INVESTIGATIONS ON LUBRICITY AND SURFACE PROPERTIES OF SELECTED PERFLUOROPOLYETHER OILS

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Abstract

In the paper the investigative results of lubricity and surface properties for four synthetic perfluoropolyether (PFPE) oils, comparing with the high quality gear oil Mobilube 1SHC 75W-90 and two base oils PAO-6 and SN-650, are discussed. The goal of the research was to identify anti-wear and anti-seizing properties of PFPE oils correlation with their surface-energetic and viscosity-temperature properties. Modern test equipment was used for perfomed research.

The following apparatuses were used: KSV Sigma 701 and KSV CAM 100 made in Finland, AMVn Anton Paar made in Austria, and T-02 four-ball apparatus made in Poland. Measurement of density, surface tension and wetting angle were done with the use of KSV Sigma 701 apparatus, according to its instruction manual. The static wetting angle on the real surface of a steel plate was determined with the use of KSV CAM 100 apparatus.

The dynamic viscosity of the tested compounds was determined with the use of AMVn microviscometer. The tests of the lubricity properties of the synthetic oils and comparative liquids were perfomed with the use T-02 four-ball tester. The investigative results showed that PFPE oils can be used particularly in hydrodynamic and elastohydrodynamic lubrication.

Keywords: *tribology, perfluoropolyethers (PFPE), surface tension, contact angle lubrication*

1. Introduction

Many changes in construction of mechanical vehicles and other machines, and technical equipment took place with the years. Because of this fact the demands for lubricating substances were redefined.

In modern friction nodes there are various complex units where there is no possibility to avoid the negative friction effects, i.e. the movement energy loss and wear of interacting parts. More and more intensive operation of the technical equipment, extension of their overhauling period, and their durability and reliability increase, in spite of mechanical and thermal loads increase, require applying the appropriate counter-measures in order to limit the wear intensity and the energy loss. Synthetic lubricating substances, in comparison with the mineral ones, have better performance characteristics, provide higher reliability of the machine and technical equipment movable couplings. Modern synthetic oils have various unique properties: chemical and electrochemical stability, good lubricity properties (anti-wear and anti-seizing ones), low evaporative power, small changes of viscosity, thermal stability across a wide range of temperatures, and easy biodegradation. Thanks to these properties synthetic oils are considered as the very interesting group of oils from the point of view of the lubrication techniques.

Researchers are particularly interested in perfluoropolyether (PFPE) oils used, until now, in the space engineering. In this paper, as the continuation of the research carried out previously [1, 2], the analysis of lubricity and surface properties of four PFPE oils, and their comparison with the high quality gear oil and two base oils, will be described. The goal of the research is to identify anti-wear and anti-seizing properties of PFPE oils in correlation with their surface-energetic and viscosity-temperature properties.

2. Research subjects

Modern perfluoropolyether (PFPE) oils are liquids with the unique structure and properties. Only three elements make up these substances: carbon, oxygen and fluorine atoms. Strong bonds join atoms, and the whole polymer chain is very elastic. The C-F bond is the strongest interatomic bond known in nature, and simultaneously fluorine is the most electronegative element, so the molecule is exceptionally durable. The lack of hydrogen, the common element of all standard liquid lubricants, contributes to the thermooxidizing stability of PFPE oils [8]. The substances have some unique properties [7, 8]:

- the widest temperature range among all lubricating substances (from –90°C to 290°C) - Figure 1,

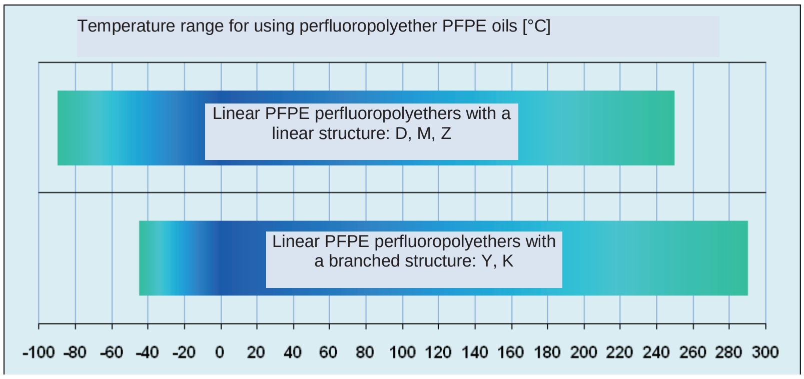

Fig. 1. Temperature range for using Fomblin perfluoropolyether oils [8]

- high viscosity index (for Fomblin it reaches values above 300),
- good high and low temperature anti-wear properties,
- zero ozone depletion potential (ODP),
- high degree of thermal and oxidizing stability, excellent resistance to radiation, minimum mass loss for maximally long operating time of equipment - Figure 2. (evaporation loss for branched and line PFPEs, ASTM 2595 test, 22 hours, 204°C, % wt),

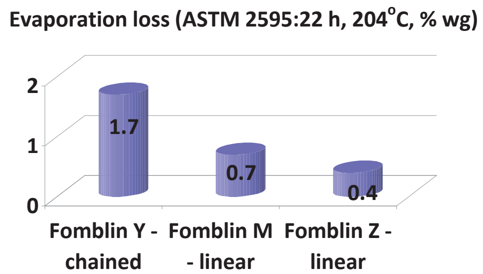

Fig. 2. Evaporation loss for branched and linear Fomblin PFPEs [8]

- incombustibility, nontoxicity, no volatile organic compounds (VOCs),
- compatibility with most materials: plastics, metals, elastomers.

