed, and polymerization, degradation and gases emission take place. The same damages take place in case of gamma radiation.

Infrared radiation may cause thermal degradation of the lubricant, and this phenomenon may be accelerated by combination of ultraviolet and infrared radiation.

Excessive radiation may cause decrease and then increase of the oils viscosity, and hence the oil may become "rubber" or hard. The lubricants degrade considerably faster under the influence of radiation, become denser right to transition into a solid state. The liquid lubricants volatility, acidity and corrosivity increase under the influence of radiation, and their resistance to oxidizing decrease. The liquid lubricants which are the most resistant to radiation are the most thermally stable, too.

3.13. Vacuum

Absolute pressure in space amounts from about 10^{-13} Tr over the Earth's atmosphere to 10^{-16} Tr in interstellar space [6].

Degree of evaporation depends on temperature exponentially. In vacuum the temperature change, caused only by radiation, may influence significantly the lubricating substances loss.

Moreover, at negative pressure in space, and consequently the lack of oxygen, a thin oxide layer that protects the tribological node surfaces is not being rebuilt. Hence increase of the friction factor is possible [6].

Some new liquid lubricants, that showed good results in the tests under very low pressure, were created during the last years. Such liquids are: silicic hydrocarbons (SiHC), multiply-alkylated cyclopentanes (MACs) and ionic liquids (ILs).

4. Testing methods for liquid lubricants used in space engineering

Tribological tests of liquid lubricants may be divided into two groups. The first group includes the tests run within the full operating range of the lubricating substance, for full demanded operating period, and under real ambient conditions for the given lubricant. The tests are very reliable, and they reconstruct conditions in space very well. Their main disadvantages are high costs and long testing time. The second group includes accelerated tests based on increasing of speed, load, temperature in such a way that accelerated operation is being simulated in shorter time. These tests are cheaper than the ones from the first group. However they have two main disadvantages. The first one is their complexity, because it is not easy to determine which factors are being modified under working conditions change. The second disadvantage is that there is a possibility of unintentional change of the type of lubrication designed for the given mechanism. Such situation is possible because, e.g. speed and load often significantly exceed real values met under normal working conditions the given mechanism was designed for [33]. For the accelerated tests it is necessary to pay special attention to these facts in order to avoid coming to wrong conclusions.

4.1. SOT apparatus

The SOT apparatus accurately reproduces the working conditions for a ball angular bearing (skew) under load, under boundary lubrication conditions. Only from 50 to 100 μg of the liquid lubricant is needed to run the test. Such lubricant quantity is being used very quickly and it is the only accelerating factor for this apparatus. Other parameters are being kept on the same level as under normal working conditions, i.e. load, speed and temperature do not change [28, 48].

The SOT apparatus casing is in the form of a cube. The casing is made of stainless steel. It is possible to obtain pressure less than $1.3 \cdot 10^{-6}$ Pa for this apparatus. A turbomolecular pump is used to obtain such negative pressure. A cold cathode sensor is used for pressure measurement. Besides the tests in vacuum, the SOT apparatus is capable of testing under atmospheric pressure either in the air or in the presence of other gases.

The structure details and the principle of operation of the SOT apparatus are shown in Figure 11.

It is possible to use standard balls for bearings with a diameter of 12.7 mm placed between two flat dished discs with a diameter of 50.8 mm. The lower disc is fixed steadily and separated from the base. Electric resistance is being measured at two points of contact between the ball and the lower disc and at the point of contact of the ball and the upper disc. It is possible to determine degree of the ball separation from the disc achieved with the use of a lubricating substance on the basis of measurement of resistance between the ball and the lower and upper disc [28]. The upper disc guides the ball along the spiral orbit with a radius of about 21 mm, and may rotate with maximum rotational speed of 200 rpm. As a result of turning along the spiral trajectory, the ball leaves its initial orbit along a spiral curve toward the disc edge in steps of 0.5 mm on the average per revolution. If the movement along the spiral curve had not been limited the ball would have fallen out from the space between the discs. Therefore the ball is being guided by a vertical guiding disc. Contact between the ball and the guiding disc lasts shortly and is enough for the ball returning to its initial orbit. A force transducer, mounted in the same grip as the guiding disc,

makes it possible to measure the force needed for moving the ball back to its initial orbit. Thanks to this measurement it is possible to determine the value of a friction factor.

