INITIAL STUDIES ON LUBRICITY AND SURFACE PROPERTIES OF SELECTED IONIC LIQUIDS

Tomasz Jan Kałdoński, Mateusz Stańczyk
Łukasz Gryglewicz, Tadeusz Kałdoński

Military University of Technology, Faculty of Mechanical Engineering
Institute of Motor Vehicles and Transportation
Gen. S. Kaliskiego Street 2, 00-908 Warsaw, Poland
tel.: +48 22 6837384
e-mail: kaldonskit@wat.edu.pl

Abstract

The paper discusses the results of the studies on the surface properties and lubricating abilities of five ionic liquids compared to a high quality gear oil: Mobilube 1SHC 75W90 and two base oils: PAO-6 and SN-650. The investigated ionic liquids were: 1) tetrafluoroborate 1- benzyl-3-methylmidazolium, 2) bis (trifluoromethylsulfonyl) imide 3-methyl-1-propylpyridinium, 3) bis (trifluoromethylsulfonyl) imide 1,2-dimethyl-3-propylimidazolium, 4) bis (trifluoromethylsulfonyl) imide trihexyltetradecylphosphonium), 5) tetrafluoroborate trihexyltetradecylphosphonium.

The density, surface tension and wetting angle as well as dynamic and kinematic viscosity were measured. Next, the lubricity properties were evaluated using the four-ball tester.

The research results showed the more better lubricity properties of ionic liquids than the base oils. The research results showed the more better lubricity properties of ionic liquids than the base oils. The ionic liquids had the comparable properties to a high quality gear oil. Obtained results of these preliminary studies confirmed a possibility of using selected ionic liquids as new lubricants. These compounds can probably replace the lubricants used so far and find a wide scope of application in lubrication technology in the future. However, particular implementations require further complex studies.

Keywords: *tribology, ionic liquids, surface tension, contact angle, lubrication*

1. Introduction

Salts with melting temperature below 100^{o}C [1] are called ionic liquids. These compounds usually consist of organic cation and most often of inorganic anion of poor coordination ability, however the volume of one ion or both ones is quite high. There is a weak interaction between ions in the ionic liquid molecule and it reduces their packing degree.

According to many literature sources [1-10], apart from a low harmful effect on the environment, ionic liquids possess a series of unique properties (they are non-volatile, thermally stable within a wide scope of temperature values, chemically and electrochemically stable, low melting temperature, non-flammable, can be mixed with water and organic solvents), which result in a high interest in them as lubricating agents or even as additives to base oils, both synthetic and mineral ones.

According to the studies carried out so far [2-4, 7-10], ionic liquids often show better tribologic properties compared to the oils being currently in use. Tested ionic liquids [2] showed the lubricating layer resistance almost twice as high in the room temperature and in the increased temperatures compared to the synthetic oils used, for example, in the space technology, i.e.. PFPE (perfluoropolyether oils) or X-1P (tetrakis-(3-trifluoromethylphenoxy)-bis(4-fluoro-phenoxy)-cyclotriphosphazene) [2]. Moreover, the results of performed tests [3] proved that tested ionic liquids generate lower friction coefficient than other reference lubricants. The wear of friction layers lubricated with new compounds was smaller than in case of lubrication with base oils [2].

However, there is no information about spectacular, practical use of ionic liquids as a lubricant or additive to a lubricant of any real tribologic nodes.

This paper, as a continuation of studies carried out by the authors [7] according to the development project No. 0R00002904 financed by Ministry of Science and High Education of the Republic of Poland during 2007-2011, the analysis of lubricating and surface abilities of five ionic liquids, never evaluated for tribologic abilities so far, has been performed, compared to a high quality gear oil and two base oils. The purpose of those studies is searching for ionic liquids of the best anti-wear and anti-tear properties, in correlation to their surface-energy and viscosity-temperature properties, useful as lubricants for saturating porous slide bearings, sintered with iron powders [18-20].

2. Research Scope and Methodology

2.1. Research Subject

The subject of the research included five ionic liquids purchased from Sigma-Aldrich, i.e. 1) tetrafluoroborate 1-benzyl-3-methylimidazolium (CJ005), 2) bis(trifluoromethylsulfonyl)imide 3-methyl-1-propylpyridinium (CJ006), 3) bis(trifluoromethylsulfonyl)imide 1,2-dimethyl-3-propylimidazolium (CJ007), 4) bis(trifluoromethylsulfonyl)imide trihexyltetradecylphosphonium (CJ008), 5) tetrafluoroborate trihexyltetradecylphosphonium (CJ009). Structural formulas of these compounds are presented on Fig. 1. One of the basic criteria for choosing those liquids was the fact that they are immiscible with water and simultaneous good miscibility with basic organic substances (hydrocarbons). Efforts were made to choose the liquids of diversified viscosity, density and melting temperature. The authors followed the information given by the supplier (SIGMA-ALDRICH) which was verified in the following studies. Melting temperatures of ionic liquids amount to respectively: 77^{o}C, 0^{o}C, 15^{o}C, -50^{o}C, 17^{o}C.

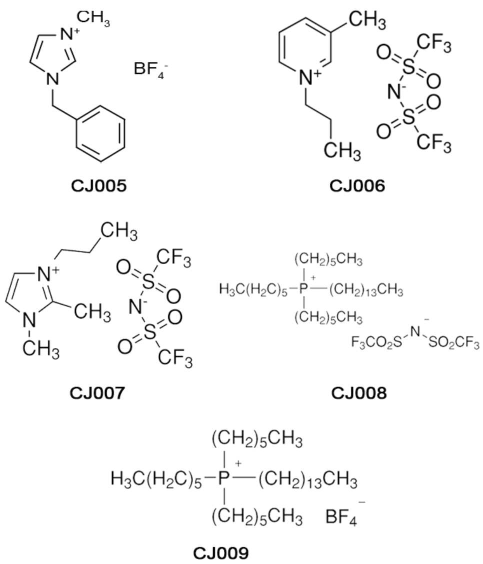

Fig. 1. Structural formulas of tested ionic liquids

The comparison included, like in the paper [16], two organic oil bases coming from the refinery, PAO-6 synthetic base oil and SN-650 mineral base oil and fine gear oil: Mobilube 1SHC 75W-90 which meets the requirements of API MT-1/GL-5/GL-4 classification. The scope of studies was the same as in the paper [16] concerning synthetic perfluoropolyether oils.