There are five various types of PFPE liquids: K, Y, D, M, and Z. Each type contains carbon, oxygen and fluorine atoms, but they have different molecular structures, i.e. a way of combination of atoms. These differences significantly influence the low temperature and lubricity properties, viscosity index and volatility of liquids. From the point of view of the structure every PFPE liquid may be categorised as branched or linear one, like it is shown in Figure 3. Perfluoropolyether liquids D, M and Z have a linear structure, and Y and Z oils the branched one. Line PFPEs are very elastic, and their flow temperatures are significantly lower than for the branched ones and, in dependence of viscosity, may reach –75°C. The flowing temperature of Z liquid with very low viscosity may be lower than – 90°C.

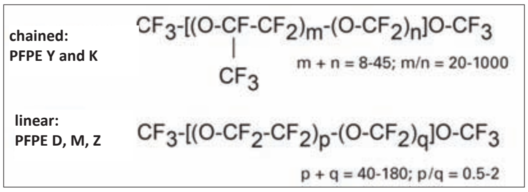

Fig. 3. Molecular structure of PFPE perfluoropolyethers [7]

Selected parameters of linear and branched perfluoropolyethers are shown in Table 1.

Tab. 1. Selected Parameters of Linear and Branched Perfluoropolyethers [3]

PFPE	Operating Temperature [°C]	Viscosity at 40°C [cSt]	Flow Temperature [°C]	Viscosity Index VI
K and Y	–54 to 250	25 – 510	–56 to –28	105 – 150
D	–70 to 250	25 – 200	–75 to –53	150 – 210
M	–70 to 250	90 – 150	< –70	340
Z	–90 to 250	90 – 355	–90 to –63	303 – 360

The subjects of research described in this paper are four modern perfluoropolyether (PFPE) synthetic oils bought previously at Solvay Solexis Company: the two with relatively low viscosity and the two with high viscosity, with linear (M) and branched (Y) structure.

Selected PFPE synthetic oils and their basic properties, provided by the manufacturer, are shown in Table 2.

Tab. 2. Basic Physicochemical Properties of Selected PFPE Oils [7]

Typical Properties	Y04	YPL1500	M15	M60
ISO Class	15	460	100	320
Molecular Mass	1500	6600	8000	12500
Density (ASTM D891) at 20°C [g/cm³]	1.87	1.91	1.83	1.86
Kinematic Viscosity (ASTM D445) at 20°C [cSt] at 40°C [cSt] at 100°C [cSt]	 38 15 3.2	 1500 420 40	 150 85 22	 550 310 86
Viscosity Index (ASTM D2270)	60	135	253	343
Flow Temperature (ASTM D97) [°C]	–58	–25	–75	–60
Unique Features	- excellent stability at high temperatures - good low temperature and anti-wear properties - low evaporativity		- excellent viscosity index - good thermal stability - very low evaporativity - very low torque at negative temperatures	

Two organic oil bases from a refinery (the synthetic and the mineral one) and high class gear oil were used as the comparative liquids:

- PAO-6 - polyalphaolephines (PAO), hydrogenated oligomers of olephines obtained by the catalytic polymerization of linear (chain) alphaolephines, without isoparaffins, used for industrial oils arrangements (flow temperature <–40°C);
- SN-650 - oil mineral base obtained from the vacuum distillation of the petroleum atmospheric distillation residues, including maximum 1% of secondary sulphur, used for the industrial oils arrangements (flow temperature <–9°C);

- Mobilube 1SHC 75W-90 gear oil that meets demands of API MT-1/GL-5/GL-4 classification, used for lubrication of gearboxes and live axles working across a wide range of ambient temperatures, under overloads and percussive loads (flow temperature <–48^{o}C).

3. Test methods and equipment

Modern test equipment was used for the performed research. The following apparatuses were used: KSV Sigma 701 and KSV CAM 100 made in Finland, AMVn Anton Paar made in Austria, and T-02 four-ball apparatus made in Poland.

3.1. Determination of viscosity, surface tension and wetting angle with the use of KSV Sigma 701 apparatus

Measurements of density, surface tension and wetting angle were done with the use of KSV Sigma 701 apparatus, according to its instruction manual [10]. The test stand for measurements of the parameters mentioned above is shown in Figure 3.

