

Pressure-viscosity behavior and film thickness in EHL lubrication of ionic liquids and other base oils

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ABSTRACT

Viscosities at high pressures for 16 base oils (six polyolesters, three polyglycols, six ionic liquids and squalane) were used to analyze the influence of their chemical structure on the pressure-viscosity coefficient, α . Comparisons with literature α values for vegetable bases (canola, soybean and jojoba oils) are also performed. For the molecular lubricants we found trends that are coherent with the literature, whereas for ionic liquids, ILs, new trends were found. ILs based on tris(pentafluoroethyl)trifluorophosphate anion [FAP]⁻ are those which present higher α values. The role of the lubricants in the central thickness in isothermal EHL regime was evaluated through the product $\eta_0^{0.69} \alpha^{0.56}$. η_0 being the viscosity at 0.1 MPa. One of the [FAP]⁻ ILs provides film thicknesses close to the polyglycols with similar viscosity. bis(trifluoromethylsulfonyl)imide ILs and the shorter polypropyleneglycoldimethyl ethers are the lubricants that better avoid the changes on the film thicknesses with the temperature owing to a high viscosity index.

KEYWORDS: pressure-viscosity coefficient, film thickness, ionic liquid, vegetable base oils, synthetic base oils

INTRODUCTION

Over the last decade our group has measured viscosities at high pressure of a large number of fluids¹⁻⁷ in order to analyze their potential uses as lubricants for gearboxes, as refrigeration oils or hydraulic fluids. The base lubricants under study can be grouped in three types: synthetic vegetable and ionic liquids (ILs), apart from squalane which can be considered a model of mineral lubricants. The synthetic oils studied in this work are poly(propylene glycol) dimethyl ethers (PAGs) and polyolesters (POEs). The PAGs present high viscosity index (VI), low volatility, high polarity and a high affinity towards metal surfaces. PAGs generally have lower toxicity and cause less environmental damage during accidental spillage than mineral oils. Another important advantage of PAG is that its oxidation does not generate solid deposits, thus avoiding the problem of varnish generation, which is an important problem with petroleum-based oils⁸. These lubricants are used as high-temperature hydraulic and thermal fluids, and in different applications as automotive refrigeration, brakes, compressors, gears, textile oils and metal working lubricants^{1,3,8-13}. POEs present high thermal and oxidative stability, high polarity and high affinity for metals. Furthermore, these bases have the highest stability against acids and generally good hydrolytic stability, but moderate compatibility with paints and seal materials^{14,15}. POEs are used in compressors or gas turbines, and as engine oil or aircraft turbine oil, among other applications^{14,16}. The main disadvantage of synthetic oils is that they are more expensive in general than mineral oils and, the majority is obtained from petroleum. Vegetable oils (VOs) which are non toxic, present excellent VI, a high lubricity, and, most important, they are biodegradable and renewable oils. But, VOs present poor properties at high and low temperatures, a poor viscosity grade range, high pour points and they are expensive.

They are, however, a feasible alternative to synthetic and mineral oils in the mid and long term due to increasing cost of extraction of the petroleum reserves and environmental awareness by the general public. Their main applications are as hydraulic and tractor transmission fluids, and in air compressors and 2-stroke engines for farm, agricultural and marine equipment, among others^{15,17-20}.

ILs were proposed as lubricants for the first time²¹ in 2001 and since then, several studies²²⁻²⁷ have shown their good potential properties to be used as base lubricants or lubricant additives. There are several recent reviews in the literature^{22-24,27,28} which report most of the results of these studies. Their outstanding physicochemical characteristics include negligible volatility, non-flammability, high thermal stability and conductivity, low melting point, low temperature fluidity, and broad liquid range. Ionic liquids are able to form strong adsorption films on the lubricated surfaces^{29,30}. Post friction surface characterizations have proved the existence of tribochemical layers on wear²⁷. That suggests that under high load, harsh sliding conditions and high temperature conditions, chemical reactions occur, the ionic liquid and the lubricated surface react leading to the apparition of tribochemical layers. Both mechanisms contribute to the prominent antiwear capability of ILs.

The physicochemical properties of the ILs, e.g. viscosity can be adjusted by modifying the molecular structure of the IL: chemists can choose from a wide array of cations with different lengths for the alkyl chain and different anions also³¹, allowing for a plethora of possibilities in order to synthesize an IL lubricant or additive for specific tribological applications.

Lubricants are employed to minimize friction and wear between interacting surfaces by adding a thin layer of fluid between the areas in contact. Tribological contacts have to

support the load being carried by surfaces in relative motion. If a liquid film is present, as in the elastohydrodynamic regime of lubrication (EHL), load support is obtained from the elevated pressure within the film. Therefore, the response of the liquid to shear is determined by the rheological properties of the liquid at elevated pressure³². Thus, the knowledge of the variation of the viscosity with the pressure is especially important because films of fluid are compressed between sliding or rolling surfaces under very high loads in most mechanical applications. Hence viscometrical data for a fluid over a broad range of pressure and temperature grants access to the determination of other physical properties that affect lubrication, such as the viscosity index, the pressure-viscosity and the temperature viscosity coefficients. Viscosity grade and pressure-viscosity coefficient are largely determined by base oil chemistry and hence applied to characterize the film thickness in the EHL regime. However, the study of the effect of pressure on the flow properties of lubricants is often overlooked mainly due to experimental constraints involving high-pressure measurements^{3,18,25,33-37}. Of particular interest are the studies on high-pressure viscosities and film thickness performed by Bair and his colleagues, especially for mineral and synthetic lubricants^{32,38-40}. Larsson et al.⁴¹ and Gold et al.⁴² have analyzed the influence of the pressure-viscosity coefficients on the film thickness and on the lubrication capability for mineral and synthetic oils. Our group has measured the high-pressure viscosities for squalane, POEs and PAGs oils¹⁻⁵.