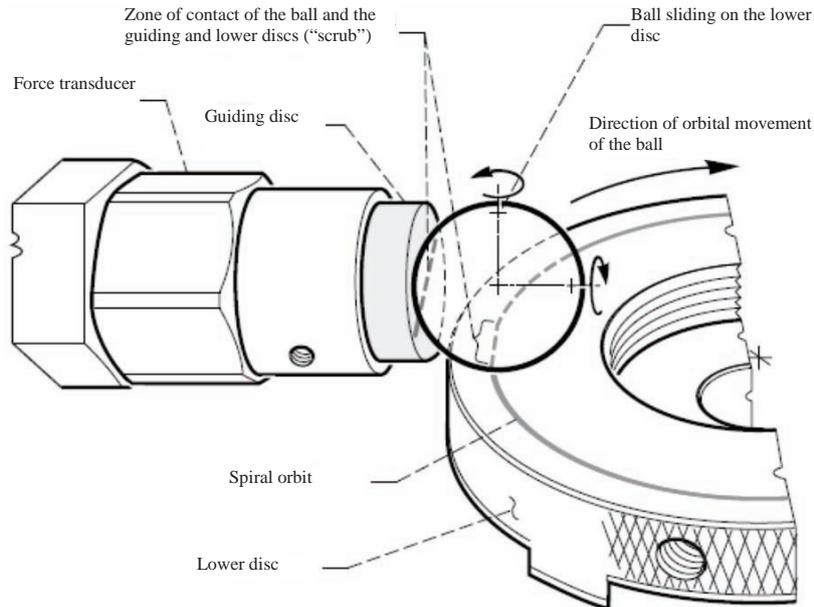


Fig. 11. Scheme of the structure and operation of the SOT apparatus [15]

The lubricating substance is being placed onto the ball by means of submersion the ball into dissolved lubricant. After the ball taking out from the liquid it is necessary to wait until the solvent has evaporated and a thin lubricating layer has remained on the ball surface. The lubricant quantity is being determined by means of the ball mass measurement before and after the lubricating substance deposit forming. Normally about $50 \mu\text{g}$ of the lubricant remains. The discs are not being lubricated. It is possible to test layers formed on the balls with the use of the SOT apparatus.

Full process is under control of a computer. It is necessary to place the discs within the apparatus and place the ball between the discs. It is important that the ball does not touch any of the discs. Thanks to this fact it is possible to avoid lapping and other phenomena which cause the ball does not reach the guiding disc. Then it is necessary to load the coupling with demanded tension. The test begins when pressure $1.3 \cdot 10^{-6}$ Pa is achieved, and lasts until determined value of the friction factor is exceeded. The value is usually three times greater than the friction factor at the beginning of the test.

The lubricant period of correct operation is defined as a number of the ball turns divided by initial quantity of the lubricant on the ball. In order to obtain good results it is necessary to repeat the test four times or more [28].

The SOT apparatus makes it possible to determine and evaluate, in an easy way, the period of correct operation of tribological couplings, the values of the friction factor, working conditions of bearings, the lubricant degradation, changes of the ball surface, analysis of pressure and the gas composition in the environment of the test chamber [48].

4.2. Four-ball vacuum apparatus

The four-ball vacuum apparatus is manufactured on the basis of a typical four-ball device. It mainly serves for testing properties of liquid lubricants and wear of surfaces of bearings immersed into the liquid lubricant. It is possible to determine the type of lubrication, too.

The upper ball under load slides and turns on the surfaces of three fixed balls immerses in a liquid lubricant. The advantages of the device are as follows: user-friendliness, ability to run the tests under high loads and use the standard balls for bearings that are easily accessible [45].

The structure of the four-ball vacuum apparatus is shown in Figure 12.