Fig. 3. Test equipment for measurements of density, surface tension and dynamic wetting angle: 1 – JULABO F-12 thermostatic bath; 2 – KSV Sigma 701 tensiometer; 3 — personal computer for test control

The density determination of tested lubricating liquids was performed after the apparatus calibration, i.e. after verification of the parameter under evaluation for the test liquid with known density. Distilled water was used for the apparatus calibration. During the calibration procedure the software automatically detected phase boundary (water, air) and the zero position of the sampler. After the apparatus calibration determination of the density of the tested compounds was possible. The measurement consisted in submerging the sampler into the liquid to a fixed depth. Then the programme converted measured force value into the density of the liquid under test, on the basis of Archimedes' principle. The measurements were performed for the following temperatures: 25^{o}C, 40^{o}C and 100^{o}C. The measurements for each temperature were performed three times.

The surface tension measurement consisted in measurement of the force between the sampler (Wilhelmy plate with the following dimension: thickness — 0.1 mm, width — 19.6 mm) and the phase boundary for the two liquids (in this case it was the gaseous phase of the tested liquid, i.e. the air). Wilhelmy plate was lowered, with the use of a scale, in such a way that the plate was in contact with the phase boundary of the tested liquid. The apparatus for calculation of surface tension used the values of the force between the sampler and the liquid surface automatically. The result of determination of surface tension was the mean value for a single test cycle consisting of 10 submersions.

The wetting angle measurement was performed after the surface tension test. Wilhelmy plate, described above, was used for the measurement. During the sampler submersion (Wilhelmy plate) the advance wetting angle was calculated, and during the plate raising — the descent one. The procedure is shown in Figure 4.

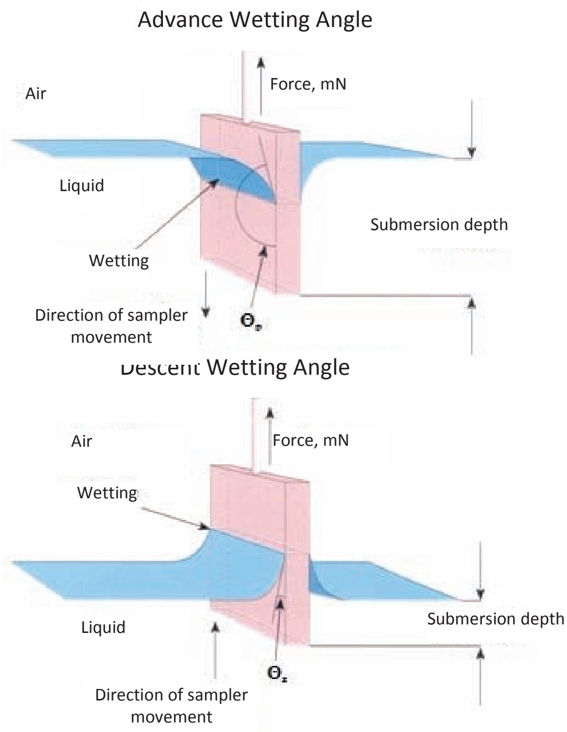

Fig. 4. Dynamic wetting angle: advance and descent [10]

In this paper, for the purpose of the comparative analysis of synthetic oils, the maximum values of the advance wetting angle were used. The angle values were obtained during the sampler submersion into the tested sample. As described in instruction manual [10], it is possible to consider this value the static wetting angle of the platinum plate by the tested liquid.

The measurements of surface tension and wetting angle of Wilhelmy platinum plate were performed at 25°, 40°C and 100°C, as for the density measurement. During the test the samples were heated with the use of JULABO F-12 thermostatic bath which is designed with "1" in Figure 3. Before each measurement of the surface tension and wetting angle Wilhelmy plate was heated by means of gas flame in order to remove all impurities.

3.2. Determination of static wetting angle with the use of KSV CAM 100 apparatus

The static wetting angle was determined with the use of KSV CAM 100 apparatus, according to its instruction manual. The apparatus is shown in Figure 5 [12].

Fig. 5. Test stand for measurement of static wetting angle: 1 – notebook for test control with appropriate software installed; 2 – KSV CAM 100 apparatus

Each measurement was performed three times. The measurement consisted on placing drops of the tested liquid lubricant on the surface of a plate with 62 HRC hardness and roughness of R_a=0.01÷0.02 μm (NC4 type-alloyed tool steel). The tests were performed at 25°C, 40°C and 60°C, and the apparatus was set to take 15 photos every 500 ms. Thanks to using the software provided with the apparatus it was possible to determine automatically the static wetting angle and curve fitting on the basis of Young-Laplace equation.

3.3. Determination of absolute and kinematic viscosity, and viscosity index

The dynamic viscosity of the tested compounds, also called absolute viscosity, was determined according to the manufacturer's instructions [13], with the use of AMVn Anton Paar microviscometer. The apparatus is a falling ball viscometer by Höppler, where the time of the ball falling into transparent and non-transparent liquids is being measured. The test stand for measurements of the absolute viscosity is shown in Figure 6.

Fig. 6. Test stand for measurements of absolute viscosity: 1 – notebook for test control with appropriate software installed; 2 – AMVn viscometer

According to Höppler principle the time necessary for the ball to cover a reference distance in a glass tube filled with the tested liquid sample is being measured. The result of the test is the absolute viscosity [mPas] that is calculated by multiplying the measured time by the difference between the densities of the ball and the liquid tested, and by the ball constant. Each measurement was performed six times. The inclination angle (15^o–90^o) of the capillary tube was being selected for each sample and temperature in such a way that the falling time of a steel ball, if possible, was between 18 and 23 seconds. The temperature was being verified before each measurement.