The experimental high-pressure viscosity measurements on ionic liquids have been recently reviewed^{6,43}. As regards to film thickness, Arora and Cann⁴⁴, Xie et al⁴⁵ and Xiao et al.⁴⁶ have recently reported experimental values. for several ILs. It is also worth mentioning the interest behind the simulation of the EHL regime⁴⁷ and prediction of the thermophysical properties⁴⁸ under its extreme temperature and pressure conditions.

Further theoretical studies, like those recently performed by Mendonça et al.^{49,50} with ILs and metallic surfaces, will grant a deeper understanding of the physical interactions taking place between the contacting surfaces and the fluid.

In this work we present an analysis of the viscosity index, as well as the derived properties obtained from the measurements of the viscosity at high pressures (the pressure-viscosity coefficient and the film thickness) performed in our laboratory for 16 unformulated lubricants of different type (POEs, PAGs and ILs¹⁻⁷). In addition, comparisons with results published by Biresaw and Bantchev⁵¹ on vegetable bases (canola, soybean and jojoba oils) are also performed.

EXPERIMENTAL PROCEDURE

Materials

In Table 1 the lubricants under study together with their kinematic viscosity and the VI are presented. Some representative molecular structures are depicted in Figures 1-4.

Regarding the synthetic oils, PAG1 and PAG2¹ are double end-capped polypropyleneglycols, $\text{CH}_3\text{O}-[\text{CH}_2\text{CH}(\text{CH}_3)\text{O}]_m-\text{CH}_3$, with average polymerization degrees of $m=23$ and $m=29$ and PAG3² is a mono end-capped polypropyleneglycol $\text{OH}-[\text{CH}_2\text{CH}(\text{CH}_3)\text{O}]_{21}-\text{CH}_3$. The samples of these PAGs together with those of the POEs dipentaerythritol hexapentanoate (DiPEC5) and dipentaerythritol hexaheptanoate (DiPEC7) were provided by Croda (Wilton, UK)³. Nikko Chemicals (Osaka, Japan) was the supplier of pentaerythritol tetra-2-ethylhexanoate (PEB8). Pentaerythritol tetrapentanoate (PEC5), pentaerythritol tetraheptanoate (PEC7) and pentaerythritol tetranonanoate (PEC9) were synthesized in our laboratory via a reaction between nonanoic acid and pentaerythritol catalyzed by p-toluenesulfonic acid^{5,52}. Squalane was obtained from Sigma-Aldrich⁴.

The cations of the six ILs are 1-ethyl-3-methylimidazolium [C₂C₁Im]⁺, 1-butyl-2,3-dimethylimidazolium [C₄C₁C₁Im]⁺, 1-butyl-1-methyl-pyrrolidinium [C₄C₁Pyrr]⁺, 1-(2-methoxy-ethyl)-1-methyl-pyrrolidinium [C₁OC₂C₁Pyrr]⁺. One of the six ILs is based on the ethylsulfate anion [C₂C₁Im][C₂SO₄] (IL1). Three of them, [C₁OC₂C₁Pyrr][NTf₂] (IL2), [C₄C₁Pyrr][NTf₂] (IL3), [C₄C₁C₁Im][NTf₂] (IL4), were based on the bis(trifluoromethylsulfonyl)imide anion whereas [C₁OC₂C₁Pyrr][FAP] (IL5) and [C₄C₁C₁Im][FAP] (IL6) were based on the tris(pentafluoroethyl)trifluorophosphate anion, also known as [FAP]⁻. ILs samples were kindly provided by Merck KGaA (Darmstadt, Germany). Before measuring the properties, these ILs were dried under constant stirring and moderate vacuum to remove the residual volatile impurities at room temperature^{6,7,31}. The water content was assessed by means of Karl-Fischer titration. Their values expressed as weight fraction range from 6·10⁻⁶ for [C₁OC₂C₁Pyrr][NTf₂] to 326·10⁻⁶ for [C₂C₁Im][C₂SO₄].

We have also included three vegetable bases (canola, soybean and jojoba) studied by Biresaw and Bantchev⁵¹ that we consider somehow representative of the viscosity spectrum comprised by the available oils obtained from crops. These bases have viscosity grades of VG22 and VG32 like the majority of the oils produced from seeds. In the present work comparisons between these vegetable bases and synthetic and ionic fluids are reported.