2.2. Test Methodology

2.2.1. Measurement of density, surface tension and wetting angle

The measurements of density, surface tension and the wetting angle have been performed using KSV Sigma 701 tensiometer (made in Finland) according to the apparatus operation manual

[11], at temperatures of 25°C, 40°C and 100°C. The density measurement has been performed by means of a sampler, i.e. a glass ball of identified volume, immersed in the tested liquids to the depth of 12 mm. The measurement was repeated 3 times for each tested temperature. Before each measurement the ball was washed in the extraction naphtha and technical acetone. The other two parameters were identified using the Wilhelmy platinum plate, of known dimensions (thickness: 0.1 mm, width 19.6 mm), as a sampler immersed to the depth of 6 mm with a velocity of 0.1 mm/s. The results of the surface tension are the average of 1 measurement cycle including 10 immersions. The wettability analysis used the maximum value of the progressive wetting angle, obtained from generated data during sampler immersion in a tested sample. A detailed methodology was described in [16]. Before each measurement of the surface tension and wetting angle, the Wihelmy plate was fired with a gas flame in order to remove any contaminations. The measurement temperatures were obtained using Julabo F-12 circulator combined with KSV Sigma 701 tensiometer. Testing stations are presented on Fig. 2.

Fig. 2. Testing station for the measurement of density, surface tension and wetting angle

2.2.2. Static wetting angle measurement

A static wetting angle was determined on KSV CAM 100 machine according to the apparatus operation manual [12] at temperatures of 25°C, 40°C and 60°C using the drop shape evaluation method from Young-Laplace equation. The testing station is presented on Fig. 3. Tested compound was dropped on a plate made of NC4 (R_a = 0.01-0.02 μm) class tool steel. Fig. 4 shows the image of a software used to determine the wetting angle using the drop shape evaluation method. During each measurement, 15 measuring photos were taken in 500 ms intervals and then an average was calculated based on obtained results for each frame. Each measurement was performed three times. Measuring temperatures were obtained by means of Julabo F-12 circulator, as in the paper [16].

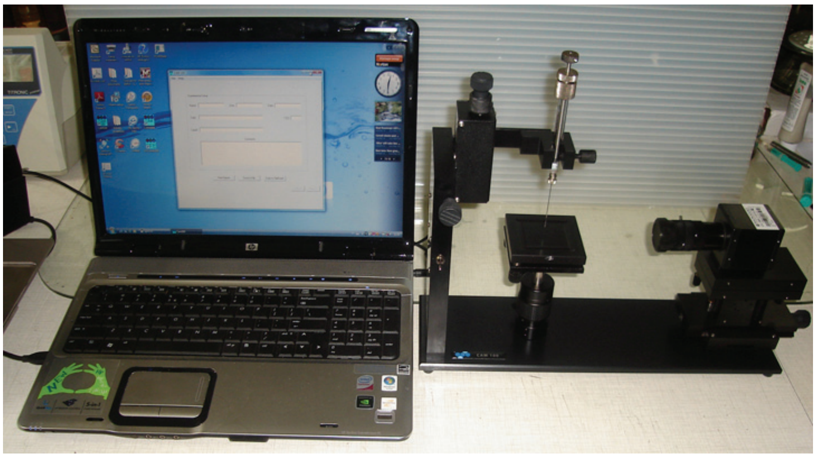

Fig. 3. Testing station for static wetting angle tests

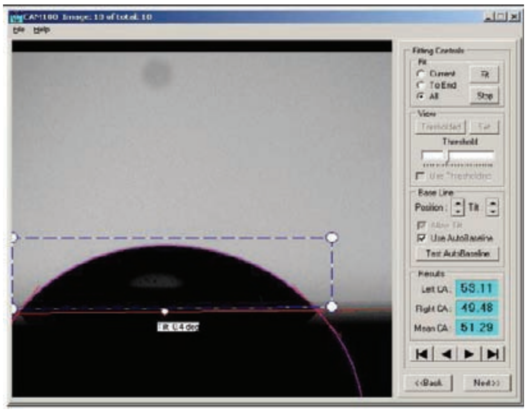

Fig. 4. Image of the software for determining the wetting angle [12]

2.2.3. Measurement of dynamic and kinematic viscosity – viscosity index calculation

Dynamic viscosity (also known as absolute) of tested compounds has been determined by means of AMVn viscometer manufactured by Anton Paar (Austria). This is the Höppler's ball viscometer, which measures the ball sinking time in transparent and non-transparent liquids. A possibility of taking measurements using microvolume of liquids (150 μL) makes an advantage of that apparatus. And due to the prices of some ionic liquids that advantage becomes even more significant. The measurements were performed at the following temperatures: 25^{o}C, 40^{o}C and 100^{o}C. Fig. 5 presents the testing station consisting of AMVn microviscometer and a laptop computer.