The viscosity index of the tested synthetic oils and the comparative liquids were being calculated according to PN-ISO-2909 - “Petroleum Products”. Calculation of Viscosity Index on the Basis of Kinematic Viscosity [5].

3.4. Tests of lubricity properties

The tests of the lubricity properties of the selected synthetic oils and comparative liquids were performed according to PN-76/C-04147 standard, which is a modification of ASTM D4172, with the use of ITE T–02 four-ball apparatus designed for determining anti-wear and anti-seizing properties of lubricating oils and greases. The test stand is shown in Figures 7 and 8. The stand was fitted with the measurement and control system consisting of a measuring amplifier, a set of measuring transducers and a personal computer with the appropriate control and measurement software installed.

Three parameters were determined: two normative, i.e. seizing load (P_t) and wear boundary load (G_{oz}) according to [4], and additionally seizing boundary pressure (p_{oz}) after complete 18-second runs under load increasing linearly. Selection of these parameters was dictated by the

meritorious reasons and small amounts of individual synthetic oils. The first parameter (P_t) was characteristic of anti-seizing properties, the second one (G_{oz}) — anti-wear properties, and the third one — surface thrust (p_{oz}) — was characteristic of behaviour of a liquid during the seizing process. P_t is being determined under smoothly increasing load of 409 N/s, i.e. 490.5 daN (500 kG for every 100 revolutions of the upper ball) at the engine speed of 500 rpm. Rapid increase of the moment of friction (jump) determines the moment of the lubricating film break under P_t seizing load. So-called wear boundary load G_{oz} was determined at the rotational speed of 500 rpm, under load of P=147.15 daN (150 kG) during the 60-second run.
G_{oz} parameter was calculated on the basis of the following formula:

$$p_{oz} = 0.52\frac{P}{d_{śr}^{2}}, \quad (1)$$

where: P - applied load of 147.15 daN, 0.52 - factor for the force distribution in the friction node (regular tetrahedron), $d_{śr} = \sum d/6$, where: d –wear trace diameters on the lower balls.

The method of calculation of p_{oz} was the same as for the normative parameter
G_{oz} [4], but was applied to P_{oz} = const at the end of the 18-second run, under continuous load, as in the case of determining P_t.

Fig. 7. Test stand for measurements of lubricity properties: 1 — personal computer for test control with appropriate software installed; 2 — T-02 four-ball apparatus with a digital amplifier and a set of transducers

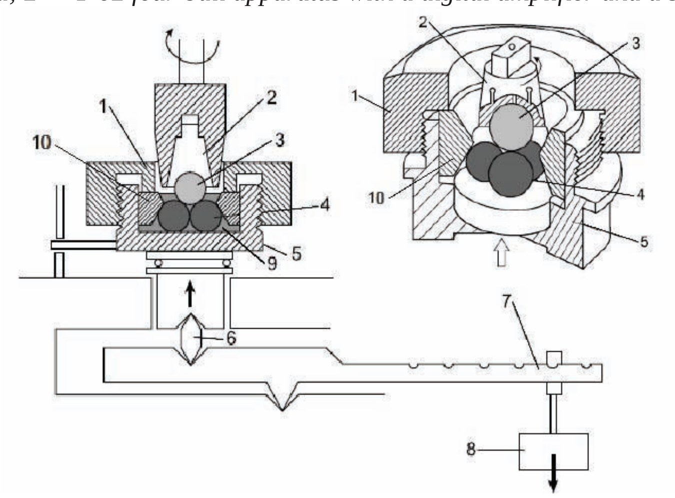

Fig. 8. Diagram of the measurement unit with a four-ball apparatus: 1 - lower balls fixing cover; 2 - upper ball grip; 3 - upper ball (rotated); 4 - lower balls (motionless); 5 - vessel with tested oil; 6 - prism; 7 - lever; 8 - load; 9 - tested oil; 10 - retaining ring [6]

The measurement of diameters of the wear traces on the lower balls was performed with the use of Eclipse LV100 polarizing microscope made by Nikon. It is possible to get measurement accuracy of 0.01 μm with the use of the apparatus. However, in this case the results were rounded off to 0.01 mm according to [4] standard requirements. It is understandable taking into consideration the force and intensity of wear of the balls within the four-ball apparatus, and the need to observe distinct, definite differences, with no doubt raise.

4. Test results and analysis

4.1. Results of measurements of density and result analysis

The results of measurements of density of selected perfluoropolyether oils and comparative oils in dependence of temperature are shown in Table 3, and their graphic presentation is shown in Figure 9. The PFPE oils density was over two times greater than the one for reference oils at 25°C temperature and reached values from 1.8223 to 1.9080 g/cm^3.