Experimental Techniques

Kinematic and dynamical viscosities at atmospheric pressure were measured using a rotational automated viscometer Anton Paar (Graz, Austria) Stabinger SVM3000 with a reproducibility of 0.35 %. This apparatus allows measuring density and dynamic and

kinematic viscosity from (233.15 to 373.15) K, in a viscosity range from 0.2 mPa·s to 20 Pa·s. The SVM 3000 Stabinger viscometer has a cylindrical geometry, and it is based on a modified Couette principle with a rapidly rotating outer tube and an inner measuring bob that rotates more slowly^{31,53}. The viscosity index was also determined using this device according to the ASTM D2270-04 standard. Viscosities at higher pressure were performed using a falling body viscometer (VisLPT1) and a rolling body viscometer (Ruska). VisLPT1 can work over the temperature interval from 313.15 K to 363.15 K and at pressures up to 150 MPa. This apparatus is similar to that previously designed by Daugé et al.⁵⁴. Figure 5 represents a scheme of the Ruska viscometer. This device can operate in the temperature range 303.15 K - 373.15 K and at pressures up to 60 MPa^{4,53}. The measuring principle of all these viscometers is based on the relationship between the time that a solid takes to fall or roll, once it has reached its terminal velocity under conditions of laminar flow, through a viscous fluid and its viscosity^{4,6}. A further description and their calibration procedures have been described previously^{4,6,53}. Estimated experimental uncertainty of VisLPT1 and Ruska ranges from 3% to 5%, depending on the calibration method, the reference fluids and the viscosity ranges used. Viscosities of squalane, PAGs and esters were measured using the Ruska viscometer¹⁻⁵, those of the ILs were carried out with VisLPT1^{6,7}.

RESULTS AND DISCUSSION

In Figure 6 and Table 1, the kinematic viscosities at atmospheric pressure of the different lubricants studied in this work at 313.15 K can be compared. The values range from 16 to 61 mm²·s⁻¹. As expected for the base oils analyzed the viscosity increases with the length of the alkyl chain, the branching degree and the number of polar groups.

With regard to the ILs with the same cation, those with the [FAP]⁻ anion have higher viscosities than those with [NTf₂]⁻ anion. The trend of the viscosity of ILs with the cation is as follows³¹: [C₄C₁C₁Im]⁺ > [C₄C₁Pyrr]⁺ > [C₁OC₂C₁Pyrr]⁺.

A useful parameter for lubricants is the viscosity index, which gives information about the temperature-viscosity dependence at atmospheric pressure. The viscosity index is a measure of the variation in kinematic viscosity arising from variations in the temperature of a crude oil or a lubricant between 313.15 K and 373.15 K. As defined by the standard, the higher the VI, the lower the change of the viscosity with temperature, and therefore, lubrication conditions are more stable against temperature variations in the machinery. The VI values are gathered in Table 1 and plotted in Figure 7. These values range from 85 to 263, being the VOs, poly(propylene glycol) dimethyl ethers, and the ILs with [NTf₂]⁻ anion those that present the best values of VI. On the other hand, the branched pentaerythritol ester (PEB8) presents the lowest values of this property (its viscosity is more sensitive to temperature changes) comparable to those of many group I commercial mineral oils. .

Lubrication engineers represent the pressure-viscosity- behavior of oils at a given temperature with only two parameters, η_0 , the viscosity of the oil at atmospheric pressure and the pressure-viscosity coefficient, α . Thus, following the American Gear Manufacturers Association, at isothermal conditions⁵⁵, the central film thickness h_{cent} of the oil in a rolling element in EHL regime at speed U is:

$$h_{cent} = k\eta_0^{0.69}\alpha^{0.56}U^{0.69} \quad (1)$$

where the parameter k depends on surface geometry, the applied load and the elastic parameters of the rolling elements⁵⁵.

For the pressure-viscosity coefficient, α , several definitions have been proposed. In this work, as in our previous articles^{2,25}, the expression selected is the universal pressure-viscosity coefficient, α_{film} , proposed by Bair³⁸

$$\alpha_{film} = \frac{1 - \exp(-3)}{p_{iv}(3/\alpha^*)} \quad (2)$$

where p_{iv} is the isoviscous pressure given by:

$$p_{iv}(p) = \int_0^p \frac{\eta(p'=0)dp'}{\eta(p')} \quad (3)$$

The asymptotic isoviscous pressure coefficient, α^* , has been proposed by Blok⁵⁶, in order to reproduce the EHL film thickness of Newtonian liquids of general piezoviscous response. Its expression is:

$$\alpha^* = \frac{1}{p_{iv}(\infty)} = \left[\int_0^\infty \frac{\eta(p=0)dp}{\eta(p)} \right]^{-1} \quad (4)$$

Higher α_{film} values means higher film forming capability, so boundary wear is better avoided. Low pressure-viscosity coefficients: save friction energy, reduce sub-surface stress and pressure peaks, so avoid wear and failure of gear elements and bearings. But the low film thickness could give wear problems if contact between the lubricated surfaces occurs^{2,25,41,57}.

As can be observed in Figure 8, for the analyzed lubricants, the highest values of the general film-forming pressure-viscosity coefficients have been obtained for squalane followed by [C₄C₁C₁Im][FAP]. For esters and PAGs the sequences found in this work agree with previous studies of Bair³² with the same definition of the pressure-viscosity coefficient and with those of Gold et al.⁴² with different definitions of the pressure-

viscosity coefficient. Bair showed for several isomers of dodecane that the piezoviscous effect (the increase of $\ln\eta$ with pressure) grows with the branching degree. This explains the high α_{film} values obtained for squalane. In addition, Bair indicated that this effect also increases going from linear to cyclic and then to polycyclic structures. Gold et al.⁴² concluded that for each type of lubricant, the pressure-viscosity coefficient increases with the kinematic viscosity at 0.1 MPa, and at equal viscosity the sequence of increasing pressure-viscosity coefficient is polyglycols < esters < PAOs < mineral, paraffinic < mineral, naphthenic. According with the studies of Randles on esters¹⁴, the viscosity-pressure coefficient of a lubricant is influenced by the length of the side chains in branched esters (the longer the higher) and the degree of branching (the more the higher). Our results on esters agree with these trends with the exception of DiPEC7, which has a lower α_{film} than PEC7.