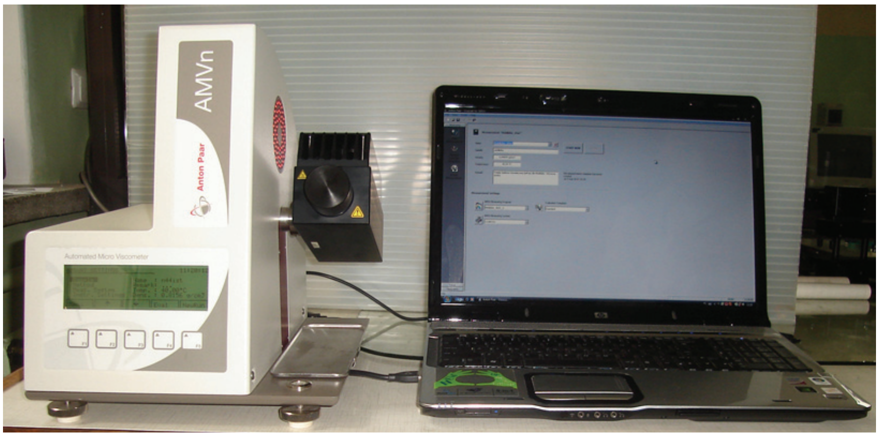

Fig. 5. Testing station for dynamic and kinematic viscosity tests

Each measurement was carried out 6 times. Capillary inclination angle (15^{o}-90^{o}) was chosen for each sample and temperature in a way the steel ball sinking time could fall between 10 and 30 seconds, if possible, according to the manufacturer's recommendation. The temperatures was verified before each measurement.

The viscosity index for ionic and reference liquids was calculated using the PN-ISO 2909 standard ”Oil products. Viscosity index calculation on the basis of kinematic viscosity” [17].

2.2.4. Evaluation of lubricity properties

The lubricity properties of ionic liquids and reference oils were tested according to the PN-76/C-04147 standard [13], using the four-ball ITE T-02 apparatus (Fig. 6), which is intended for determining the anti- wear and anti- seizure abilities of oils and greases. The testing stations was also equipped with the measurement-control system, which includes: digital measurement amplifier, measurement converter assembly, PC computer with special measurement-recording software.

Testing node (Fig. 7) consists of three immobilized (4) balls (2), pressed to the upper ball with applied force P (1). The ball (1) is installed in a spindle (3) rotating with a set speed n. The balls are made from ŁH-15 (Cr 106) bearing steel, diameter: 12,7 mm, hardness: 62-65 HRC [13].

Fig. 6. Testing station for lubricity property tests

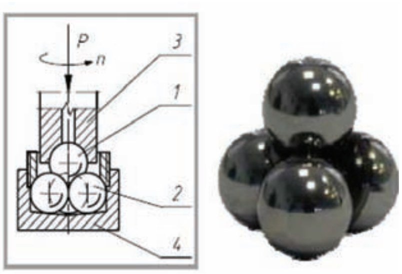

Fig. 7. Testing node diagram [14]

Three parameters were determined: two standard ones i.e. seizing load (P_t) and boundary wear load (G_{oz}) according to [13] and additionally unit pressures after seizing (p_{oz}) obtained after full runs of smooth load until the maximum acceptable load of the friction node is obtained, when the apparatus switched off automatically [16]. The first parameter (P_t) characterized the anti-seizing properties and the second one (G_{oz}) characterized the anti-wear properties. The parameter (p_{oz}) allows for observation of lubricant behaviour after the seizing period at increasing load and for identification of proper wear values.

Surface pressures (p_{oz}) were determined at increasing load of 409 N/s i.e.. 490.5 daN (500 kG) per each 100 revolutions of the upper ball. The apparatus engine was rotating at the speed of 500 rpm. When the full length of the apparatus lever goes through the weight, obtaining the load of P_{oz} = const in all trials, the apparatus engine switched off automatically. The parameter (p_{oz}) was determined based on the formula:

$$p_{oz} = 0.52 \frac{P_{oz}}{d_{śr}^2}, \tag{1}$$

where: P_{oz} – load after 18.05 seconds (738.25 daN), 0.52 – coefficient considering the distribution of forces in the friction node (regular tetrahedron), $d_{śr}$ – average scar diameter on the lower ball surface [mm], calculate according to the formula:

$$d_{śr} = \sum \frac{d}{6}, \tag{2}$$

where: d – measured diameters.

The measurement of wear scar diameters on the lower balls was carried out on the Nikon Eclipse LV 100 microscope. The results were rounded up to 0.01 mm, according to the requirements of the standard [13]. Fig. 8 shows the software window when determining wear scar diameters.

3. Test results and analysis

3.1. Density

Density measurement results are presented in Table 1. The measurement of CJ005 ionic liquid density at temperatures of 25°C and 40°C was not performed due to its melting temperature of 77°C (at lower temperatures the liquid becomes a solid) and a measurement for CJ008 at the temperature of 100°C as this is a temperature higher than its ignition temperature, which amounts to 52°C according to the information given by the manufacturer (Solvay-Solexis). CJ009 ionic liquid at the temperature of 25°C, close to its melting temperature (17°C), is a non-homogeneous liquid and also prevented from proper measurement of density at that temperature.

