

Thermophysical properties of phosphonium-based ionic liquids



Arijit Bhattacharjee^a, José A. Lopes-da-Silva^b, Mara G. Freire^a, João A.P. Coutinho^a, Pedro J. Carvalho^{a,*}

^a CICECO - Aveiro Institute of Materials, Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal

^b QOPNA Unit, Departamento de Química, Universidade de Aveiro, 3810-193 Aveiro, Portugal

ARTICLE INFO

Article history:

Received 4 March 2015

Received in revised form 28 April 2015

Accepted 6 May 2015

Available online 12 May 2015

Keywords:

Phosphonium

Ionic liquids

Density

Viscosity

Refractive index

Surface tension

ABSTRACT

Experimental data for density, viscosity, refractive index and surface tension of four phosphonium-based ionic liquids were measured in the temperature range between (288.15 and 353.15) K and at atmospheric pressure. The ionic liquids considered include tri(isobutyl) methylphosphonium tosylate, $[P_{i(444)}]_1[Tos]$, tri(butyl) methylphosphonium methylsulfate, $[P_{4441}][CH_3SO_4]$, tri(butyl) ethylphosphonium diethylphosphate, $[P_{4442}][(C_2H_5O)_2PO_2]$, and tetraoctylphosphonium bromide, $[P_{8888}][Br]$. Additionally, derivative properties, such as the isobaric thermal expansion coefficient, the surface thermodynamic properties and the critical temperatures for the investigated ionic liquids were also estimated and are presented and discussed. Group contribution methods were evaluated and fitted to the density, viscosity and refractive index experimental data.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

In recent years, ionic liquids (ILs) appeared as effective replacement solvents for many volatile organic compounds (VOCs), and thus contributed to the promotion and enlargement of more sustainable chemistry and technological processes. ILs are composed of large organic cations and organic or inorganic anions that cannot easily form an ordered crystal and thus remain liquid at or near room temperature. The academic and industrial interest, on these molten salts, results from their outstanding properties, such as negligible volatility, non-flammability, wide liquid electrochemical window, large liquidus temperature range, thermal stability, and the ability to dissolve a wide range of organic, inorganic and polymeric compounds [1–8], but mostly derived from the possibility of synthesizing an IL with a set of target properties suitable for a specific process or application. This ability to tune the ILs properties, through the combination or functionalization of cations and anions, lead to the designation of ‘*designer solvents*’. Moreover, these outstanding characteristics make ILs suitable candidates for a large number of applications, viz. as extractants, lubricants, thermal fluids, ionogels, plasticizers, catalysts, capacitors, sensors, among others [2,9–13].

For the accurate design, optimization, and operation of (industrial) processes and an efficient investigation of the ILs potential as

designer solvents, the knowledge of their thermophysical properties, namely viscosity, density, and interfacial tension, is important. Furthermore, reliable thermophysical data is required for the application of models employed in the development of efficient industrial processes and equipment design. Due to the large number of ILs that can be synthesized, the measurement of the thermophysical properties for all of them stands impractical, even unviable. Therefore, the selection and investigation of systematic series of compounds, representative of the different families, can provide insights on the ILs structure–property relationships and thus, allow the development of adequate correlations, equations of state or other models for these properties.

Phosphonium-based ILs, thermally more stable (in basic and nucleophilic conditions due to the absence of acidic protons in their moieties) and less expensive than their equivalent imidazolium ILs [14–16], are widely reported in the literature covering a large set of properties [17–24]. Fraser and MacFarlane [19] stated that phosphonium ILs clearly offer, in some cases, several advantages over other types of ILs, including, in specific cases and applications, higher thermal stability, lower viscosity, and higher stability in strongly basic or strongly reducing conditions. Frackowiak et al. [22] demonstrated that phosphonium ILs are potential compounds for application as super capacitors due to their enhanced electrochemical window. Tsunashima and Sugiya [23] studied the applicability of phosphonium ILs as battery electrolytes; their studies revealed that through chemical tuning, the low-viscosity phosphonium ILs display excellent electrochemical and thermal stabilities. Furthermore, their extreme low

* Corresponding author. Tel.: +351 234 370 958; fax: +351 234 370 084.

E-mail address: quijorge@ua.pt (P.J. Carvalho).

melting temperatures are of great importance in separation processes. These characteristics offer better scope and have proved to be valuable for many specific applications, like in the purification of biomolecules in aqueous two-phase systems [25,26], in the separation of ethanol–water mixtures as entrainers able to break the system azeotrope [27,28], in the extraction of metals [29,30] and in CO₂ capture and gas separation processes [31–33].

Despite the numerous advantages reported for phosphonium ILs, their applications will remain limited without further characterization of their thermophysical properties. Thus, the collection of novel experimental density, viscosity, refractive index and surface tension data measured in this work, as well as other retrieved from literature, allows to infer on specific structural effects of ILs, such the impact of the cation's alkyl chain length, ramification and symmetry and on the anion type. Additionally, derivative properties, such as the isobaric thermal expansion coefficient, the surface thermodynamic properties and critical temperature were also determined. Group contribution methods [34,35] for the density, viscosity and refractive index were also applied and evaluated.

2. Materials and methods

2.1. Materials

Four ILs were studied in this work, namely tri(isobutyl) methylphosphonium tosylate [P₍₄₄₄₎][Tos], tri(butyl) methylphosphonium methylsulfate [P₍₄₄₄₎][CH₃SO₄], tri(butyl) ethylphosphonium diethylphosphate [P₍₄₄₂₎][(C₂H₅O)₂PO₂] and tetraoctylphosphonium bromide [P₍₈₈₈₎][Br].

methylphosphonium methylsulfate [P₍₄₄₄₎][CH₃SO₄], tri(butyl) ethylphosphonium diethylphosphate [P₍₄₄₂₎][(C₂H₅O)₂PO₂] and tetraoctylphosphonium bromide [P₍₈₈₈₎][Br]. The ILs chemical structures and corresponding designations are presented in Table 1. All the ILs were kindly offered by CYTEC Industries Inc. with mass fraction purities higher than 98%.

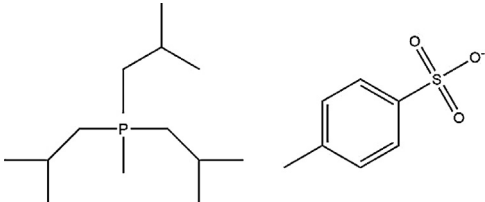
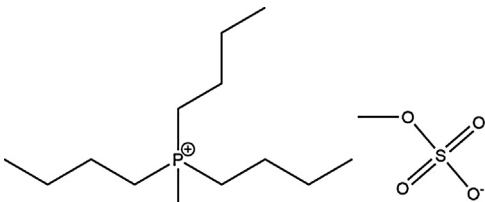
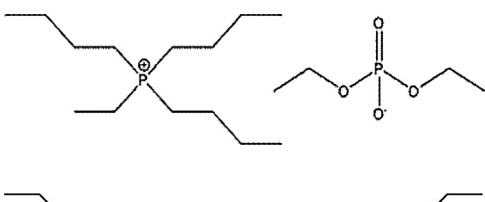
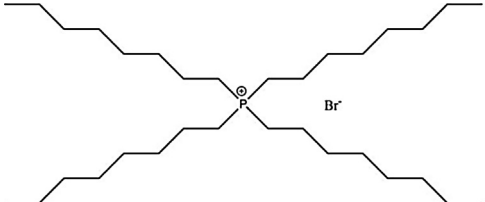
The water content plays an important role in the IL properties, especially on the surface tension and viscosity [36,37], and significant deviations can be found due to small amounts of water. Therefore, in order to remove traces of water and volatile compounds, individual samples of each IL were dried at moderate temperature (≈323 K), vacuum (≈10⁻¹ Pa) and under continuous stirring, for a minimum period of 48 h prior to the measurements. The purity of each IL was checked by ¹H and ¹³C NMR to assure that no degradation occurred during the purification procedure and measurements. The final IL water content, after the drying step and immediately before the measurements, was determined with a Metrohm 831 Karl Fischer coulometer (using the Hydranal-Coulomat AG from Riedel-de Haën as analyte) and is reported in Table 1.

2.2. Experimental

2.2.1. Density and viscosity

Density (ρ) and dynamic viscosity (η) measurements were carried out using an automated SVM3000 Anton Paar rotational Stabinger viscometer–densimeter in the (283.15–353.15) K temperature range and at atmospheric pressure (≈0.1 MPa). The

Table 1
Ionic structure, compound description, CAS number, molecular weight, water content and mass fraction purity of the studied ILs.