Biresaw and Bantchev⁵¹ found from film thickness measurements that the pressure-viscosity coefficients of the seed oils at 313.15 K, are 10.7, 8.3 and 7.4 GPa⁻¹ for canola, soybean and jojoba oils, respectively. These authors remark that for a reference oil (PAO6) this coefficient is 13.5 GPa⁻¹. Such a value is in line with the values showed here for all synthetic oils and [FAP]⁻ based ionic liquids. As can be seen in Figure 8, the representative vegetable bases display in general α_{film} values rather low when compared to the rest, the three of them below PEC5 which is the synthetic oil showing the lowest value of all synthetics. In previous articles^{2,25} we calculated the α_{film} values for other twelve ILs, where the highest value was 12.4 GPa⁻¹ obtained for [C₈C₁Im][PF₆] at 313.15 K. It was also observed that α_{film} increases with increasing viscosity and that [NTf₂] ILs displays higher α_{film} than those expected from their viscosity, when compared previously studied ILs composed by other anions. The α values found in the

present article for [C₁OC₂C₁Pyrr][FAP] and [C₄C₁C₁Im][FAP] are even higher. At 313.15 K the lowest α_{film} value found in the present work is 6.73 GPa⁻¹ for [C₂C₁Im][C₂SO₄]. This agrees with our previous article² in which the lowest alpha values were found for [C₁C₁Im][C₁SO₄]. By comparison among pyrrolidinium-based ILs, it can be observed that replacing a carbon atom for an oxygen one in the alkyl chain leads to a decrease of around 10% in the universal pressure-viscosity coefficient.

Once the pressure-viscosity coefficient has been determined, it is possible to estimate the product $\eta_0^{0.69} \alpha^{0.56}$, which is directly proportional to h_{cent} (equation 1). This factor is plotted for several lubricants in Figure 9. For the vegetable bases at 313.15 K we have obtained values of 42, 25 and 34 for the product $\eta_0^{0.69} \alpha^{0.56}$ for canola, jojoba and soybean, respectively. We have calculated these values from the dynamic viscosities and the pressure-viscosity coefficient reported by Biresaw and Bantchev⁵¹. The film thickness portion dependent on the lubricant at 313.15 K is clearly quite low for the biobased fluids, as well as for [C₂C₁Im][C₂SO₄] and [C₁OC₂C₁Pyrr][NTf₂]. This means that the protective layer at this temperature provided by these liquids is substantially thinner than that provided by the other studied bases. However, the viscosity index of the seed oils is remarkably high, thus the change that takes place with increasing temperature is smoother than most of the bases studied in this work.

For ILs with the same anion ([NTf₂]⁻) the following trend is observed: [C₄C₁C₁Im]⁺ > [C₄C₁Pyrr]⁺ > [C₁OC₂C₁Pyrr]⁺, being the IL [C₁OC₂C₁Pyrr][FAP] that presents the higher film thickness. This IL gives film thicknesses falling in the upper range when compared to other oils of similar viscosity, like PAG2, PAG3, DiPEC5 and DiPEC7. In a previous work²⁵, even higher film thickness were found for [C₈C₁Im][PF₆] and [C₆C₁Im][PF₆] because of their higher viscosities, with values for the product $\eta_0^{0.69} \alpha^{0.56}$

exceeding 100 at 320 K. It is interesting to remark that Xiao et al.⁴⁶ have measured by the relative optical interference intensity method, the film thicknesses at pressures up to 3 GPa at room temperature for [C₄C₁Im][PF₆], [C₆C₁Im][PF₆], [C₈C₁Im][PF₆]. These authors have found the following trend: [C₄C₁Im][PF₆] < [C₆C₁Im][PF₆] < [C₈C₁Im][PF₆]. The same result has been obtained²⁵ from high pressure-viscosity data and the α_{film} definition of equations (2 and 3). Nevertheless, Xiao et al.⁴⁶ also found that even though the viscosities of three silicone oils are close to those of the ionic liquids, the measured film thicknesses of silicone oils, at both EHL and Thin Film Lubrication (TFL) conditions, are quite less than those of the ionic liquids. One possible explanation given by the authors is the existence of supramolecular aggregates on LIs observed by Bini⁵⁸ by spectroscopy. Actually, silicone oils are non-Newtonian shear-thinning fluids, the EHL film thickness being overestimated by models based on the classical Newtonian theory^{59,60}. Thus, this type of silicone oils form films thinner than most liquids of comparable viscosity and viscosity pressure coefficient. In a previous work, Xie et al. have also determined the film thickness in EHL and TFL conditions for the same three ILs and equal or similar silicon oils. In EHL conditions, the experimental film thicknesses agree with those calculated using the reciprocal asymptotic isoviscous pressure coefficients determined by Pensado et al.²⁵ from experimental viscosity-pressure values^{61,62}. At EHL conditions, Arora and Cann have found for 1-butyl-3-methylimidazolium tetrafluoroborate (viscosity 104 mPa.s at 20°C) and, 1-hexyl-3-methylimidazolium tetrafluoroborate (352 mPa.s at 20°C) that present thicknesses lower than a formulated mineral oil (124 mPa.s at 20°C). Thus, at least for the above-commented ILs the experimental film thicknesses are coherent with their viscosities and viscosity-pressure coefficients. It is important to remark that a low viscosity-pressure coefficient may present the advantage of a lower friction coefficient under EHL, but the

accompanying decrease in the film thickness could, if too steep, pose a threat to the wear protection⁶³.