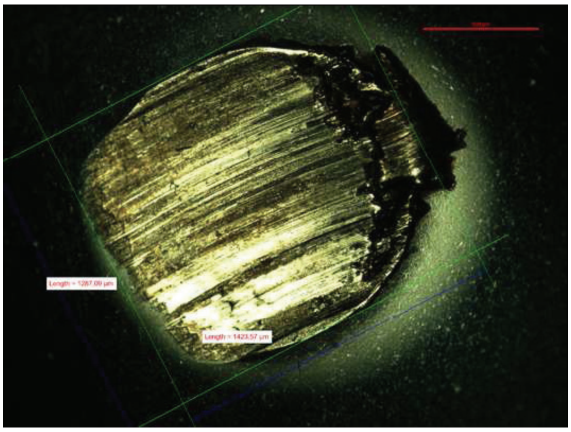

Fig. 8. The software window when determining the wear scar diameters

Tab. 1. Density measurement results

Parameter	Lubricating liquids							
	PAO-6	SN-650	Mobilube	CJ005	CJ006	CJ007	CJ008	CJ009
Density ρ [g/cm^3]								
25°C	0.816	0.881	0.856	-	1.447	1.449	1.061	-
40°C	0.806	0.869	0.843	-	1.430	1.437	1.048	0.936
100°C	0.769	0.829	0.804	1.242	1.375	1.380	-	0.888

Obtained results of ionic liquid density at all tested temperatures (25°C, 40°C, 100°C) are higher than density of oil bases and Mobilube 1 SHC 75W-90 gear oil. Density values of ionic liquids at temperature of 25°C fluctuates in the range of 1.0-1.5 g/cm^3. As the temperature increases, density of each compound decreases linearly, as illustrated on Fig. 9. Density values are arranged in the following order: CJ007>CJ006>CJ005>CJ008>CJ009>SN-650>Mobilube>PAO-6 (however the values for CJ007 and CJ006 ionic liquids are very similar). Higher values for ionic liquids result from the ionic structure of those compounds.

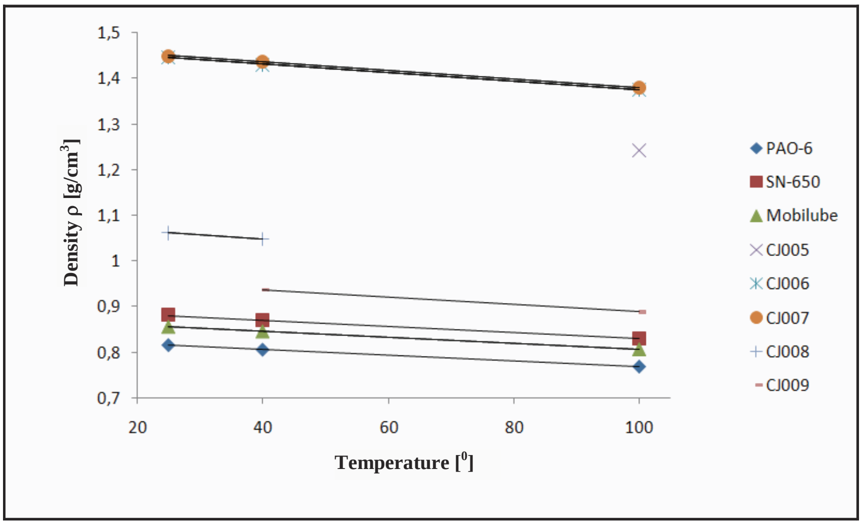

Fig. 9. Diagram of temperature and density dependence of tested compounds

In performed tests, two liquids (CJ008 and CJ009) had the same phosphon cation $[C_{32}H_{68}P]^+$, and different anion. In case of CJ008 it is bis(trifluoromethylosulfonyl)imid and in case of CJ009 it is tetrafluoroborate (Fig. 1). On the basis of density measurement results for the temperature of 40°C, it was found that the anion mass increase results in density increase and it is in accordance with the information from the literature [1].

3.2. Surface tension

The surface tension measurement results are presented in table 2. Some measurements were not performed for CJ005, CJ008 and CJ009 due to the same reasons as the ones listed in p. 3.1. Value of the surface tension σ of tested lubricating liquids decreased linearly as the temperature increased and it can be seen on fig. 10. The highest surface tension values at temperatures of 25°C and 40°C were obtained for CJ007 and CJ006 ionic liquids. At temperature of 100°C, the highest surface tension (31,415 mN/m) was obtained by CJ005 liquid of melting temperature of 77°C. The values for CJ007 and CJ006 at the highest tested measurement temperature are also much higher than the ones for other tested compounds. Among the comparative substances, SN-650 shows the highest surface tension value at all temperatures, much higher than for CJ008 and CJ009 ionic liquids. The lowest tension values can be observed for the tested gear oil and PAO-6. Values for these two compounds at temperatures of 25°C and 40°C are similar.

Tab. 2. Surface tension measurement results

Parameter	Lubricating liquids							
	PAO-6	SN-650	Mobilube	CJ005	CJ006	CJ007	CJ008	CJ009
Tension. σ [mN/m]								
25°C	27.523	30.460	27.565	-	32.993	33.166	28.099	-
40°C	26.846	29.384	26.432	-	32.510	32.274	27.699	28.259
100°C	23.869	25.785	22.419	31.415	29.681	30.159	-	23.097