Tab. 3. Results of Density Measurements

Parameters	Liquid Lubricants						
	PAO–6	SN–650	Mobilube	YPL1500	Y04	M60	M15
Density ρ [g/cm^3]							
25°C	0.816	0.881	0.856	1.908	1.868	1.828	1.822
40°C	0.806	0.869	0.843	1.868	1.827	1.788	1.783
100°C	0.769	0.829	0.804	1.755	1.711	1.655	1.656

High density of synthetic PFPE oils is a result of their high atomic mass and the molecular structure. M15 and M60 oils have similar atomic masses and have the linear molecular structure what is translated into similar densities of these oils. Y04 and YPL1500 oils, with the branched molecular structure, had slightly higher densities than M15 and M60 oils. PAO-6 oil had the lowest density among all tested liquid lubricants.

Change of PFPE oils density at 100°C in comparison with the density at 25°C is almost two times greater than the change for the comparative oils, what may be seen in Figure 9.

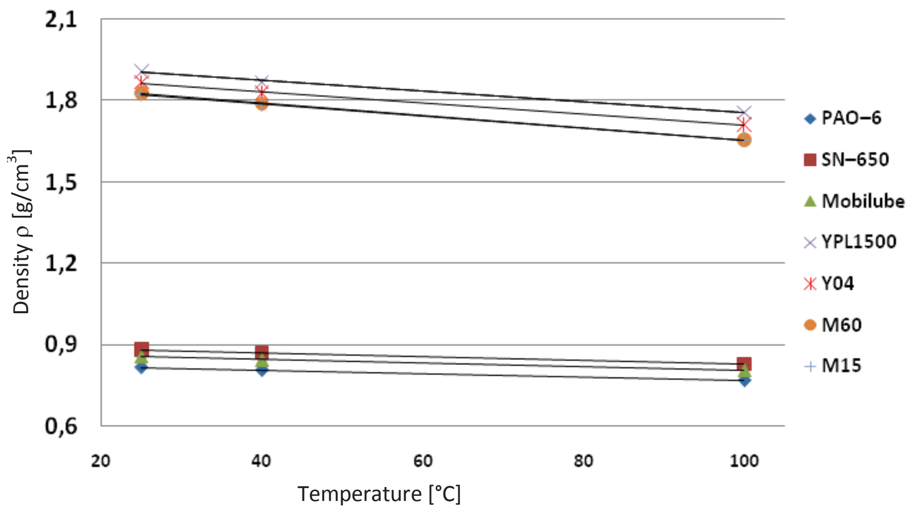

Fig. 9. Relationship between density and temperature for tested liquid lubricants

4.2. Results of measurements of surface tension and wetting angle with the use of Sigma 701 apparatus, and wetting angle with the use of CAM 100 apparatus, and result analysis

The results of measurements of surface tension and the wetting angles of tested lubricating oils are shown in Table 4 and, graphically, in Figure 10. The trend, also described in bibliography [9], indicates the linear relationship between surface tension and temperature for all tested oils.

Tab. 4. Results of Measurements of Surface Tension and Wetting Angle with the Use of Sigma 701 Apparatus, and Wetting Angle with the Use of CAM 100 Apparatus

Parameters	Liquid Lubricants						
	PAO–6	SN–650	Mobilube	YPL1500	Y04	M60	M15
Surface Tension σ [mN/m]							
25°C	27.523	30.460	27.565	17.634	16.880	18.237	20.522
40°C	26.846	29.384	26.432	16.739	15.239	17.360	19.553
100°C	23.869	25.785	22.419	14.198	11.115	14.930	13.504
Wetting Angle CAM 100							
25°C	18.79	24.51	15.11	49.01	23.92	36.84	35.75
40°C	15.47	19.26	11.08	39.63	21.63	35.03	32.88
100°C	12.04	15.82	8.32	34.63	19.66	32.09	28.32
Wetting Angle Sigma 701							
25°C	34.78	35.03	26.96	53.01	0.00	28.74	25.81
40°C	31.88	32.12	23.48	43.00	0.00	26.00	25.75
100°C	20.88	19.25	8.76	22.48	0.00	0.00	9.05

All tested perfluoropolyether oils had lower values of surface tension than the comparative ones. From among selected PFPE oils M15 oil had the highest surface tension at 25°C equal to 20.522 mN/m. At temperatures of 25°C and 40°C the oils with a linear structure (M15 and M60) had higher surface tensions than the ones with a branched structure (Y04 and YPL1500). At 100°C temperature M15, M60 and YPL1500 oils had similar surface tension values between 13.504 mN/m and 14.930 mN/m. Y04 oil had the lowest surface tension across the entire range of temperatures. Y04 also had, from among PFPE oils, the lowest molecular mass. Taking into consideration the comparative oils, SN-650 oil had the highest surface tension across the entire range of temperatures, and PAO-6 and Mobilube synthetic oils had similar surface tensions at temperatures of 25°C and 40°C.