Once a given value for the thickness has been set, it is desirable for the lubricant to be able to yield the best possible results within the range of working temperature in which the machinery operates. Thus, we should analyze the slopes when the product $\eta_0^{0.69} \alpha^{0.56}$ is plotted against temperature (Figure 9). Smoother slopes are better in order to avoid important variations in the thickness of the lubricant layer with a shift in temperature⁵. Lower changes of the film thickness with the temperatures were found for the ILs with [NTf₂]⁻ anion and PAG1, which are oils with high viscosity index.

CONCLUSIONS

The analysis of different tribology relevant properties for several lubricants was performed. PAGs, VOs and ILs with [NTf₂]⁻ anion, present the lowest variation of the viscosity against temperature changes. From viscosity values at higher pressure, the pressure-viscosity coefficient and the film thickness were determined for six ILs whereas those of ten synthetic oils and three vegetable bases were taken from the literature. The main results are that the highest values of the general film-forming pressure-viscosity coefficients have been obtained for squalane and [C₄C₁C₁Im][FAP], whereas the vegetable bases and the ILs not containing a [FAP]⁻ anion present the lowest values. The IL [C₁OC₂C₁Pyrr][FAP] gives film thicknesses close to the PAG oils with similar viscosity. The ILs with [NTf₂]⁻ and PAG1 are the lubricants which better avoid the changes on the film thicknesses with the temperature owing to a high viscosity index. The selected vegetable oils are expected to behave in a similar fashion due to that very same reason.

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Table 1. Properties of the base oils investigated in this work. ν , kinematic viscosity in $\text{mm}^2 \cdot \text{s}^{-1}$ at 313.15 K and 0.1 MPa.

LUBRICANT	TYPE	ν ($\text{mm}^2 \cdot \text{s}^{-1}$)	VI	Reference
PEC5	Synthetic	16	114	5
Squalane	Model	19	119	4
[C ₁ OC ₂ C ₁ Pyrr][NTf ₂] (IL2)	Ionic Liquid	22	191	6
PEC7	Synthetic	22	134	5
Jojoba	Vegetable	23	263	51
[C ₄ C ₁ Pyrr][NTf ₂] (IL3)	Ionic Liquid	30	176	6
PEC9	Synthetic	31	146	4
Soybean	Vegetable	33	208	51
[C ₁ OC ₂ C ₁ Pyrr][FAP] (IL5)	Ionic Liquid	35	137	7
[C ₄ C ₁ C ₁ Im][NTf ₂] (IL4)	Ionic Liquid	36	150	7
Canola	Vegetable	40	200	51
[C ₂ C ₁ Im][C ₂ SO ₄] (IL1)	Ionic Liquid	41	174	6
PEB8	Synthetic	44	85	4
[C ₄ C ₁ C ₁ Im][FAP] (IL6)	Ionic Liquid	44	107	7
PAG1	Synthetic	44	218	1
DiPEC5	Synthetic	52	138	3
DiPEC7	Synthetic	55	145	3
PAG3	Synthetic	56	187	2
PAG2	Synthetic	61	220	1

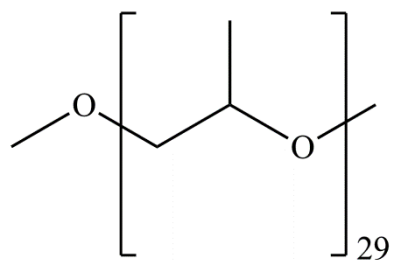


Figure 1. Molecular structure of PAG2.

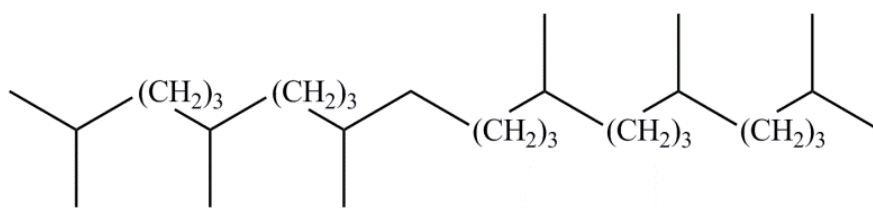


Figure 2. Molecular structure of squalane.

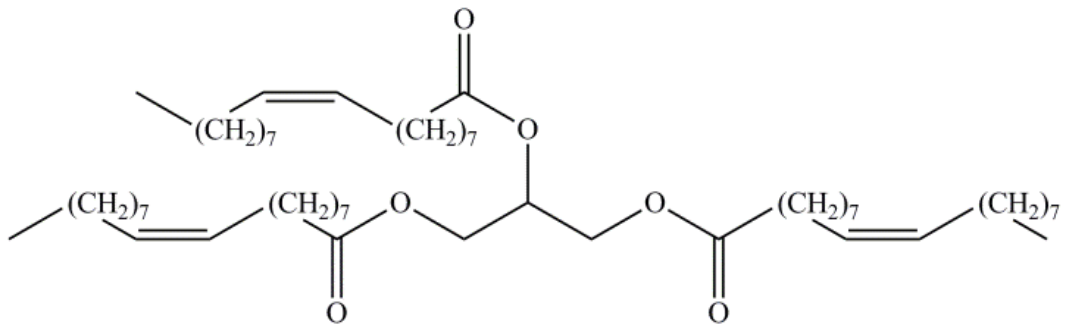


Figure 3. Molecular structure of triolein, an example of triglyceride of vegetable oils.