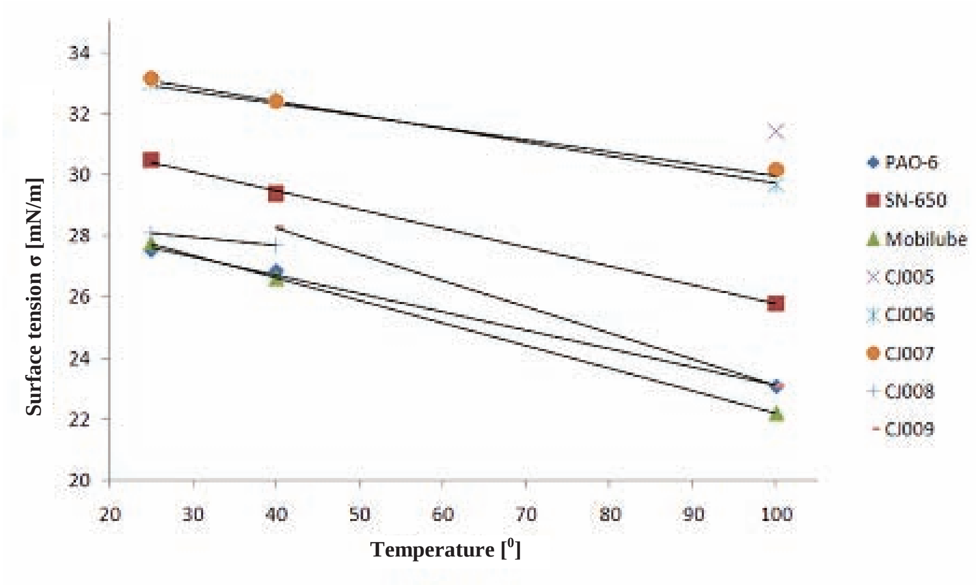

Fig. 10. Tested compound surface tension dependence on temperature

At temperature of 40°C, the surface tension value for CJ009 (28,259 mN/m) is higher than the value for CJ008 (27,699 mN/m). Apart from the fact that the difference is small, one can come to a conclusion that the anion mass increase results in the decrease of the value of surface tension of tested ionic liquids. This result is in accordance with results obtained by Portuguese researchers [15].

3.3. Wettability

The results of wetting angle measurements using KSV Sigma 701 apparatus are presented in Table 3. Some measurements were not made, as in case of p. 3.1, due to high melting temperature (CJ005 and CJ009) and low ignition temperature (CJ008). All tested lubricants, both oil bases usually used for blending the industrial oils with additives, Mobilube 1 SHC 75W-90 gear oil and all ionic liquids, could be characterized by good wetting of the platinum plate of the KSV Sigma 701 sampler. Fig. 11 presents obtained results which allow to observe that as the measurement temperature increases the wetting angle value decreases in a linear way. As one can notice, the wetting angle determined by KSV Sigma 701 apparatus is bound for 0^o, which would mean full wettability. At the lowest tested temperature, two ionic liquids CJ006 and CJ008 showed the best wetting properties. Obtained angle values amount to respectively: $25{,}90^o$ and $25{,}40^o$. Value for the tested gear oil was slightly higher than those results: $26{,}96^o$. However, PAO-6 and CJ007 liquid showed the lowest wetting ability at the temperature of 25^oC: $34{,}78^o$) and $31{,}02^o$. But this liquid has the best wetting abilities at the highest tested temperature, i.e. at 100^oC. CJ005 liquid showed the worst wetting ability at high temperature (CJ005).

Tab. 3. Wetting angle measurement results

Parameter	Lubricating liquids							
	PAO-6	SN-650	Mobilube	CJ005	CJ006	CJ007	CJ008	CJ009
Wetting angle θ [^{o}]								
25^oC	34.78	35.03	26.96	-	25.90	31.02	25.40	-
40^oC	31.88	32.12	23.48	-	23.07	27.59	17.50	28.26
100^oC	20.88	19.25	8.76	73.73	7.69	4.59	-	25.80
Wetting angle cosine cosθ								
25^oC	0.821	0.819	0.891	-	0.890	0.857	0.903	-
40^oC	0.848	0.846	0.917	-	0.920	0.886	0.953	0.881
100^oC	0.935	0.994	0.988	0.280	0.991	0.997	-	0.900

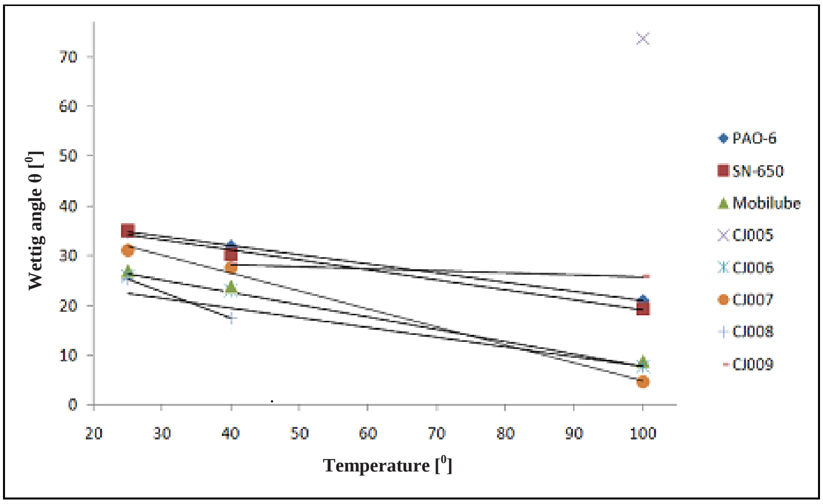

Fig. 11. Dependence of tested compound wetting angle on temperature

A linear dependence between the surface tension and wetting angle cosine was recorded for all tested lubricating liquids. Increasing surface tension resulted a decrease of the wetting angle cosine cosθ determined by means of the KSV Sigma 701 apparatus (Fig. 12).

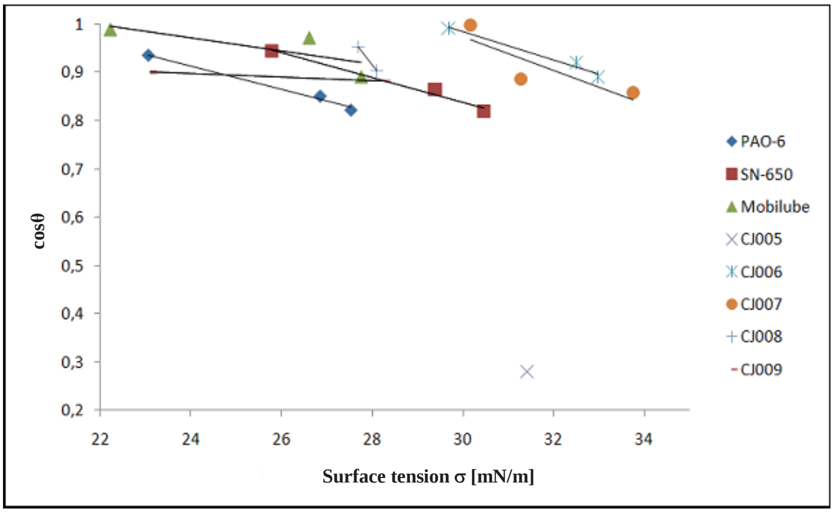

Fig. 12. Cosθ dependence on surface tension

Table 4 presents the results of static wetting angle defined by means of KSV CAM 100. Measurements at all temperatures were not performed for CJ005 and at temperature of 25^{o}C for CJ009, due to their high melting temperature.