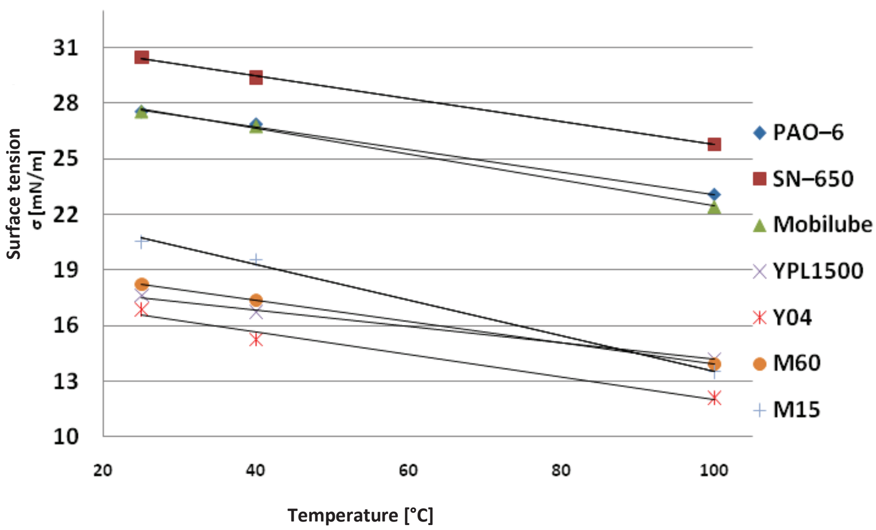

Fig. 10. Relationship between surface tension σ and temperature for tested liquid lubricants

Y04 synthetic PFPE oil had perfect wettability at temperature of 25ºC (Table 4). YPL1500 had the worst wettability of the platinum sampler among PFPE oils is spite of having very low surface tension. It may be connected with its viscosity that is the highest one from among all tested oils. The wettability of YPL1500 PFPE oil at temperature of 100ºC is comparable with the wettability of SN-650 and PAO-6 reference oils.

Relationship between static wetting angle and temperature for all tested comparative and PFPE oils determined with the use of KSV CAM 100 apparatus is shown in Figure 11.

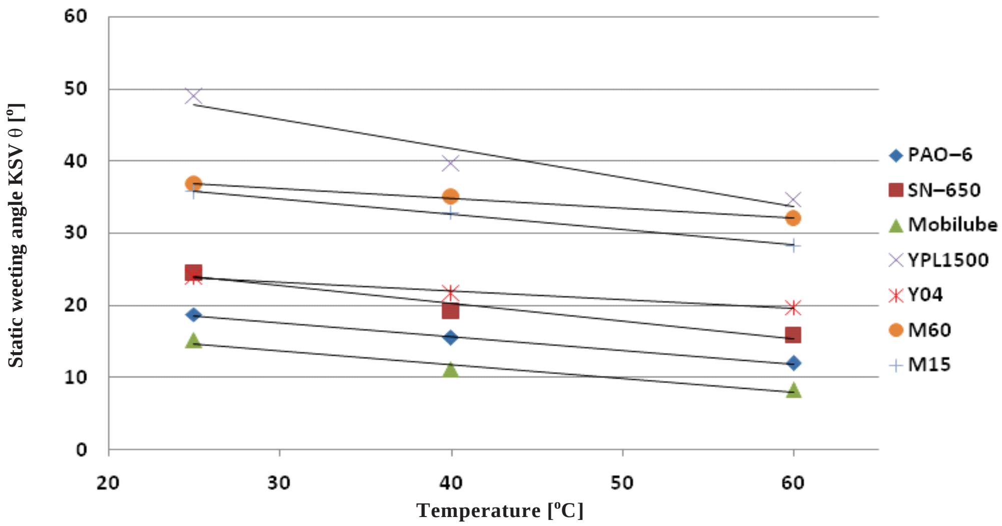

Fig. 11. Relationship between static wetting angle θ and temperature measured with the use of KSV CAM 100 apparatus

The results of measurements of the static wetting angle made by placing a single drop of the tested liquid lubricant on a sample made from NC4 type-alloyed tool steel also show a tendency to increase wettability together with temperature increase. The tendencies are linear. YPL1500 PFPE oil, also in this case, had the worst wettability of the steel sample. The comparative oils, particularly Mobilube 1SHC 75W-90, had very good wetting properties during the tests performed with the use of KSV CAM 100 apparatus. Y04 again had the best wetting properties among PFPE oils.

4.3. Results of measurements of absolute and kinematic viscosity, and result analysis

Absolute viscosity is a parameter describing shearing stress to shearing speed ratio. On the basis of the test results shown in Table 5 it can be found that PAO-6 oil had the lowest absolute viscosity value across the entire range of temperatures. Its viscosity at temperature of 25 °C was equal to 47.36 mPas and was less by 12.68 mPas than the one for Y04 PFPE oil. YPL1500 PFPE oil had the highest absolute viscosity at this temperature (1879.73 mPas). It can be observed that there is a relationship between the molecular mass, molecule structure and absolute viscosity of PFPE oils.