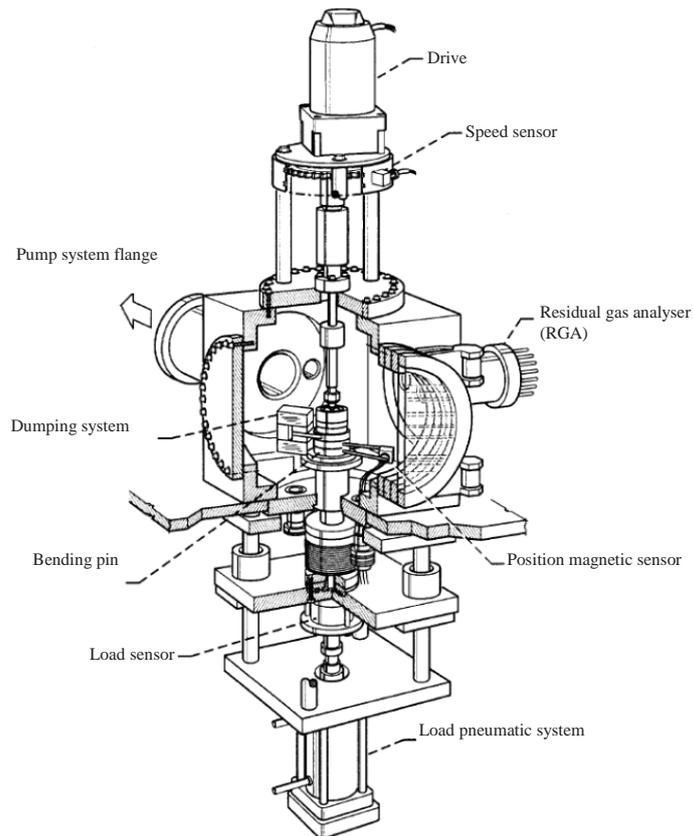


Fig. 12. Scheme of the four-ball vacuum apparatus [27 for 31]

The main parts serving for running tests are similar to the ones in a standard four-ball device. However, there are some differences in details. Owing to the fact that the apparatus is placed in a vacuum chamber it is possible to run tests under high vacuum conditions. Vacuum is being obtained with the use of a turbomolecular pump with efficiency of $140 \frac{l}{s}$ and a mechanical pump that is used for initial emptying of the chamber. Thanks to this solution it is possible to obtain negative pressure from 10^{-4} Pa to 10^{-6} Pa. Besides the tests run under pressure, there is a possibility of performing tests in the atmospheric air or in nitrogen atmosphere. The vacuum chamber is fitted with an ionization vacuum gauge for pressure measurement, and a residual gas analyser (RGA) [45].

The upper ball, that turns, is mounted on a rotary mandrel, and three lower balls are placed below, in a saucer for a liquid lubricant. The saucer is mounted on the base. It is possible to lift the base by means of a pneumatic load system [45].

Torque is being measured by means of measuring the angle relocation of the saucer for a liquid lubricant with the three balls [45].

It is possible to run tests at rotational speeds from 10 rpm to 500 rpm, at ambient temperature.

Before the test it is necessary to clean the balls, the saucer for a liquid lubricant and the rotary mandrel. The balls made of AISI 440C stainless steel should be stored in a nitrogen dry box.

In order to perform the test it is necessary to fill the saucer with a liquid lubricant, and then place the three balls on it. The saucer with a liquid lubricant and the balls prepared as described above should be placed within a glass jar for an hour, and — with the use of a mechanical pump — achieve negative pressure of about 1 Pa. This procedure is being performed in order to remove the air dissolved in a liquid lubricant.

Then it is necessary to place the saucer on the base inside the vacuum chamber and switch on the vacuum pump. After 10 minutes negative pressure should amount about 10 Pa. If it is so, the turbomolecular pump can be switched on.

The test begins when negative pressure reaches 10^{-5} Pa or less. Moment of friction is being recorded during the entire test. The liquid lubricant wear is being evaluated on the basis of measurement of a diameter of the wear trace on the three balls placed on the saucer with a liquid lubricant. In order to do it an optical microscope is being used. The microscope is designed in such a way that it is not necessary to take the balls out of the saucer. Owing to this fact it is possible to continue the tests of the same balls after the measurements with the microscope [45].

4.3. Pin-on-disk friction tester for tests in vacuum

At least several models of the friction testers of the pin-on-disk type were designed. Some are designed for testing of solid lubricants, while the other ones for liquid lubricants. Over the course of time and together with the increase of knowledge about the environment in space the need occurred for constructing an apparatus which, besides tests in the atmospheric air, could run tests under conditions similar to those ones in space. Thanks to various efforts the pin-on-disk devices were constructed. The apparatuses make it possible to run the tests under pressure, in the gaseous atmosphere and at elevated temperatures.

The main parts of the pin-on-disk friction tester (Fig. 13) are: a mandrel with a semicircular surface (it may be a ball mounted in a grip) and a flat disc the mandrel is pressed against. The disc rotates in relation to the mandrel. The mandrel grips have three various lengths in order to achieve three wear tracks on the same disc [12]. The speed range covers values from $3.6 \frac{m}{min}$ to $18.2 \frac{m}{min}$ at the rotational speeds of the disc equal to 25, 50, 75 i 100 rpm, when the three mandrel grips are being used. The load is being imposed via the levers system. Average load value amounts from 0.5 kg to 1 kg [46]. The disk may be immersed within a tank for a liquid lubricant either horizontally or vertically (Fig. 13).