Tab. 4. Static wetting angle measurement results

Parameter	Lubricating liquids							
	PAO-6	SN-650	Mobilube	CJ005	CJ006	CJ007	CJ008	CJ009
Static wetting angle θ_s [^{o}]								
25^{o}C	18.79	24.51	15.11	-	46.77	49.04	23.42	-
40^{o}C	15.47	19.26	11.08	-	39.48	47.71	20.20	25.40
60^{o}C	12.04	15.82	8.32	-	38.55	44.21	17.53	21.63

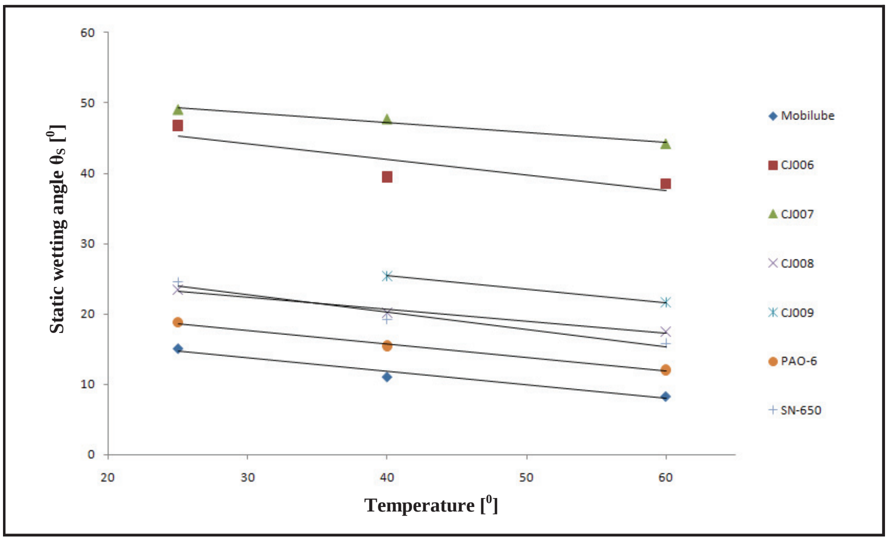

Fig. 13. Static wetting angle dependence on temperature in tested compounds

Fig. 13 presents a dependence of static wetting angle on temperature in tested compounds. The smallest values of static wetting angle on NC4 class tool steel samples at tested temperatures can be observed for Mobilube 1 SHC 75W-90 gear oil. Very good wetting ability in the performed test was also observed in case of two oil bases and ionic liquids with phosphon cation CJ008 ($23,42^o$ at temperature of 25^oC, $20,20^o$ at 40^oC and $17,53^o$ at 60^oC) and CJ009 ($25,4^o$ at temperature of 40^oC and 21,63 at 60^oC). The other two ionic liquids had significantly higher static wetting angles.

3.4. Dynamic and kinematic viscosity – viscosity index

Obtained values of dynamic and kinematic viscosity are presented in Table 5. Some measurements were not made due to the same reasons as the ones listed in p. 3.1.
On the basis of obtained results, it can be stated that PAO-6 showed the lowest dynamic viscosity at all tested temperatures. A drop of value of that parameter at the temperature increase is significantly lower than for SN-650, gear oil or for ionic liquids (a small drop can be noticed only in case of CJ006 ionic liquid). Viscosity changes in the temperature function are defined with the viscosity index value VI (table 5).

The higher VI value the higher oil resistance to temperature variations, i.e. viscosity change is smaller. The highest dynamic viscosity value at temperature of 25°C was obtained for SN-650, i.e. 345,47 mPa.s. Slightly smaller, just by 18.23 mPa.s, dynamic viscosity value was obtained for CJ008. At temperature of 40°C, phosphon based ionic liquid (CJ009, 292.49 mPa.s.) showed the highest dynamic viscosity. Also at temperature of 100°C, the result for that liquid (30.83 mPa.s) is the highest results among all tested lubricating liquids. Values for other tested compounds at the highest temperature fell between 4 and 19 mPa.s.

Tab. 5. Dynamic and kinematic viscosity measurement results

Parameter	Lubricating liquids							
	PAO-6	SN-650	Mobilube	CJ005	CJ006	CJ007	CJ008	CJ009
Dynamic viscosity η [mPa.s]								
25^oC	47.36	345.47	188.88	-	51.53	86.61	327.24	-
40^oC	24.52	131.96	91.15	-	29.40	46.24	145.51	292.49
100^oC	4.56	11.51	12.93	18.37	6.23	8.27	-	30.83
Kinematic viscosity ν [mm^2/s]								
25^oC	58.05	392.13	220.59	-	35.61	59.77	308.43	-
40^oC	30.42	151.85	108.13	-	20.56	32.18	138.84	312.49
100^oC	5.93	13.88	16.08	14.79	4.53	5.99	-	34.72
Viscosity index VI	144	86	160	-	138	134	-	156

Kinematic viscosity was calculated automatically in the computer software. As the CJ006 ionic liquid has much higher density than PAO-6, obtained kinematic viscosity values for that liquid are smaller than for PAO-6. So, when considering that parameter, it can be stated that at all tested temperatures that ionic liquid consisting of pyridine cation $[C_9H_{14}N]^+$, a not PAO-6, showed the lower viscosity. The highest values were obtained for SN-650 at temperatures 25^oC (392,13 mm^2/s) and CJ009 ionic liquid at other temperatures (312.49 and 34.72 mm^2/s). At the highest tested temperature, results obtained for other lubricating liquids fell between 4,5 and 16,5 mm^2/s.