Tab. 5. Results of Measurements of Absolute and Kinematic Viscosity, and Viscosity Index

Parameters	Liquid Lubricants						
	PAO–6	SN–650	Mobilube	YPL1500	Y04	M60	M15
Absolute Viscosity η [mPas]							
25°C	47.36	345.47	188.83	1879.73	60.04	697.42	224.49
40°C	24.52	131.96	91.15	739.67	32.25	382.48	138.29
100°C	4.56	11.51	12.93	62.71	5.99	123.67	36.04
Kinematic Viscosity ν [mm^2/s]							
25°C	58.05	392.13	220.59	985.18	32.14	381.52	123.21
40°C	30.42	151.85	108.13	395.97	17.65	265.82	77.56
100°C	5.93	13.88	16.08	35.73	3.50	74.72	21.76
VI	144	86	160	134	55	347	306

Taking into consideration Y04 and YPL1500 oils with identical molecular structure (branched chains), the one with higher molecular mass has higher viscosity. Similar relationships may be observed when M15 and M60 PFPE oils with the linear structure are taken into consideration. The results of measurements of absolute viscosity are shown in Figure 12.

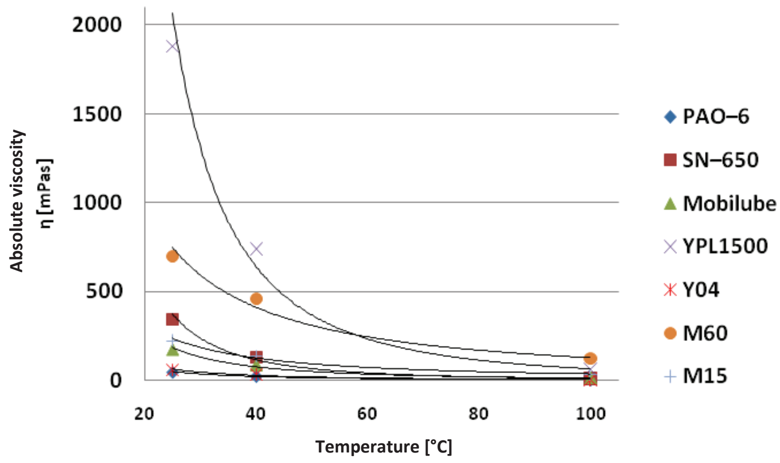

Fig. 12. Relationship between absolute viscosity η and temperature

On the basis of determined absolute viscosity of tested liquid lubricants it was possible to determine kinematic viscosity necessary to calculate viscosity index. For SN-650, PAO-6 and Mobilube 1SHC 75W-90 comparative liquids, which have density ρ < 1, the kinematic viscosity had higher values than the absolute viscosity, and for PFPE oils the kinematic viscosity values were lower because their density ρ > 1 - Fig. 13.

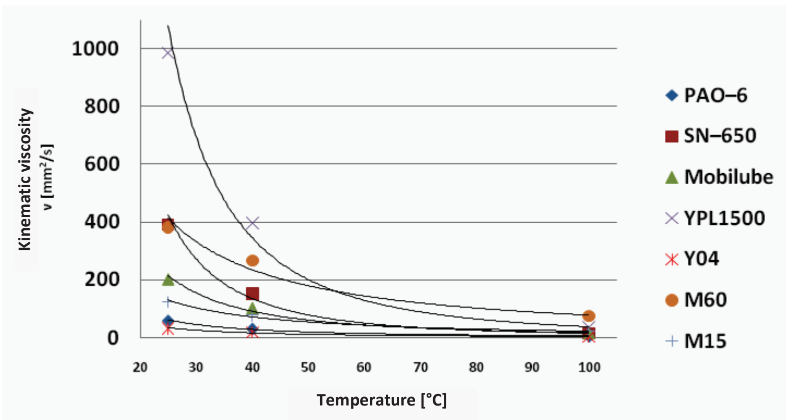

Fig. 13. Relationship between kinematic viscosity ν and temperature

Y04 PFPE oil had the lowest kinematic viscosity across the entire range of temperatures, and YPL1500 PFPE oil had the highest one. At temperature of 25ºC this oil had kinematic viscosity equal to 985.18 mm^2/s while Y04 kinematic viscosity was only 32.14 mm^2/s. The kinematic viscosity of the oils tested at temperature of 100ºC was between 3.50 and 35.73 mm^2/s. M60 oil was the only exception. Its viscosity was equal to 74.72 mm^2/s. Relationship between kinematic viscosity ν and temperature is shown graphically in Figure 13.

M60 oil, at temperature of 25ºC, has kinematic viscosity similar to SN-650 oil, however at temperature of 40ºC it can be observed distinct advantage of PFPE oil over the mineral base because the viscosity change between these temperatures is equal to 240.28 mm^2/s for SN-650 and only 115.70 mm^2/s for M60.

Using the kinematic viscosity determined for 40°C and 100°C temperatures, and standard [5], the viscosity index, which mirrors kinematic viscosity changes with temperature, was determined.

The higher value of dimensionless viscosity index indicates better oil resistance to changes of viscosity in dependence of temperature. M60 and M15 oils had the highest values of viscosity index at the level of: 347 for M60 PFPE oil and 306 for M15 PFPE oil. This is a result of a linear structure of these liquids. Low viscosity index for Y04 PFPE oil is surprising. The index is equal to 56. It is possible that it is the result of its very low kinematic viscosity. Mobilube 1SHC 75W-90 synthetic oil had the best viscosity index among the comparative oils. Its VI was equal to 160. Viscosity index values for all tested oils are shown in Figure 14.