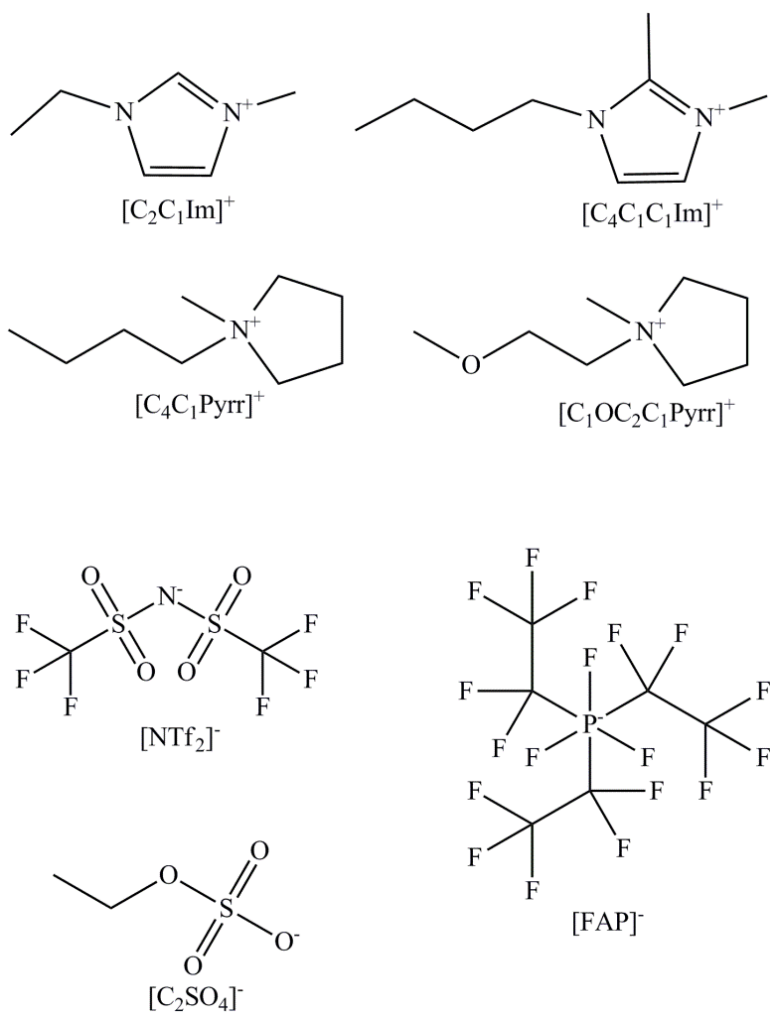


Figure 4. Anions and cations of the studied ILs.

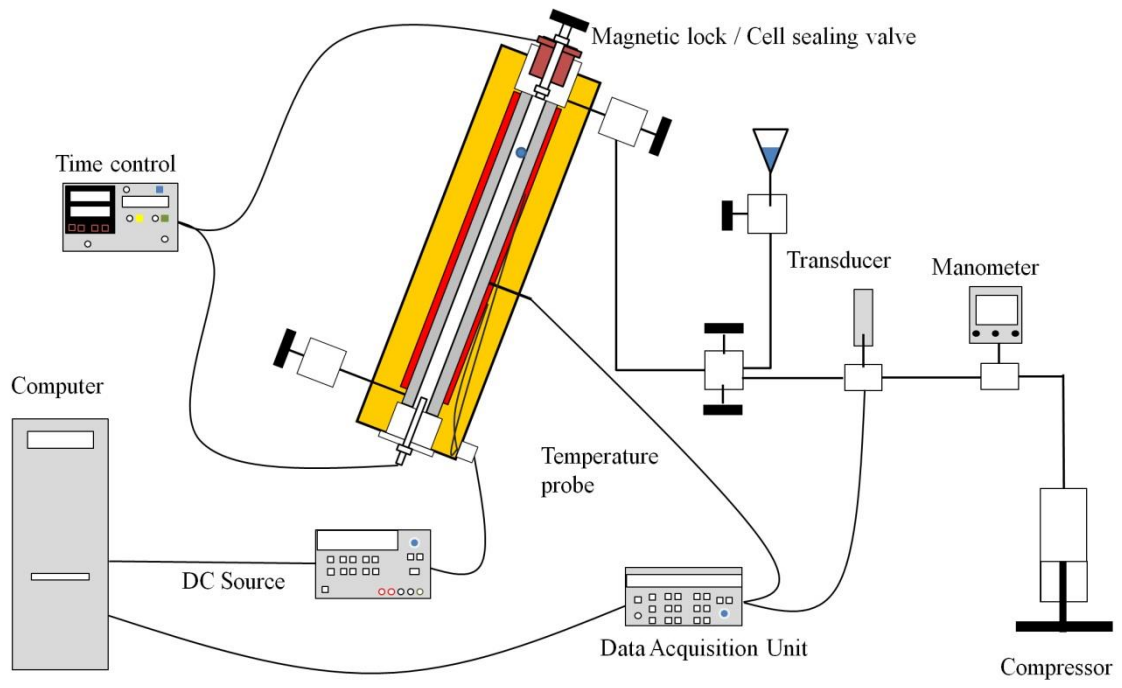


Figure 5. Scheme of the Ruska rolling body viscometer.