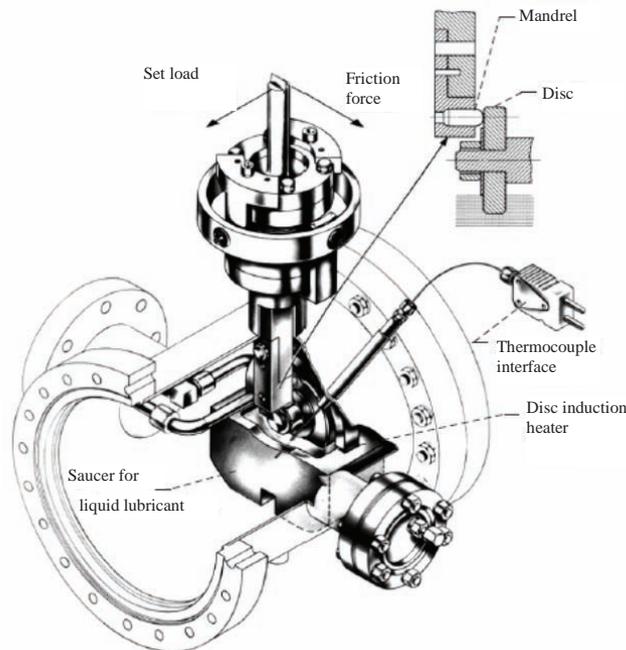


Fig. 13. Scheme of the pin-on-disk friction tester with a tank for a liquid lubricant in a vertical position [15]

The mandrel and the disc should possess perfectly smooth surfaces in order to reduce abrasion. Surface roughness should be less than $0.10 \mu m$. The liquid temperature is being measured with the use of a thermocouple. The friction force measurement is being performed with the use of a strain gauge and recorder with the use of a plotter.

The upper and lower (or left and right) disc surfaces should be parallel, concentric and flat in order to prevent against the inertial force occurrence.

The wear volume of the material of the mandrel is being determined by means of the mass loss measurement or change of the wear trace diameter what makes it possible to calculate the wear volume. The wear volume of the disc is being determined by means of the mass loss measurement on the disc cross-section. A profilometer is being used for the wear track measurement, and then the loss volume is being calculated. The measurement with the use of the profilometer is proffered for the material migration from one part to another, what may cause errors of the mass loss measurements.

The pin-on-disk friction tester in vacuum is shown in Figure 14.

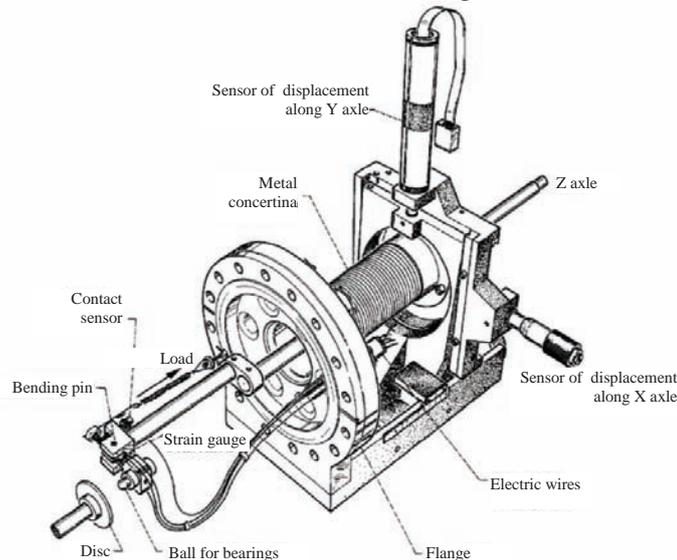


Fig. 14. Scheme of the pin-on-disk friction tester designed for tests in ultra-high vacuum [15]

The beam the mandrel is placed on is mounted in a vacuum flange. The unit is sealed with a metal concertina. The strain gauge measures the load and friction forces between the mandrel and the disc. The XPS spectrometer is mounted to the flange [15].

4.4. Artificial neural networks

The processes in the tribological nodes are very complicated, and the model and the stations for simulating the given friction types are imperfect. Artificial neural networks, for their properties, may be an interesting solution. The networks were designed on the basis of knowledge about biological neural networks. The artificial neural networks are calculating algorithms that simulate behaviour of the human brain cells. They may learn how to analyse complex models and non-linear processes hard to explain.