IL	Ionic structure
Tri(isobutyl) methylphosphonium tosylate [P ₍₄₄₄₎][Tos] (CAS: 374683-35-9; M = 388.5 g mol ⁻¹ ; H ₂ O wt% = 0.0842%; wt% = 98%)	
Tri(butyl) methylphosphonium methylsulfate [P ₍₄₄₄₎][CH ₃ SO ₄] (CAS: 69056-62-8; M = 328.5 g mol ⁻¹ ; H ₂ O wt% = 0.0783%; wt% = 98%)	
Tri(butyl) ethylphosphonium diethylphosphate [P ₍₄₄₂₎][(C ₂ H ₅ O) ₂ PO ₂] (CAS: 20445-94-7; M = 384.5 g mol ⁻¹ ; H ₂ O wt% = 0.0741%; wt% = 98%)	
Tetraoctylphosphonium bromide [P ₍₈₈₈₎][Br] (CAS: 23906-97-0; M = 563.8 g mol ⁻¹ ; H ₂ O wt% = 0.0105%; wt% = 98%)	

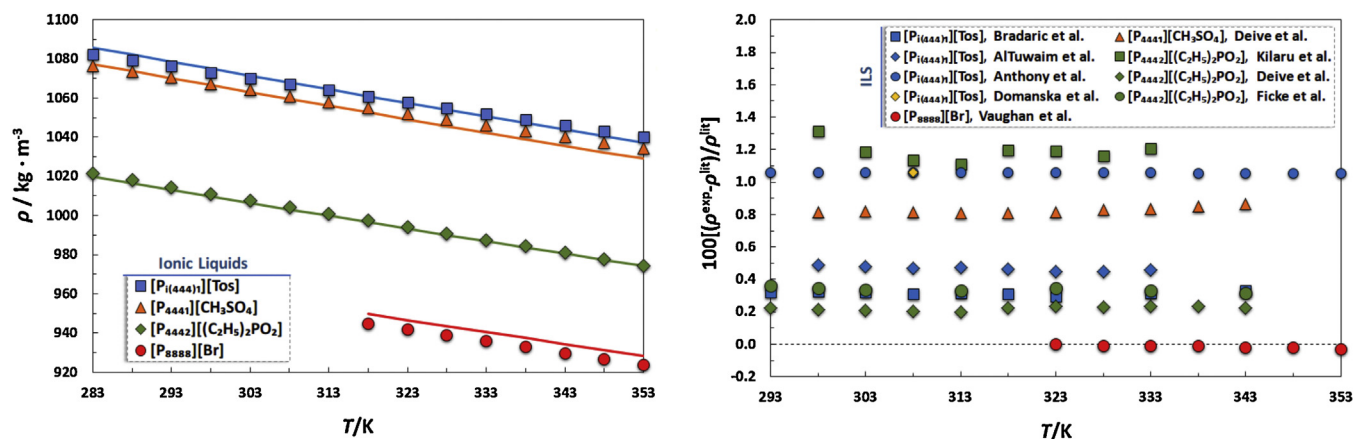


Fig. 1. Density as a function of temperature (left) and relative deviations between the experimental data from this work and those available in the literature [14,18,20,47–51] (right). The solid lines represent the Gardas and Coutinho [34] group contribution method.

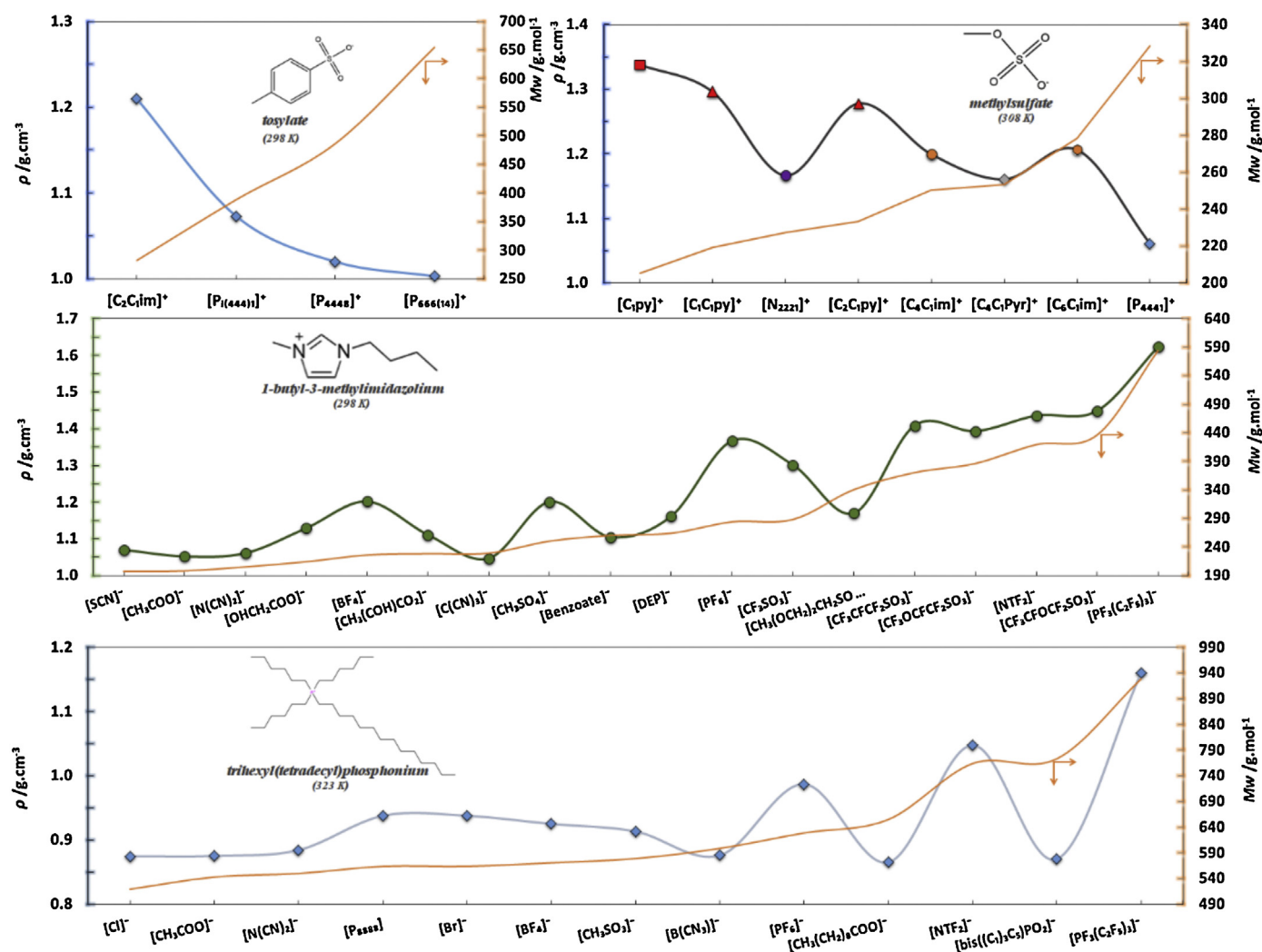


Fig. 2. Density as function of ionic liquids' molecular weight, for tosylate- (308 K), methylsulfate- (298 K), 1-butyl-3-methylimidazolium- (298 K) and trihexyl(tetradecyl) phosphonium-based ILs (323 K) [20,47,48,52–62]. The lines are guides for the eyes.

molecular weight, and consequently the overall size and charge dispersion, there is an increase in the density, as depicted in Fig. 2.

Molar volumes, V_m , were calculated and are reported in Table 2 and depicted in Fig. 3, as function of temperature. For the studied ILs, the molar volumes present a small temperature dependency

and increase in the order: $[\text{P}_{8888}][\text{Br}] > [\text{P}_{4442}][(\text{C}_2\text{H}_5\text{O})_2\text{PO}_2] > [\text{P}_{1(444)}][\text{Tos}] > [\text{P}_{4441}][\text{CH}_3\text{SO}_4]$.