When comparing values obtained at temperature 40^oC for two liquids made on the basis of phosphon cation $[C_{32}H_{68}P]^+$ one can come to a conclusion that anion mass increase results in a viscosity value decrease for a tested ionic liquid. Considering the analysis presented in [9], such tendency can result from higher Van der Waals influence, which is higher in case of bigger anions

$[N(CF_3SO_2)_2]^- > [BF_4]^-$. According to the standard [17], viscosity of Mobilube gear oil and CJ009 ionic liquid show the lowest sensitivity to temperature variations. PAO-6 base oil and CJ006 and CJ007 ionic liquids had similar viscosity-temperature characteristics.

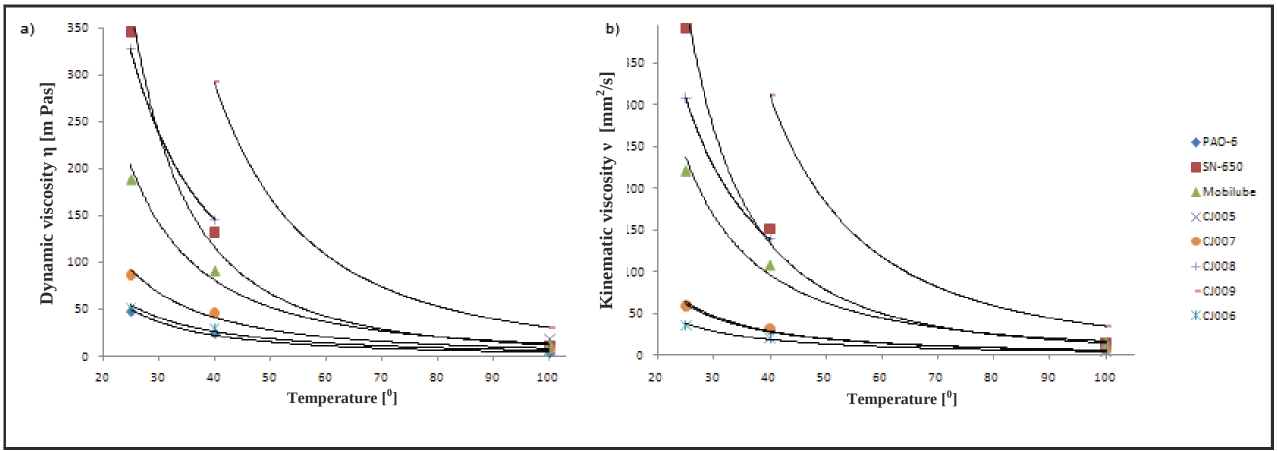

Fig. 14. Temperature dependence of a) dynamic viscosity η b) kinematic viscosity ν of tested compounds

3.5. Lubricity properties

Specification of tested lubricity properties is presented in Table 6. Before the measurement, CJ009 ionic liquid was heated to the temperature of 40°C. Tests for CJ005 ionic liquid have been not performed due to its high melting temperature.

Tab. 6. Lubricating ability measurement results

Parameters	Lubricating liquids						
	Mobilube 1SHC 75W-90	CJ006	CJ007	CJ008	CJ009	PAO-6	SN-650
Seizing load P_t [daN]	296.53	265.85	302.66	396.73	327.20	116.57	132.93
Boundary wear load G_{oz} [daN/mm^2]	318.70	272.40	306.07	306.07	252.85	45.28	58.88
Surface pressure p_{oz} [daN/mm^2]	306.04	295.39	443.86	230.69	227.15	126.80	117.18

The best lubricating abilities, defined with a seizing load parameter (P_t), were shown by the ionic liquid consisting of phosphon cation $[CH_3(CH_2)_5]_3P(CH_2)_{13}CH_3]^+$ and non-organic anion $[N(SO_2CF_3)_2]^-$ i.e. CJ008 of the highest viscosity. The seizing load value amounted to 396.73 daN. However, it can be noticed that values of that parameter obtained for Mobilube gear oil and other ionic liquids of significantly lower viscosity (CJ006, CJ007) are also much higher (almost twice as high) than the ones for oil bases. Values obtained for PAO-6 and SN-650 are similar and they amount to 116.57 and 132.93 daN respectively (Fig 15).
Fig.16 presents the values of calculated unit pressure (p_{oz}) for tested ionic liquids, gear oil and two oil bases. The highest value was obtained for ionic liquid CJ007 (443.86 daN/mm^2) and the lowest one for SN-650-117,18 daN/mm^2). Surface pressure values are much higher for ionic liquids than for PAO-6 and SN-650. It results from significantly lower wear of balls lubricated with ionic liquids – much smaller wear scars on the balls (Table 7).