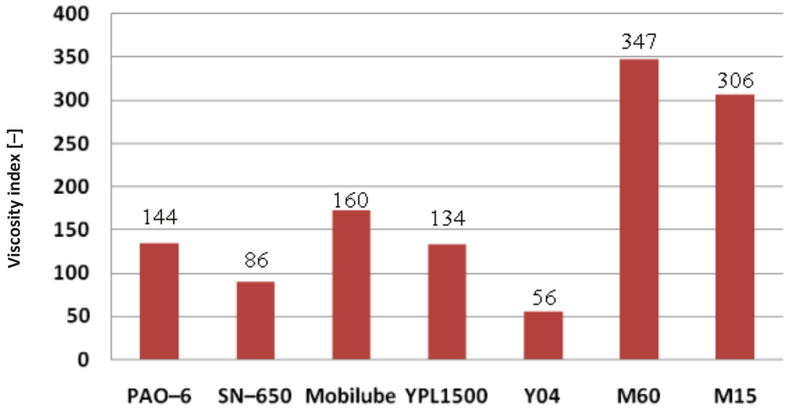

Fig. 14. Viscosity indexes for tested oils

4.4. Results of tests of lubricity properties, and result analysis

Lubricity properties of selected perfluoropolyether oils and comparative oils were described with the following parameters: P_t, G_{oz}, and p_{oz} (§3.4). The test results are shown in Table 6.

Tab. 6. Results of Lubricity Tests

Parameters	Liquid Lubricants						
	PAO–6	SN–650	Mobilube	YPL1500	Y04	M60	M15
Wear Boundary Load G_{oz} [daN/mm^2]	45.28	58.88	318.70	132.48	181.11	160.72	151.79
Seizing Boundary Pressure p_{oz} [daN/mm^2]	126.80	117.18	306.04	495.73	329.12	473.94	495.73
Seizing Load P_t [daN]	116.57	132.93	296.53	184.05	94.07	61.35	53.17

Mobilube 1SHC 75 W/90 gear oil had the best lubricity properties when P_t parameter was taken into consideration. Its seizing load was equal to 296.53 daN. Other oils had relatively low seizing load values. PAO-6 and SN-650 base oils had higher values of P_t in comparison with PFPE oils, except for YPL 1500 oil the viscosity of which was several times higher than for all other tested oils.

Boundary pressure p_{oz} is a parameter characterizing a lubricating substance behaviour when Pt boundary value is exceeded [11, 14]. The higher value of this parameter, the more effective is the oil film operation after breaking the boundary film, i.e. after exceeding P_t value and creating new elastohydrodynamic lubrication conditions.

PFPE oils had the highest values of p_{oz} parameter among tested liquid lubricants. These values exceeded 3 – 4 times the values obtained for SN-650 and PAO-6 comparative oils. Mobilube 1SHC 75W-90 oil also had definitely lower value of p_{oz} (306.04 daN/mm^2) than YPL1500, M60 and M15, and similar to Y04 oil for which p_{oz} value was equal to 329.12 daN/mm^2, and was the lowest among all PFPE oils (Table 6).

Wear boundary load was determined with the use of the four-ball apparatus, according to standard [4]. The parameter characterized unitary load determining pressures within the friction node under constant load of 147.15 daN during the 60-second run. The highest value of G_{oz} parameter was obtained for Mobilube 1SHC 75W-90 oil (318.70 daN/mm^2). The values of the wear boundary load for PFPE oils were between 132.48 daN/mm^2 and 181.11 daN/mm^2. The values were over two times higher than the ones for PAO-6 (45.28 daN/mm^2) and SN-650 (58.88 daN/mm^2) comparative oils.

5. Conclusions

In the light of described tests of surface and lubricity properties of selected synthetic oils the following preliminary conclusions may be drawn:

1. M60 i M15 synthetic PFPE oils had very high values of the viscosity index what, in combination with their low temperature properties and resistance to oxidizing make it possible to use them in the applications especially sensitive to the viscosity changes across a wide temperature range.
2. The wear boundary load G_{oz} for PFPE oils had reached values at the level of 132.48 – 181.11 daN/mm^2. It makes possible to think that these oils would be applicable in not too much loaded systems, particularly in hydrodynamic and elastohydrodynamic lubrication.
3. Tested perfluoropolyether oils had low values of surface tension and good wettability of the platinum plate and steel samples. It influences their ability to coat lubricated surfaces and recover the lubricating film in spite of weaker anti-seizing properties.
4. Tested synthetic oils had the smallest diameters of the wear traces on the lower balls, obtained after the complete 18-second run of the four-ball apparatus, under the load increasing linearly and constant rotational speed, what was translated into very high values of p_{oz} parameter. It proves good anti-wear properties of PFPE oils and their ability to the elastohydrodynamic lubricating film recovery.

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