The relative deviations between the density data measured in this work and those available in the literature [14,18,20,47–51] are displayed in Fig. 1. Experimental data for the studied ILs are in good

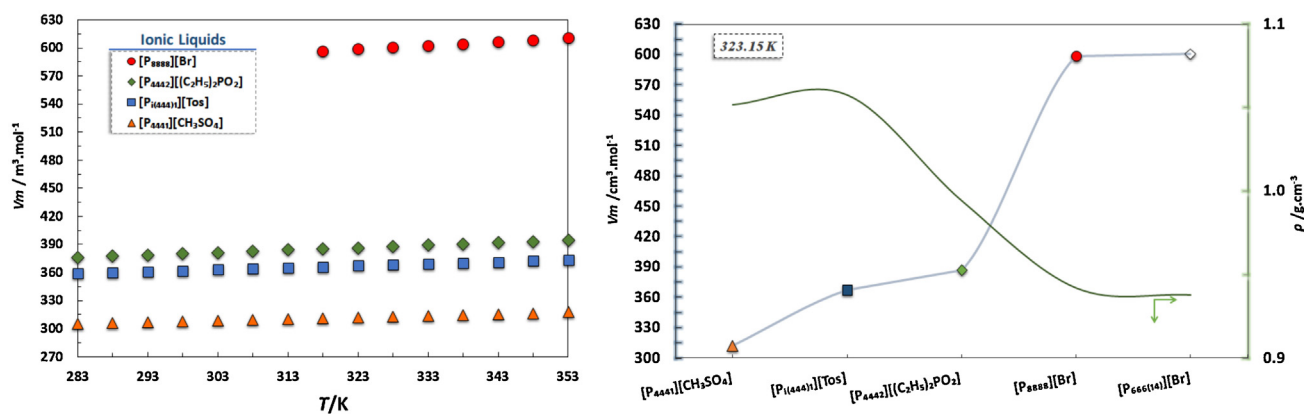


Fig. 3. Molar volumes as function of temperature for the studied ILs (left) and molar volume and density as function of ILs at 323.15 K (right).

agreement with the available literature values, with absolute average relative deviations ranging from (0.02 to 1.19)%. The absolute average relative deviations toward $[\text{P}_{i(444)}]_1[\text{Tos}]$ reported by Bradaric et al. [14], AlTuwa'im et al. [18], Anthony et al. [50] and Domańska et al. [51] are 0.32%, 0.47%, 0.31% and 0.57% respectively. The absolute average relative deviations toward the $[\text{P}_{4441}][\text{CH}_3\text{SO}_4]$ reported by Deive et al. [20] is 0.83%. Absolute relative deviations of 0.22%, 1.19% and 0.34% for $[\text{P}_{4442}][(\text{C}_2\text{H}_5)_2\text{PO}_2]$ were found against the data of Deive et al. [20], Kilaru et al. [48] and Ficke et al. [47], respectively. The data from Kilaru et al. [48] present the higher deviations found, that seem to be related with the high amount of water present in the authors' sample (1080 ppm). Absolute relative deviations toward $[\text{P}_{8888}][\text{Br}]$ was found to be 0.02% when compared to the data reported by Vaughan et al. [49].

Gardas and Coutinho [34] extended the Ye and Shreeve [63] approach to the estimation of IL densities for a wide range of temperatures, (288.15–353.15) K, pressures, (0.10–100) MPa, and ILs families according to the equation

$$\rho = \frac{M}{NV(a + bT + cp)} \quad (1)$$

where ρ is the density in $\text{kg} \cdot \text{m}^{-3}$, M the molecular weight in $\text{kg} \cdot \text{mol}^{-1}$, N the Avogadro constant, V the molecular volume in \AA^3 , T the temperature in K and p the pressure in MPa. The universal coefficients a , b and c are 0.8005 ± 0.0002 , $6.652 \times 10^{-4} \pm 0.007 \times 10^{-4} \text{ K}^{-1}$ and $-5.919 \times 10^{-4} \pm 0.024 \times 10^{-4} \text{ MPa}^{-1}$, respectively, at a 95% confidence level.

The experimental density data were additionally used to extend the parameter table on the group contribution method previously proposed by Gardas and Coutinho [34]. Volumes for the $[\text{P}_{i(444)}]_1^+$ and $[\text{P}_{1111}]^+$ cations and $[(\text{C}_2\text{H}_5)_2\text{PO}_2]^-$ and $[\text{CH}_3\text{SO}_4]^-$ anions were estimated based on density values taken from literature [20,47,48,52–60,62,64] and those reported in this work. With density data, for the anions investigated here, mainly available for the well characterized imidazolium family, the group contribution anionic volumes were determined using 240 experimental data points from six compounds. Despite the deviations found among different authors, a percentage absolute average deviations of 0.92% and 0.62% were obtained against data for $[\text{CH}_3\text{SO}_4]^-$ and $[(\text{C}_2\text{H}_5)_2\text{PO}_2]^-$ anion-based ILs, respectively. Once the anions volume determined, that of the $[\text{P}_{1111}]^+$ cation was fitted against our experimental data and those of Deive et al. [20], Ficke et al. [47] and Kilaru et al. [48] with percentage absolute average deviation of 0.40%. The volumetric parameters for the anions $[\text{Tos}]^-$ and $[\text{Br}]^-$ were taken from previous works [24,46]. Both the estimated and literature values of cationic and anionic volumes are reported in Table 3. The proposed volumes provide a good description of the

experimental density data, as shown in Fig. 1, with an absolute relative average deviation of 0.16%, 0.20%, 0.046% and 0.52% for $[\text{P}_{i(444)}]_1[\text{Tos}]$, $[\text{P}_{4441}][\text{CH}_3\text{SO}_4]$, $[\text{P}_{4442}][(\text{C}_2\text{H}_5)_2\text{PO}_2]$ and $[\text{P}_{8888}][\text{Br}]$, respectively.

3.1.1. Thermal expansion coefficient

The isobaric thermal expansion coefficients, α_p , of the studied ILs, which reflect the ILs volumetric changes with temperature, were calculated from the fitting of the experimental data with the following equation,

$$\alpha_p = \frac{-1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p = - \left(\frac{\partial \ln \rho}{\partial T} \right)_p \quad (2)$$

where ρ is the density in $\text{kg} \cdot \text{m}^{-3}$, T the temperature in K, and p a fixed pressure.

The calculated thermal expansion coefficients for the pure liquids are listed in Table 4 where it can be seen that the change in the ILs volume is small as the temperature increases which confirms the weak expansion ability of IL fluids [65]. The values obtained vary between 5.7 and $6.7 \times 10^{-4} \text{ K}^{-1}$ and are of the same order of magnitude, $(5-7) \times 10^{-4} \text{ K}^{-1}$, of those reported for other ILs families, like ammonium-, sulfonium-, imidazolium-, pyridinium- and pyrrolidinium-based ILs [39,41,42,65–69]. The results also indicate that the alkyl side chain length presents a lower impact on the thermal expansion coefficient than that observed for the anion replacement [39,46,65,69].

3.2. Viscosity

Viscosity is an important property for the design of industrial processes involving heat and/or mass transfer, dissolution or

Table 3

Ionic volumes, V , determined using the Gardas and Coutinho Group Contribution Model [34] for the studied ILs.

Ionic species	$V/\text{\AA}^3$
Cation	
$[\text{P}_{i(444)}]_1^+$	544
$[\text{P}_{1111}]^+$	154
Anion	
$[\text{Tos}]^-$ [46]	248
$[\text{CH}_3\text{SO}_4]^-$	106
$[(\text{C}_2\text{H}_5)_2\text{PO}_2]^-$	199
$[\text{Br}]^-$ [24]	36
Group	
$-\text{CH}_2$ [34]	28

Table 4

Coefficients of thermal expansion, α_p , refractive indices, n_D , isotropic polarizabilities, derived molar refractions, R_m , and free volumes, f_m , surface entropy, S^s , surface enthalpy, H^s , and estimated critical temperatures using both Eötvös $T_{c,Eot}$ [86] and Guggenheim, $T_{c,Gug}$ [87] empirical equations for the studied ILs.