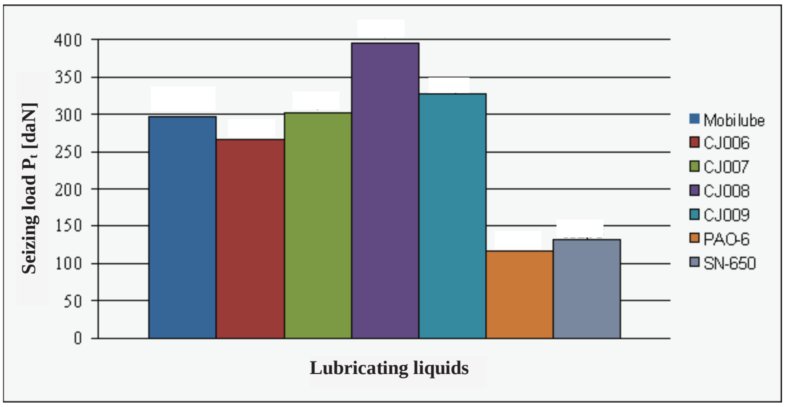

Fig. 15. Seizing load P_t obtained for tested lubricating liquids

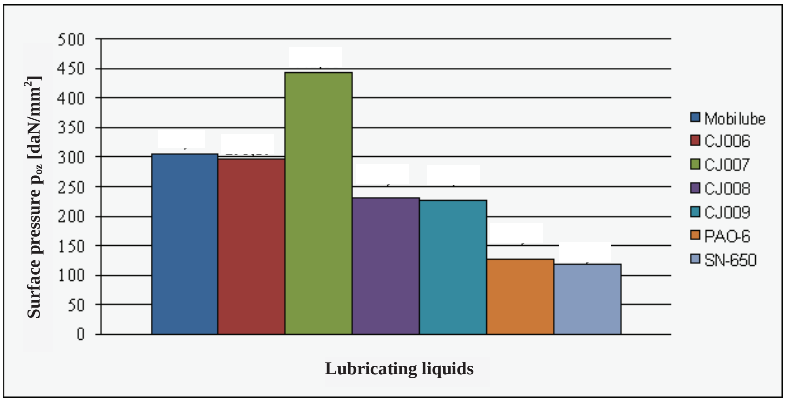

Fig. 16. Surface tensions p_{oz} for tested lubricating liquids

Tab. 7. Average scar diameters when determining parameter p_{oz}

	Lubricating liquids							
	Mobilube	CJ005	CJ006	CJ007	CJ008	CJ009	PAO-6	SN-650
Diameter [mm]	1.12	-	1.14	0.93	1.29	1.30	1.74	1.91

The highest boundary wear loading value G_{oz} (Fig. 17) according to PN-76/C-04147 was obtained for Mobilube 1SHC 75W-90 gear oil (318,70 daN/mm^2). However, not much lower values were obtained for CJ007 ionic liquid (306,07 daN/mm^2) and CJ008 ionic liquid (306,07 daN/mm^2). The lowest value was obtained for PAO-6 (45,22 daN/mm^2) and SN-650 (58,88 daN/mm^2) oil bases. All results of parameter G_{oz} obtained for ionic liquids fall between 252 and 307 daN/mm^2. It can be stated that all tested ionic liquids have very good anti-wear properties.

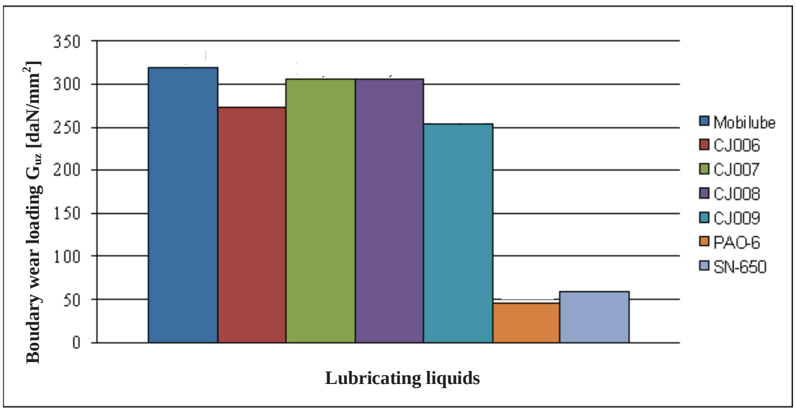

Fig. 17. Boundary wear loading of tested lubricating liquids

4. Summary

Obtained results of preliminary studies confirmed a possibility of using selected ionic liquids as new lubricants. These compounds can probably replace the lubricants used so far and find a wide scope of application in lubrication technology, including the space technology, in the future. Comparison of obtained ionic liquid test results with PFPE oil test results, described by the authors in their previous paper [16], seems to confirm that possibility. However, particular implementations require further complex studies.

Among all tested ionic liquids, CJ008 and CJ009 ionic liquids of the highest viscosity showed very good anti-seizing properties, compared to reference liquids, defined by parameter P_t. However, other tested ionic liquids of significantly lower viscosity also have good anti-seizing properties described by that parameter. All tested ionic liquids obtained high boundary wear loading (G_{oz}), compared to reference compounds, and it confirms their very good anti-wear properties. Tested salts were characterized by good surface parameters and undoubtedly it has a significant influence on formation of the boundary film in the working connection. Among all tested ionic liquids, special attention was paid to CJ007 ionic liquid. In spite of its slightly worse wetting ability, higher surface tension and relatively low viscosity, it showed the ability to regenerate the boundary oil film and as a result it determined the highest surface pressure p_{oz} (lowest wear) at the end of increasing continuous loading test, with high P_t and G_{oz} values at the same time (Table 6 and 7). CJ007 liquid can behave in that way due to tribochemical reactions of the ionic liquid and lubricated surface. That possibility is mentioned in the literature [1,2]. However, in order to confirm that assumption, more detailed studies, using specialist measurements techniques (e.g. SEM with EDXA, FTIR) are required.

Due to obtained results indicating very good lubricity and surface properties of ionic liquids, the studies should be continued and possibilities of practical application in lubrication technology should be sought. The next stage will include tribologic studies using universal micro/nano UNMT tester (CETR-USA). The analysis of steel sample element content before and after friction tests will be also performed in order to confirm the existence of tribochemical reactions between steel sample surface and lubricating liquid in the boundary friction conditions.

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