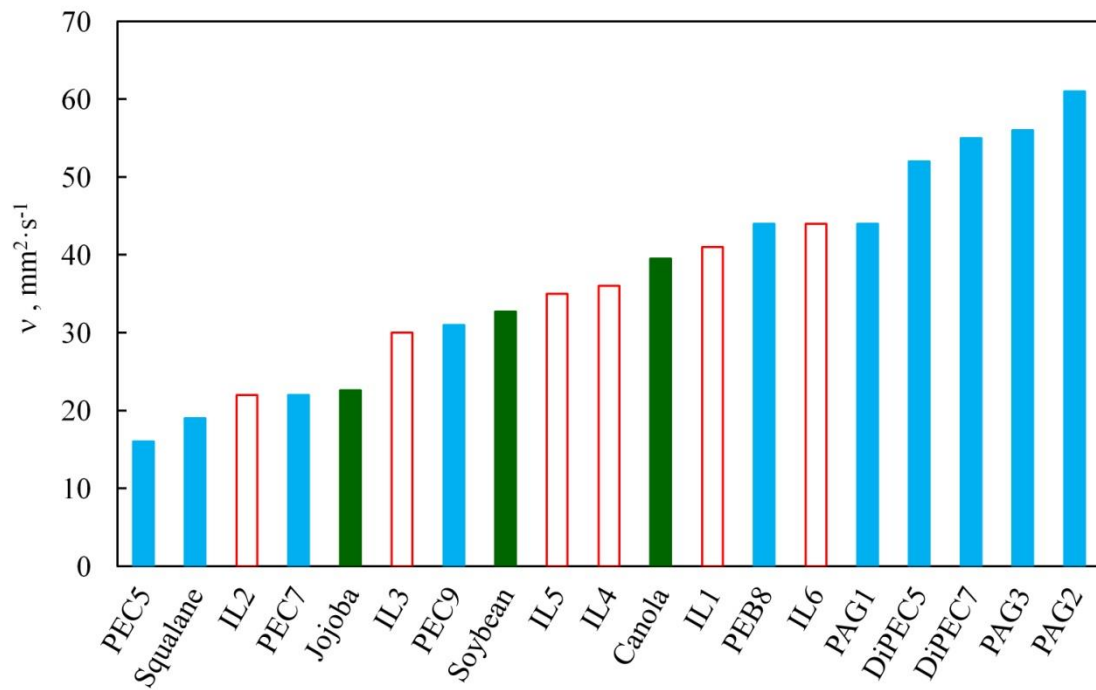


Figure 6. Kinematic viscosity, ν , at 313.15 K for the different lubricants. (□) ILs; (■) synthetic oils and (■) vegetable bases. The identifications of the IL1 to IL6 are given in Table I.

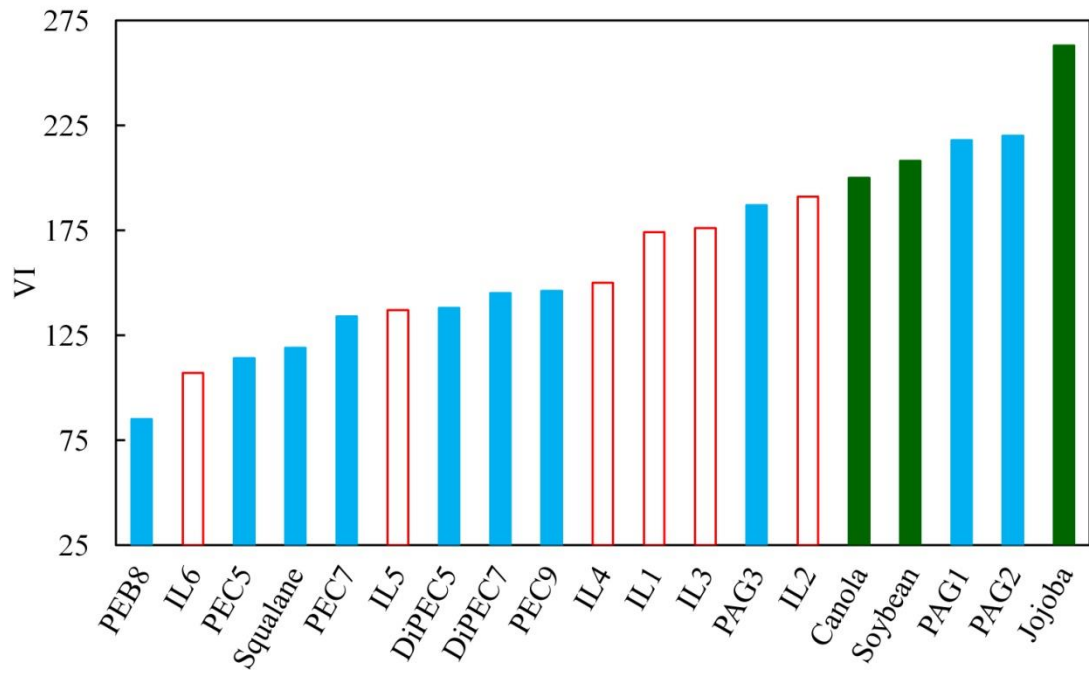


Figure 7. Viscosity Index, VI, for analyzed lubricants. (□) ILs; (■) synthetic oils and (■) vegetable bases. The identifications of the IL1 to IL6 are given in Table I.