	[P ₁₄₄₄₁][Tos]	[P ₄₄₄₁][CH ₃ SO ₄]	[P ₄₄₄₂][(C ₂ H ₅ O) ₂ PO ₂]	[P ₈₈₈₈][Br]
$10^4(\alpha_p \pm \sigma)/K^{-1}$	5.706 ± 0.073	5.715 ± 0.073	6.726 ± 0.101	6.508 ± 0.052
n_D^a	1.51233	1.46912	1.45923	1.48262
Polarizability ^a /bohr ³	294.15	232.04	281.98	455.48
$R_m^a/cm^3 mol^{-1}$	109.95	86.74	105.4	170.26
$f_m^a/cm^3 mol^{-1}$	256.28	224.65	279.99	426.31
$10^5(S^s \pm \sigma)/J m^{-2} K^{-1}$	7.7 ± 0.31	6.4 ± 0.24	7.5 ± 0.27	5.7 ± 0.17
$10^2(H^s \pm \sigma)/J m^{-2} K^{-1}$	6.1 ± 0.10	5.5 ± 0.06	8.5 ± 0.08	4.5 ± 0.05
$T_{c,Eot} /K$	891 ± 27	901 ± 3	792 ± 21	922 ± 22
$T_{c,Gug} /K$	892 ± 23	900 ± 3	796 ± 17	906 ± 17

^a At 318.15 K.

absorption of compounds in fluids; thereby, it stands as a key property on the selection of ILs suitable for a particular application. The experimental viscosity data for the studied ILs is reported in Table 2 and depicted in Fig. 4.

For the studied compounds, few viscosity data is available [18,20,70,71] in the literature. As depicted in Fig. 5, viscosity data for [P₁₄₄₄₁][Tos] shows average relative deviations of –17.52% and

51.31% against Green et al. [71] and AlTuwaim et al. [18] data, respectively. Nonetheless, very high deviations of 166.6%, were obtained for [P₄₄₄₁][CH₃SO₄] when comparing the data from Deive et al. [20]. Experimental data for [P₄₄₄₂][(C₂H₅O)₂PO₂], on the other hand, present average relative deviation of 3.44%, 9.49% and –49.51% when compared to the data reported by Deive et al. [20], Ferguson and Scovazzo [70] and Green et al. [71], respectively. To

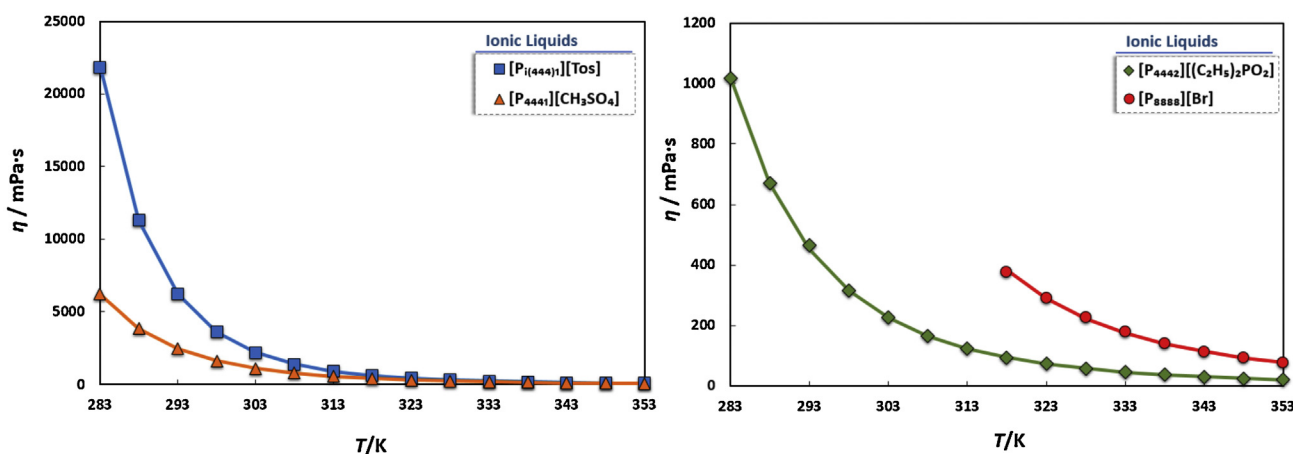


Fig. 4. Viscosity data for the studied ILs. The solid lines represent the Vogel-Tammann-Fulcher (VTF) group contribution correlation [35].

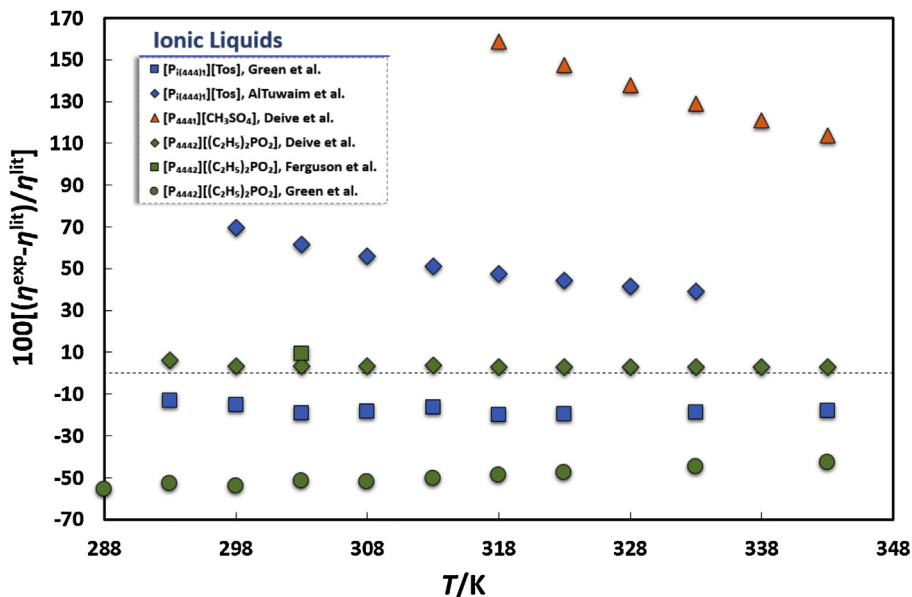


Fig. 5. Relative deviations between the experimental viscosity data of this work and those available in the literature [18,20,70,71].

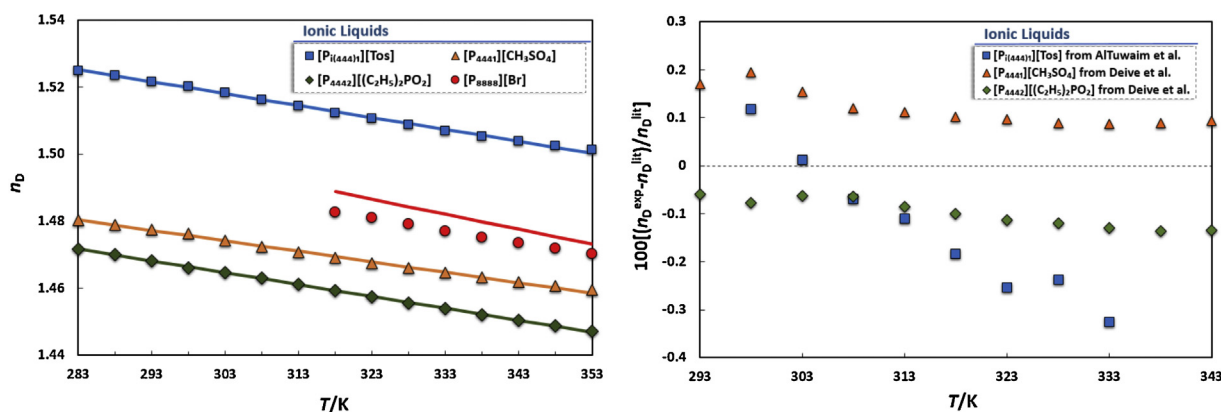


Fig. 6. Refractive index as a function of temperature (left) and relative deviations (right) between the experimental data from this work and those available in the literature [18,20]. The solid lines represent the Gardas and Coutinho [35] group contribution method.

the best of our knowledge no viscosity data are available for [P₈₈₈₈][Br]. When compared with experimental density data, larger differences are detected within viscosity values obtained by different authors. It is well known that viscosity is highly “sensitive” to the presence of impurities, namely to the adsorption of moisture during the experimental manipulation. Therefore, a purification step and a correct sample manipulation are of vital importance to achieve accurate viscosity data. While Green et al. [71] and Altuwaim et al. [18] reported a purification procedure using vacuum for several days, Ferguson and Scovazzo [70] degassed the IL in a desiccator for 3 hours under low vacuum and Deive et al. [20] used the IL as received without further purification. Furthermore, most of the authors evaluated the ILs’ viscosity as a secondary measurement for calculations and, therefore, no special attention was given to its determination. In addition, while Altuwaim et al. [18] and Deive et al. [20] report viscosity measurements using Anton Paar apparatuses, other authors do not mention the equipment and technique adopted. Thus, large discrepancies, in the viscosity values, are expected and observed among the different authors.