The neural networks may be used for modelling processes in the friction nodes. A possibility of simulation of very long operation time effect on the basis of data obtained during short-term tests is a very precious advantage of the artificial neural networks. Owing to this fact it is possible to eliminate substantial part of the costs of laborious long-term tests. For the space missions this is a fact of great significance.

Neurons connected with each other form the network structure. They are responsible for processing input signals into the output ones.

Teaching the neural networks consists in entering input data and adjusting the weights of connections between neurons until correct results are reached (similar to the ones obtained during the short-term tests). During learning process the individual weights change until the desired output values are obtained. Then the individual weights are being analysed for their influence on variables.

The neural network usefulness is determined by its ability to predict results correctly. It is easy to determine it thanks to calculating test errors for the selected type of the network [17, 33].

5. Developmental trends within the scope of lubrication of tribological nodes in space engineering

5.1. Direction of development of lubricating substances

Current liquid lubricants may operate up to 260°C, and solid lubricants operate up to 1200°C. The solid lubricants have higher friction factor and higher tribological node parts wear in comparison to liquid lubricants [16]. Therefore liquid lubricants operating within the wider temperature range are needed.

Planned missions to Mars and the Moon determine the need for further tests of liquid lubricants. The liquids with very low vapour pressure, like PFPE, ionic liquids, synthetic hydrocarbons, are needed. Design of liquids with dedicated properties may be a new trend within the scope of selection of a liquid lubricant. Already today it is possible to obtain ionic liquids and multiply-alkylated cyclopentanes (MACs) with demanded parameters by means of selection of reactants and appropriate run of chemical reactions.

5.2. Development of lubricating substances research

The conditions of testing lubricating substances must reflect accurately the real operation environment for each application. Some phenomena and factors taking place in space are hard to simulate on the Earth.

State of weightlessness, various types of radiation, the atmosphere with the atomic oxygen occur on a low circumearth orbit, but their simulation on the Earth needs many attempts. The influence of overloads and vibrations taking place during the rocket launch into space is hard to simulate, too. Meanwhile these factors may be the reason for the lubricating system incorrect functioning or drastic shortening of the period of correct operation. It is recommended to run tests of degradation processes of the lubricating substances (e.g. their oxidizing) that may begin still before the mission start.

5.3. Lubrication technologies for space engineering in the future

5.3.1. Lubrication systems in inert atmosphere

Oxidizing process goes quicker in higher temperature. It means that long-term operation of the liquid lubricant may take place only below some temperature, because after exceeding certain threshold the accelerated oxidizing takes place and the liquid lubricant do not play its part any more. When the presence of oxygen is limited or it is eliminated completely (another gas replaces oxygen, e.g. nitrogen) from the environment, the liquid lubricant may operate correctly at higher temperatures than in case of the atmosphere with oxygen. The main disadvantage of the solution is that it is necessary to store large quantities of an inert gas (e.g. nitrogen) [16, 43]. Using, in the same system, new liquid lubricants which are in the research stage this time, e.g. the task specific ionic liquids (TSILs), should be considered.

5.3.2. Mist lubrication

The mist lubrication system is able to decrease significantly the bearings operating temperature by means of eliminating violent oil mixing at high rotational speeds. It is possible because the liquid lubricant in the form of soft mist is being injected and closed into the region of the bearing contact, and it does not get back to the circulation system after using. Thanks to such a system the liquid lubricant is in contact with the bearings for a very short time. In this case the liquid lubricant distribution is insignificant. The mist lubrication system is lighter and less intricate than the lubricant circulation system. There is less probability of accidental leakages and blocking atomizing nozzles and filters [41 for 42]. The system is not in use for large dimensions of the oil tanks [16].

5.3.3. Lubrication with fine grade powder

Fine grade powders, under strictly determined conditions, behave similarly to liquid lubricants during hydrodynamic friction. Owing to this fact it is possible to use this solution for lubrication of rolling and slide bearings. Powders could be used for operation at higher temperatures liquid lubricants could not operate at [14 for 21].

5.3.4. Deposition of liquid lubricant vapours

It is proven that it is possible to use the products of decomposition of a liquid lubricant as a lubricating substance at high temperatures. High temperature causes decomposition of a liquid lubricant. Besides main decomposition products, i.e. gases, solid decomposition products are being generated, too. The solid decomposition products deposit on the lubricated surfaces and operate under the boundary friction conditions at high temperatures. This technique is still in the early phase of development, and have not been used in practice [16].