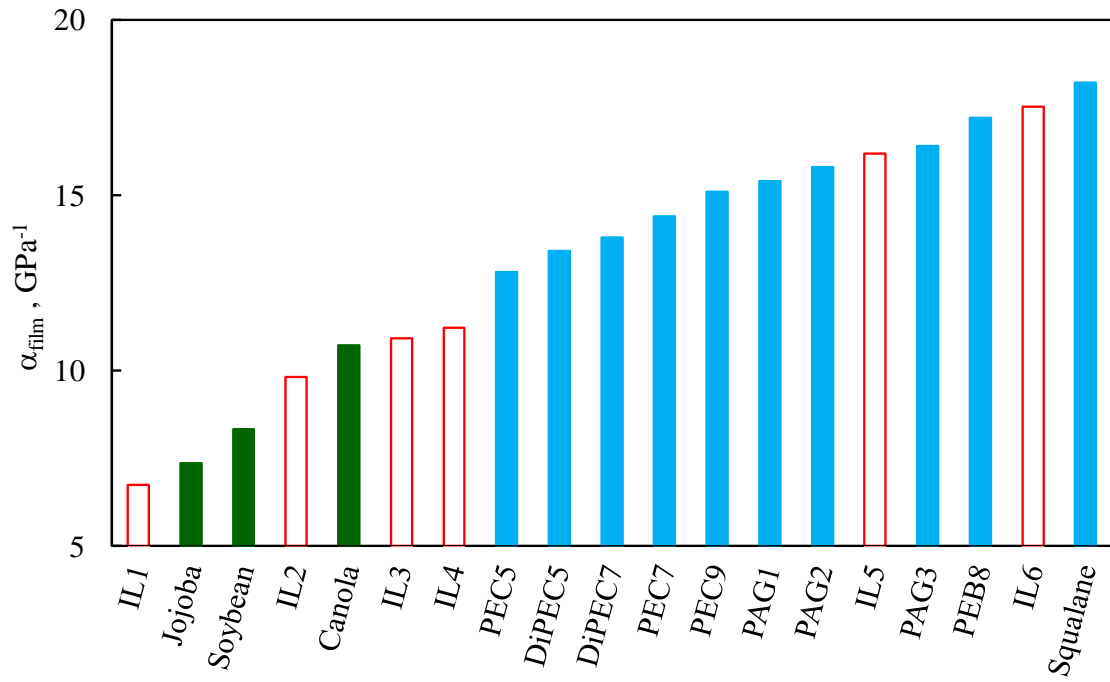


Figure 8. Universal pressure-viscosity coefficient, α_{film} for investigated oils at 313.15 K. (□) ILs; (■) synthetic oils and (■) vegetable bases. For esters and PAGs the values were taken from Pensado et al.⁴ and Paredes et al.², whereas the values of the vegetable oils were determined by Biresaw and Bantchev⁵¹ by optical interferometry.

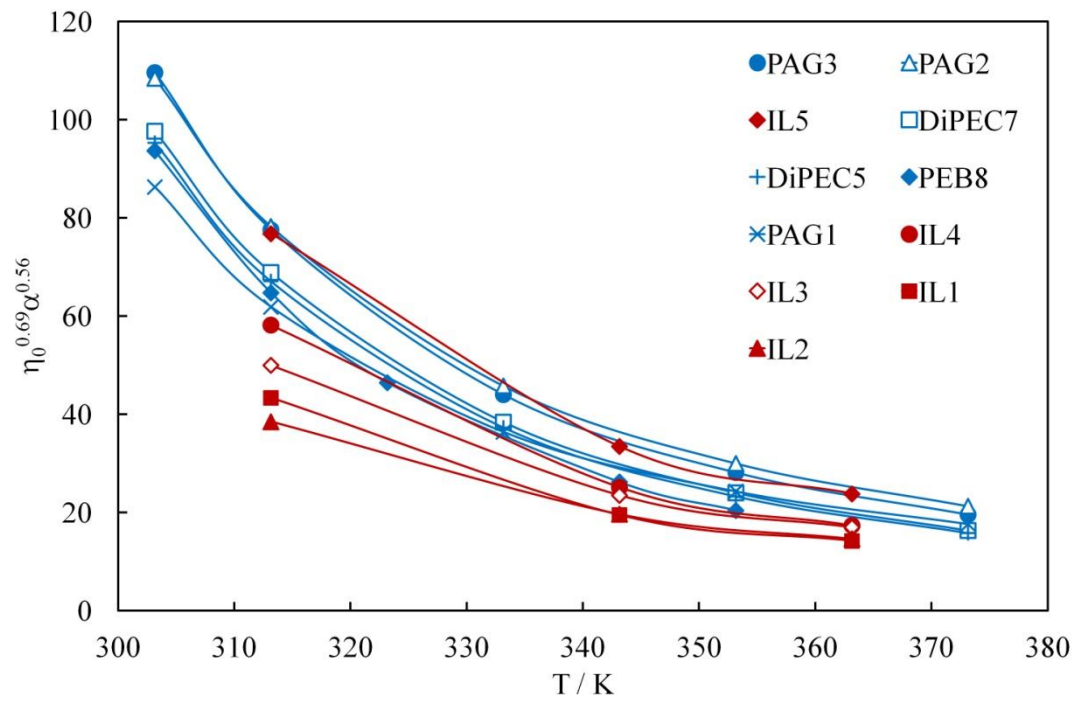


Figure 9. $\eta_0^{0.69} \alpha^{0.56}$ against temperature for different oils studied in this work. (—) Lines added as a visual guide for the eye.