As commonly observed, viscosity markedly decreases with the temperature increase. The viscosity increases in the following order: [P_{i(444)1}][Tos] >> [P₄₄₄₁][CH₃SO₄] > [P₈₈₈₈][Br] > [P₄₄₄₂][(C₂H₅O)₂PO₂]. Similar to that observed previously for imidazolium- and piridinium-based ILs [41] the π - π interactions due to the presence of an aromatic ring, now at the ([P_{i(444)1}][Tos]) anion, leads to higher resistance to shear stress, to a more rigid IL structure and therefore to a bulkier distribution and higher viscosities.

The description of viscosities for the ILs studied was carried out using the group contribution method, based on the Vogel–Fulcher–Tammann (VFT) correlation,

$$\ln \eta = A_{\eta} + B_{\eta} \frac{\eta}{T - T_{0\eta}} \quad (3)$$

where η is the dynamic viscosity in mPa s, T is the temperature in K, and A_{η} , B_{η} and $T_{0\eta}$ are adjustable parameters estimated by fitting the equation to the experimental data. The fitted parameters are

Table 5
Vogel–Fulcher–Tammann (VFT) correlation parameters, A_{η} , B_{η} and $T_{0\eta}$, for the studied ILs.

IL	A_{η}	B_{η}/K	$T_{0\eta}/K$
[P _{i(444)1}][Tos]	-3.15	1238	189
[P ₄₄₄₁][CH ₃ SO ₄]	-3.75	1559	158
[P ₄₄₄₂][(C ₂ H ₅ O) ₂ PO ₂]	-3.37	1199	167
[P ₈₈₈₈][Br]	-1.51	961	189

presented in Table 5. The fitting results are depicted in Fig. 4 and present average absolute relative deviations of 0.16% for [P_{i(444)1}][Tos], 0.11% for [P₄₄₄₁][CH₃SO₄], 0.39% for [P₄₄₄₂][(C₂H₅O)₂PO₂] and 0.93% for [P₈₈₈₈][Br].

3.3. Refractive index

The refractive index specifies the dielectric response of a fluid to an electrical field induced by electromagnetic waves and is thus, an optical property of materials. The experimental refractive indices of the investigated ILs are shown in Fig. 6 and reported in Table 2. The refractive indices were scanned upward and downward on temperature, with no hysteresis effects observed, and within the temperature range from (283.15 to 353.15) K. The refractive index decreases with the temperature increase. Furthermore, the refractive indices for the phosphonium-based ILs increase in the following sequence: [P_{i(444)1}][Tos] > [P₈₈₈₈][Br] > [P₄₄₄₁][CH₃SO₄] > [P₄₄₄₂][(C₂H₅O)₂PO₂].

The relative deviations between the data measured in this work and those reported in literature [18,20] are depicted in Fig. 6. Experimental data for [P_{i(444)1}][Tos], [P₄₄₄₁][CH₃SO₄] and [P₄₄₄₂][(C₂H₅O)₂PO₂] are in good agreement with available literature values, with absolute relative average deviations ranging from (0.1 to 0.13)%. The absolute relative average deviations toward [P_{i(444)1}][Tos] reported by Altuwaim et al. [18] is 0.13%. Experimental data for [P₄₄₄₁][CH₃SO₄] and [P₄₄₄₂][(C₂H₅O)₂PO₂] present absolute average relative deviations of 0.12% and 0.1% when compared to the values reported by Deive et al. [20], respectively. To the best of our knowledge refractive indices for [P₈₈₈₈][Br] are here reported for the first time.

Table 6
Group contribution parameters, a_{i,n_D} and b_{i,n_D} , determined using the Gardas and Coutinho group contribution method [35] for the refractive index.

Ionic species	a_{i,n_D}	$10^4 b_{i,n_D}/K^{-1}$
Cation		
[P _{i(444)1}] ⁺	1.4474	3.14
[P ₁₁₁₁] ⁺	1.3972	2.617
Anion		
[Tos] ⁻ [46]	0.1787	0.4261
[CH ₃ SO ₄] ⁻ [35]	0.1314	0.1016
[(C ₂ H ₅ O) ₂ PO ₂] ⁻	0.1302	0.4782
[Br] ⁻ [72]	0.1084	0.5866
Group		
-CH ₂ [35]	0.0045	0.04587

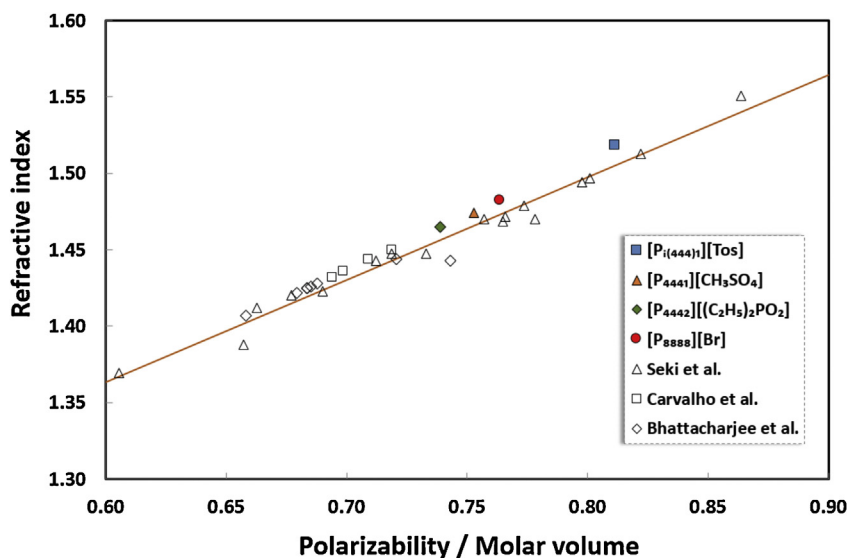


Fig. 7. Relationship between the refractive index and polarizability/molar volume for different ILs at 303.15 K. The unfilled triangles and the solid line represent the experimental data and the correlation of Seki et al. [76]. The unfilled squares and diamonds represent the experimental data reported in previous works [41,42,77]. The full symbols correspond to the ILs data determined in this work.

The refractive indices for the ILs studied were also fitted with the group contribution method proposed by Gardas and Coutinho [35], which results are depicted in Fig. 6, and that follow a linear function of the form,

$$n_D = A_{n_D} - B_{n_D} T \quad (4)$$

$$A_{n_D} = \sum_{i=1}^k n_i a_{i,n_D} \quad (5)$$

$$B_{n_D} = \sum_{i=1}^k n_i b_{i,n_D} \quad (6)$$

where n_i is the number of groups of type i and k is the total number of different groups in the molecule. The estimated parameters a_{i,n_D} and b_{i,n_D} for the cations of the studied ILs are given in Table 6 along with the anionic volume previously reported [35,46,72]. The average absolute relative deviation between the experimental and the fitting data are 0.021% for $[P_{i(444)}]_1[Tos]$ and $[P_{4441}][CH_3SO_4]$, 0.0079% for $[P_{4442}][(C_2H_5O)_2PO_2]$ and 0.0094% for $[P_{8888}][Br]$.

The derived molar refractions, R_m , free volumes, f_m , and polarizabilities were additionally determined as follows [73–75]:

$$\frac{\alpha_0}{4\pi\epsilon_0} = \left(\frac{n_D^2 - 1}{n_D^2 + 2} \right) \frac{3M}{4\pi\rho N_A} \quad (7)$$

$$R_m = \frac{N_A \alpha_0}{3\epsilon_0} = \frac{n_D^2 - 1}{n_D^2 + 2} V_m \quad (8)$$

$$f_m = V_m - R_m \quad (9)$$

where α_0 is the electronic polarizability, ϵ_0 the vacuum permittivity, R_m the compound's density, M the molecular weight and N_A the Avogadro number. The obtained values for these properties are reported in Table 4.