5.3.5. Catalytic forming of carbon from gaseous phase

It is possible that, by means of putting gases in the zone between two lubricated surfaces at high temperatures, a reaction resulting in forming a thin lubricating layer will take place. Carbon is being obtained from processed gaseous hydrocarbons. Such a reaction may take place in the presence of nickel as a catalyst on various metal and ceramic surfaces. The layer of carbon causes reduction of friction between surfaces at high temperatures. Many test conforming the effectiveness of this solution should be performed [16 for 38].

5.3.6. Gas bearings

The solid and liquid lubricants may be replaced with a gas under high pressure. The main issue of this solution is contact of lubricated surfaces at the beginning and at the end of operation. Therefore the surfaces being in contact must be separated. It is also possible to spread layers that operate as lubricants at the beginning and at the end of the bearing operation. During operation with high speeds overloads may occur. Therefore it seems to be necessary to apply layers made of solid lubricants. The gas bearings ability to transfer loads is limited. However they have a potential that, after making improvements, may be used in the future [16 for 5].

5.3.7. Magnetic bearings

For magnetic bearings, in order to separate the surfaces, opposing magnetic fields are being used. There are two types of magnetic bearings: passive and active ones. An advantage of the active bearings is a possibility to adjust magnetic field. Their disadvantage is the necessity to use large amounts of the control devices.

The passive magnetic bearings do not need large amounts of the control devices, and have potential to improve efficiency and reliability of bearings. It is possible to keep the greater distance between a stationary magnet and a rotating one when the passive bearings are being used. The passive magnetic bearings have lower rigidity and worst attenuation in comparison to the active ones.

The passive magnetic bearing cross-section is shown in Fig. 15.

The permanent magnets are magnetized axially. One magnet is mounted to a rotating sleeve, and the second one to a stationary sleeve. Each magnet has four rings. The magnetic fields of the two magnets cause the magnets repulsion [51].

The magnetic bearings are not widely used, but have great potential. An interest in this solution may increase together with the progress of electronics. It is recommended to continue research work on layers protecting the magnet surfaces against momentary contacts.

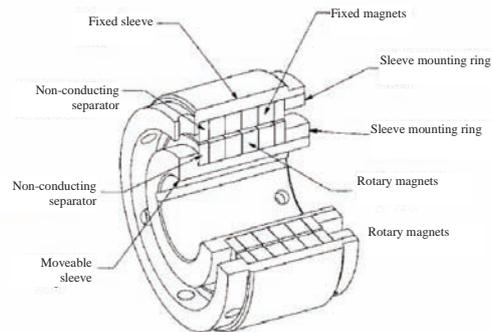


Fig. 15. Cross-section of the passive magnetic bearing [51]

6. Conclusions

Ongoing research on liquid lubricants prove that further development of some of them (perfluoropolyethers, synthetic hydrocarbons) and using new liquids for the space engineering (ionic liquids, silicic hydrocarbons) is possible. Attempts to design liquid lubricants with dedicated properties are promising.

The most important demands for liquid lubricants for lubrication of tribological nodes of the space engineering are: lower and lower vapour pressure and ability to operate within a wider temperature range. There is the continuous need to seek for the additives improving liquid lubricants properties.

The existing research methods are imperfect. Till now it is impossible to simulate many factors occurring in space (among other things state of weightlessness, the atmosphere containing the atom oxygen). It is hard to determine precisely (predict) the tribological nodes wear [2]. Therefore the research works on improvement of the existing test stations and analytical methods, and creation of new methods of tests and analysis are necessary. It is recommended to work on elimination of the disadvantages of lubrication techniques that were not applied in practice yet. These techniques could solve many problems related to lubrication in the space engineering (§5.3).

The space engineering did not make a great progress since Apollo programme. Landing of the first man on the Moon was a success of the program carried out by the United States [57]. Apollo programme proved that human spaceflights require considerable expenditure. Meanwhile ambitious plans assume: return of the man to the Moon, attempt to live on the Moon, and then human spaceflights to Mars. Such enterprises require creating and development of new technologies that will meet demands of environmental conditions on the Moon and Mars. Development of technologies needed for the man's return to the only natural earth satellite and the human spaceflight to the Fourth Planet from the Sun must be kept together with the progress of issues related to mechanics and tribology.

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Acknowledgements

This scientific work has been financed by Ministry of Science and High Education of the Republic of Poland from Found provided for scientific research under development project No. 0R 00002904/PBR 15-249/2007/WAT and authors expressed their appreciation.