Recently, on the premise that refractive indices are an indication of the dielectric response to an electrical field, induced by electromagnetic waves, and that refractive indices can be derived as the first order approximation response to electronic polarization within an instantaneous time scale, Seki et al. [76] evaluated the refractive indices of 17 ILs, as a function of temperature, against theoretical polarizabilities obtained through *ab initio* calculations. The authors proposed a correlation between

the refractive index and the polarizability normalized in terms of the molecular volume. Following the work of Seki et al. [76] the correlation was previously verified against ammonium-, sulfonium-, phosphonium-, piperidinium- and pyridinium-based ILs experimental data and shown to provide an easy and accurate way to predict the refractive index or polarizabilities of ILs [41,42,77]. Here the phosphonium-based ILs were tested against the correlation and, once again, it was shown that it is able to describe, within the uncertainty of the correlation, this IL family refractive indices and/or polarizability, as depicted in Fig. 7.

3.4. Surface tension

Experimental surface tension data measured for all the studied ILs are presented in Table 7 and depicted in Fig. 8 as a function of temperature.

Using dynamic contact angle measurements, AlTuwa'im et al. [18] reported surface tension data for $[P_{i(444)}]_1[Tos]$ that presents average relative deviations of –14.4% to the data measured here. An average relative deviation of –8.90% was obtained for $[P_{4442}][(C_2H_5O)_2PO_2]$, using the Du Noüy ring method, reported by Kilaru et al. [48]. The deviations obtained seem to be associated to small traces of water, the technique employed and/or the sample purity.

From Fig. 8, it can be seen that the surface tension of the studied ILs decreases linearly with temperature and follows the order: $[P_{i(444)}]_1[Tos] > [P_{4441}][CH_3SO_4] > [P_{4442}][(C_2H_5O)_2PO_2] > [P_{8888}][Br]$. It can be observed that both the cation and anion significantly

Table 7

Surface tension, γ , for the studied ILs as a function of temperature and at atmospheric pressure.

T/K	$[P_{i(444)}]_1[Tos]$ $\gamma/mN m^{-1}$	$[P_{4441}][CH_3SO_4]$ $\gamma/mN m^{-1}$	$[P_{4442}][(C_2H_5O)_2PO_2]$ $\gamma/mN m^{-1}$	$[P_{8888}][Br]$ $\gamma/mN m^{-1}$
293.2	38.1	35.5	31.4	
298.2				
303.2	37.3	34.7	30.5	
313.1	36.6	34.1	29.8	
318.1				27.4
323.1	35.5	33.5	29.2	27.1
333.1	35.0	32.9	28.5	26.6
343.1	34.3	32.2	27.5	26.0

Standard temperature uncertainty is $u(T) = \pm 0.1$ K and the surface tension expanded uncertainty is $U_c(\gamma) = 0.1$ mN m^{-1} , with an approximately 95% level of confidence.

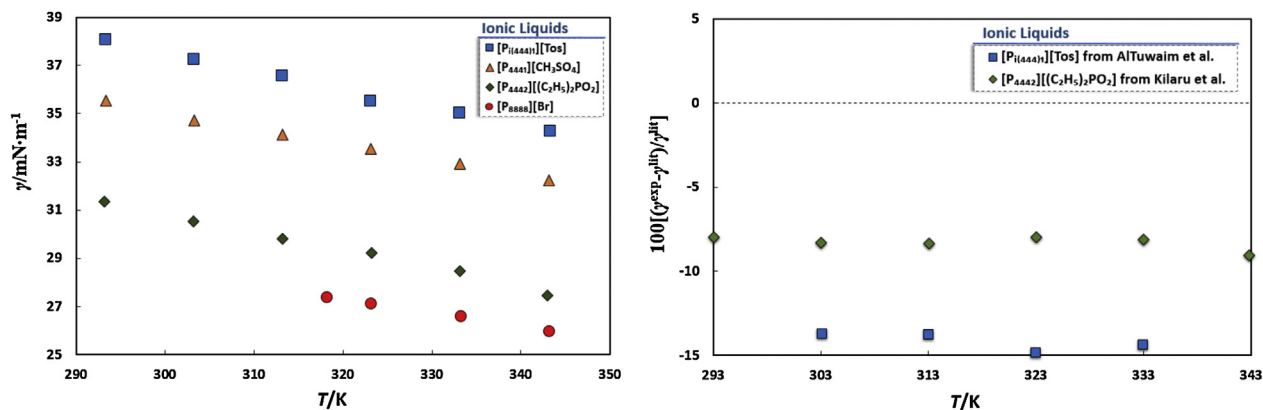


Fig. 8. Surface tension data for the studied ILs as a function of temperature (left) and relative deviations between this work experimental surface tension data and that available in the literature [18,48] (right).

contribute to the surface tension of the IL at the air–liquid interface [78,79]. It is well established that the surface tension is related with the part of the molecule that is present at the interface and pointing toward the air phase. The moiety with the lower surface energy tends to accumulate at the interface. Typically these are alkyl chains oriented toward the gas phase. Santos and Baldelli [80] showed that halide anion-based ILs may present a top layer formed entirely by the cation with the alkyl chains pointing toward the gas phase while the second layer is formed only by the halide. When the cation and anion have similar sizes and both present alkyl chains, as is the case for some of the compounds here studied, the cations and anions may occupy the same plane at the gas–liquid interface [80], with the alkyl chains projecting toward the vapor phase and the anions and cation's polar head groups forming a second layer. This structural behavior allows one to picture the surface arrangement of the studied ILs and understand the surface tension values under the light of the intermolecular interactions strength playing an important role on the compactness and strength of the interface layer composed by the anion and cation's head groups.

3.4.1. Surface thermodynamic properties

It is possible to derive the surface thermodynamic properties, viz. surface entropy and surface enthalpy, through the temperature dependence of the surface tension. The basic thermodynamic relationship applied to the surface of a homogeneous liquid is

$$H^\gamma = G^\gamma + TS^\gamma \quad (10)$$

where H^γ is surface enthalpy, G^γ is the Gibbs energy, T is the temperature (in K), and S^γ is the surface entropy. The surface entropy per unit area can be calculated according to the following equation [81,82],

$$S^\gamma = -\left(\frac{\partial \gamma}{\partial T}\right) \quad (11)$$

while the surface enthalpy according to [81,82],

$$H^\gamma = T - \left(\frac{\partial \gamma}{\partial T}\right) \quad (12)$$

where γ stands for the surface tension and T for the temperature.

The values of the thermodynamic functions for all the ILs studied and the respective expanded uncertainties, derived from the slope of the curve $\gamma=f(T)$ in combination with the law of propagation of uncertainties, are presented in Table 4 [83].

In agreement with the results previously reported for other ILs families, viz. imidazolium-, pyridinium-, pyrrolidinium- and piperidinium-based cations, [40,41,43,78,79,84], the investigated phosphonium ILs present lower surface enthalpies and entropies

when compared with molecular organic compounds. These values reflect a high surface organization, as well as an inherent highly structured liquid phase in ionic liquids. These values of low surface entropies are an indication of a high surface organization as well as a highly structured liquid phase. Moreover, the results of similar surface entropy and surface enthalpy observed, for the different IL families, are an effect of similar dependency of the surface tension with the temperature.

3.4.2. Estimated critical temperatures

The critical temperature of fluids is one of the most relevant and significant thermophysical property frequently used in corresponding state correlations concerning equilibrium and transport properties [85]. However, owing to the intrinsic nature of ILs coupled with negligible vapor pressures and relatively low decomposition temperatures, the direct determination of the critical temperatures of ILs is not feasible. Rebelo et al. [1] proposed the use of the Eötvös [86] and Guggenheim [87] equations to estimate the hypothetical critical temperature of ILs, as described below,

$$\gamma \left(\frac{M}{P}\right)^{2/3} = K_{\text{Eot}}(T_c - T) \quad (13)$$

$$\gamma = K_{\text{Gug}} \left(1 - \frac{T}{T_c}\right)^{11/9} \quad (14)$$

where T_c is the critical temperature, M the molecular weight, ρ the density, and K_{Eot} and K_{Gug} are fitted parameters. T_c , K_{Eot} and K_{Gug} were determined by fitting Eqs. (13) and (14) to the experimental data. Both equations are based on the fact that the surface tension becomes null at the critical point and although an overestimation of the critical temperature is expected, since at the critical point the pressure becomes the critical pressure, these equations provide reasonable estimations [85,88]. The critical temperature values estimated from the surface tension data are summarized in Table 4. In agreement with the results obtained for other phosphonium-based ILs studied in a previous work [72] the compounds here reported also present significantly lower critical temperatures than imidazolium-, pyridinium-, piperidinium- or pyrrolidinium-based ILs [41,43,84].

4. Conclusions

Experimental data on density, viscosity, refractive index, and surface tension for four phosphonium-based ionic liquids were measured in the temperature range between (283.15 and 353.15) K

and at atmospheric pressure. Additionally, derivative properties, such as the isobaric thermal expansion coefficient, the surface thermodynamic properties and the critical temperatures for the investigated ionic liquids were also estimated and discussed.

In general, for a common anion the density decreases with the increase of the aliphatic moieties. The anion, nonetheless, imposes a greater effect on the IL density, with the anion molecular weight increase, and consequently the overall size and charge dispersion increase, leading to an increase on density. Moreover, the alkyl side chain increase presents a smaller impact on the thermal expansion coefficient than that observed for the anion replacement.

Similar to that observed previously for imidazolium- and piridinium-based ILs, the π - π interactions due to the presence of an aromatic ring ($[P_{i(444)}]_1[To]_1$) leads to higher resistance to shear stress, to a more rigid IL structure and therefore to a bulkier distribution and higher viscosities.

The investigated ILs present low surface enthalpy and entropies when compared with molecular organic compounds. These values reflect a high surface organization, as well as an inherent highly structured liquid phase. Furthermore, the low surface entropies are an indication of a high surface organization as well as a highly structured liquid phase.

The group contribution methods proposed by Gardas and Coutinho for density, viscosity and refractive index were evaluated and fitted to the experimental data, allowing to propose new parameters for the cations and/or anions investigated in this work.

Acknowledgements

This work was developed in the scope of the project CICECO-Aveiro Institute of Materials (Ref. FCT UID /CTM /50011/2013), financed by national funds through the FCT/MEC and when applicable co-financed by FEDER under the PT2020 Partnership Agreement. P.J.C. and A.B. also acknowledge FCT for their post-doctoral grants SFRH/BPD/82264/2011 and SFRH/BPD/77858/2011, respectively. M.G. Freire acknowledges the European Research Council (ERC) for the Starting Grant ERC-2013-StG-337753. The authors also acknowledge CYTEC Industries Inc. for kindly supplying the ionic liquids investigated in this work.

References

- [1] L.P.N. Rebelo, J.N. Canongia Lopes, J.M.S.S. Esperança, E. Filipe, J. Phys. Chem. B 109 (2005) 6040–6043.
- [2] K.R. Seddon, J. Chem. Technol. Biotechnol. 68 (1997) 351–356.
- [3] M. Smiglak, W.M. Reichert, J.D. Holbrey, J.S. Wilkes, L. Sun, J.S. Thrasher, K. Kirichenko, S. Singh, A.R. Katritzky, R.D. Rogers, Chem. Commun. (Camb.) (2006) 2554–2556.
- [4] K.J. Baranyai, G.B. Deacon, D.R. MacFarlane, J.M. Pringle, J.L. Scott, Aust. J. Chem. 57 (2004) 145–147.
- [5] K. Matsumoto, R. Hagiwara, Y. Ito, Electrochem. Solid-State Lett. 7 (2004) L3.
- [6] K.N. Marsh, J.A. Boxall, R. Lichtenthaler, Fluid Phase Equilib. 219 (2004) 93–98.
- [7] M.J. Earle, J.M.S.S. Esperança, M.A. Gilea, J.N. Canongia Lopes, L.P.N. Rebelo, J.W. Magee, K.R. Seddon, J.A. Widegren, Nature 439 (2006) 831–834.
- [8] P. Wasserscheid, W. Keim, Angew. Chem. Int. Ed. Engl. 39 (2000) 3772–3789.
- [9] M.J. Earle, K.R. Seddon, Pure Appl. Chem. 72 (2000) 1391–1398.
- [10] R.D. Rogers, K.R. Seddon, Science 302 (2003) 792–793.
- [11] J.F. Wishart, Energy Environ. Sci. 2 (2009) 956–961.
- [12] D.R. MacFarlane, K.R. Seddon, Aust. J. Chem. 60 (1) (2006) 3–5.
- [13] R.D. Rogers, K.R. Seddon, Ionic Liquids IIb: Fundamentals, Progress, Challenges, and Opportunities; Transformations and Processes, American Chemical Society, 2005.
- [14] C.J. Bradaric, A. Downard, C. Kennedy, A.J. Robertson, Y. Zhou, Green Chem. 5 (2002) 143–152.
- [15] R.E. Del Sesto, C. Corley, A. Robertson, J.S. Wilkes, J. Organomet. Chem. 690 (2005) 2536–2542.
- [16] F. Atefi, M.T. Garcia, R.D. Singer, P.J. Scammells, Green Chem. 11 (2009) 1595.
- [17] G. Adamová, R.L. Gardas, M. Nieuwenhuizen, A.V. Puga, L.P.N. Rebelo, A.J. Robertson, K.R. Seddon, Dalton Trans. 41 (2012) 8316.
- [18] M.S. Altuwaim, K.H.A.E. Alkhalidi, A.S. Al-Jimaz, A.A. Mohammad, J. Chem. Eng. Data 59 (2014) 1955–1963.
- [19] K.J. Fraser, D.R. MacFarlane, Aust. J. Chem. 62 (2009) 309.
- [20] F.J. Deive, M.A. Rivas, A. Rodríguez, J. Chem. Thermodyn. 62 (2013) 98–103.
- [21] J.M.S.S. Esperança, H.J.R. Guedes, M. Blesic, L.P.N. Rebelo, J. Chem. Eng. Data 51 (2006) 237–242.
- [22] E. Frackowiak, G. Lota, J. Pernak, Appl. Phys. Lett. 86 (2005) 1–3.
- [23] K. Tsunashima, M. Sugiya, Electrochem. Commun. 9 (2007) 2353–2358.
- [24] L.I.N. Tome, R.L. Gardas, P.J. Carvalho, M.J. Pastoriza-Gallego, M.M. Piñeiro, J.A. P. Coutinho, J. Chem. Eng. Data 56 (2011) 2205–2217.
- [25] C.L.S. Louros, A.F.M. Cláudio, C.M.S.S. Neves, M.G. Freire, I.M. Marrucho, J. Pauly, J.A.P. Coutinho, Int. J. Mol. Sci. 11 (2010) 1777–1791.
- [26] R.J. Cornmell, C.L. Winder, S. Schuler, R. Goodacre, G. Stephens, Green Chem. 10 (2008) 685.
- [27] C.M.S.S. Neves, J.F.O. Granjo, M.G. Freire, A. Robertson, N.M.C. Oliveira, J.A.P. Coutinho, Green Chem. 13 (2011) 1517–1526.
- [28] P.J. Carvalho, I. Khan, A. Morais, J.F.O. Granjo, N.M.C. Oliveira, L.M.N.B.F. Santos, J.A.P. Coutinho, Fluid Phase Equilib. 354 (2013) 156–165.
- [29] Y. Liu, L. Guo, L. Zhu, X. Sun, J. Chen, Chem. Eng. J. 158 (2010) 108–114.
- [30] A. Stojanovic, D. Kogelnig, L. Fischer, S. Hann, M. Galanski, M. Groessl, R. Krachler, B.K. Keppler, Aust. J. Chem. 63 (2010) 511–524.
- [31] P.J. Carvalho, V.H. Álvarez, I.M. Marrucho, M. Aznar, J.A.P. Coutinho, J. Supercrit. Fluids 52 (2010) 258–265.
- [32] S.P.M. Ventura, J. Pauly, J.L. Daridon, J.A. Lopes da Silva, I.M. Marrucho, A.M.A. Dias, J.A.P. Coutinho, J. Chem. Thermodyn. 40 (2008) 1187–1192.
- [33] P.K. Kilaru, P. Scovazzo, Ind. Eng. Chem. Res. 47 (2008) 910–919.
- [34] R.L. Gardas, J.A.P. Coutinho, Fluid Phase Equilib. 263 (2008) 26–32.
- [35] R.L. Gardas, J.A.P. Coutinho, AIChE J. 55 (2009) 1274–1290.
- [36] J. Jacquemin, P. Husson, A.A.H. Padua, V. Majer, Green Chem. 8 (2006) 172.
- [37] E.P. Grishina, L.M. Ramenskaya, M.S. Gruzdev, O.V. Kraeva, J. Mol. Liq. 177 (2013) 267–272.
- [38] P.J. Carvalho, T. Regueira, L.M.N.B.F. Santos, J. Fernandez, J.A.P. Coutinho, J. Chem. Eng. Data 55 (2010) 645–652.
- [39] C.M.S.S. Neves, K.A. Kurnia, J.A.P. Coutinho, I.M. Marrucho, J.N.C. Lopes, M.G. Freire, L.P.N. Rebelo, J. Phys. Chem. B 117 (2013) 10271–10283.
- [40] H.F.D. Almeida, H. Passos, J.A. Lopes-da-Silva, A.M. Fernandes, M.G. Freire, J.A.P. Coutinho, J. Chem. Eng. Data 57 (2012) 3005–3013.
- [41] A. Bhattacharjee, P.J. Carvalho, J.A.P. Coutinho, Fluid Phase Equilib. 375 (2014) 80–88.
- [42] A. Bhattacharjee, A. Luís, J.H. Santos, J.A. Lopes-da-silva, M.G. Freire, P.J. Carvalho, J.A.P. Coutinho, Fluid Phase Equilib. 381 (2014) 36–45.
- [43] H.F.D. Almeida, A.R.R. Teles, J.A. Lopes-Da-Silva, M.G. Freire, J.A.P. Coutinho, J. Chem. Thermodyn. 54 (2012) 49–54.
- [44] R.L. Gardas, H.F. Costa, M.G. Freire, P.J. Carvalho, I.M. Marrucho, I.M.A. Fonseca, A.G.M. Ferreira, J.A.P. Coutinho, J. Chem. Eng. Data 53 (2008) 805–811.
- [45] R.L. Gardas, M.G. Freire, P.J. Carvalho, I.M. Marrucho, I.M.A. Fonseca, A.G.M. Ferreira, J.A.P. Coutinho, J. Chem. Eng. Data 52 (2007) 1881–1888.
- [46] M.G. Freire, A.R.R. Teles, M.A.A. Rocha, C.M.S.S. Neves, P.J. Carvalho, D.V. Evtuguin, L.M.N.B.F. Santos, J.A.P. Coutinho, B. Schröder, J. Chem. Eng. Data 56 (2011) 4813–4822.
- [47] L.E. Ficke, R.R. Novak, J.F. Brennecke, J. Chem. Eng. Data 55 (2010) 4946–4950.
- [48] P. Kilaru, G.A. Baker, P. Scovazzo, J. Chem. Eng. Data 52 (2007) 2306–2314.
- [49] J.W. Vaughan, D. Dreisinger, J. Haggins, ECS Trans. 2 (2006) 381–392.
- [50] J.L. Anthony, J.L. Anderson, E.J. Maginn, J.F. Brennecke, J. Phys. Chem. B 109 (2005) 6366–6374.
- [51] U. Domańska, K. Paduszyński, J. Chem. Thermodyn. 42 (2010) 707–711.
- [52] D. Matkowska, T. Hofman, J. Mol. Liq. 165 (2012) 161–167.
- [53] A.N. Soriano, B.T. Doma, M.-H. Li, J. Chem. Thermodyn. 41 (2009) 301–307.
- [54] A.B. Pereiro, P. Verdía, E. Tojo, A. Rodríguez, J. Chem. Eng. Data 52 (2007) 377–380.
- [55] T. Singh, A. Kumar, J. Solution Chem. 38 (2009) 1043–1053.
- [56] A.A. Miran Beigi, M. Abdouss, M. Yousefi, S.M. Pourmortazavi, A. Vahid, J. Mol. Liq. 177 (2013) 361–368.
- [57] A.J.L. Costa, J.M.S.S. Esperança, I.M. Marrucho, L.P.N. Rebelo, J. Chem. Eng. Data 56 (2011) 3433–3441.
- [58] L.I.N. Tome, P.J. Carvalho, M.G. Freire, I.M. Marrucho, I.M.A. Fonseca, A.G.M. Ferreira, J.A.P. Coutinho, R.L. Gardas, J. Chem. Eng. Data 53 (2008) 1914–1921.
- [59] D. Matkowska, T. Hofman, J. Mol. Liq. 177 (2013) 301–305.
- [60] J.Y. Wang, F.Y. Zhao, R.J. Liu, Y.Q. Hu, J. Chem. Thermodyn. 43 (2011) 47–50.
- [61] J. Palgunadi, J.E. Kang, D.Q. Nguyen, J.H. Kim, B.K. Min, S.D. Lee, H.S.H. Kim, Thermochim. Acta 494 (2009) 94–98.
- [62] A. Fernández, J. García, J.S. Torrecilla, M. Oliet, F. Rodríguez, J. Chem. Eng. Data 53 (2008) 1518–1522.
- [63] C. Ye, J.M. Shreeve, J. Phys. Chem. A 111 (2007) 1456–1461.
- [64] J.Y. Wang, F.Y. Zhao, Y.M. Liu, X.L. Wang, Y.Q. Hu, Fluid Phase Equilib. 305 (2011) 114–120.
- [65] Z. Gu, J.F. Brennecke, J. Chem. Eng. Data 47 (2002) 339–345.
- [66] A.B. Pereiro, F.J. Deive, J.M.S.S. Esperança, A. Rodríguez, Fluid Phase Equilib. 294 (2010) 49–53.
- [67] K. Machanová, A. Boisset, Z. Sedláková, M. Anouti, M. Bendová, J. Jacquemin, J. Chem. Eng. Data 57 (2012) 2227–2235.
- [68] J. Jacquemin, P. Husson, V. Mayer, I. Cibulka, J. Chem. Eng. Data 52 (2007) 2204–2211.
- [69] J. Jacquemin, P. Husson, V. Majer, A.A.H. Padua, M.F.C. Gomes, Green Chem. 10 (2008) 944–950.
- [70] L. Ferguson, P. Scovazzo, Ind. Eng. Chem. Res. 46 (2007) 1369–1374.
- [71] M.D. Green, C. Schreiner, T.E. Long, J. Phys. Chem. A 115 (2011) 13829–13835.
- [72] H.F.D. Almeida, J.A. Lopes-Da-Silva, M.G. Freire, J.A.P. Coutinho, J. Chem. Thermodyn. 57 (2013) 372–379.

- [73] J.N. Israelachvili, *Intermolecular and Surface Forces*, University, Academic Press, San Diego, 2011.
- [74] E.F. May, *Measurement of the Thermodynamic Properties of Single Phases*. IUPAC Experimental Thermodynamics, vol. VI, Elsevier, Amsterdam, 2003.
- [75] P. Brocos, Á. Piñeiro, R. Bravo, A. Amigo, *Phys. Chem. Chem. Phys.* 5 (2003) 550–557.
- [76] S. Seki, S. Tsuzuki, K. Hayamizu, Y. Umebayashi, N. Serizawa, K. Takei, H. Miyashiro, *J. Chem. Eng. Data* 57 (2012) 2211–2216.
- [77] P.J. Carvalho, S.P.M. Ventura, M.L.S. Batista, B. Schröder, F. Gonçalves, J. Esperança, F. Mutelet, J.A.P. Coutinho, *J. Chem. Phys.* 140 (2014) 64505.
- [78] P.J. Carvalho, M.G. Freire, I.M. Marrucho, A.J. Queimada, J.A.P. Coutinho, *J. Chem. Eng. Data* 53 (2008) 1346–1350.
- [79] M.G. Freire, P.J. Carvalho, A.M. Fernandes, I.M. Marrucho, A.J. Queimada, J.A.P. Coutinho, *J. Colloid Interface Sci.* 314 (2007) 621–630.
- [80] C.S. Santos, S. Baldelli, *Chem. Soc. Rev.* 39 (2010) 2136–2145.
- [81] A.W. Adamson, A.P. Gast, *Physical Chemistry of Surfaces*, 6th ed., John Wiley, 1997.
- [82] A.D. McNaught, A. Wilkinson, *Compendium of Chemical Terminology*, IUPAC Recommendations, 2nd ed., Blackwell Science, Cambridge, UK, 1997.
- [83] J.C. Miller, J.N. Miller, *Statistics for Analytical Chemistry*, 3rd ed., PTR Prentice Hall, Chichester, 1993.
- [84] P.J. Carvalho, C.M.S.S. Neves, J.A.P. Coutinho, *J. Chem. Eng. Data* 55 (2010) 3807–3812.
- [85] B.E. Poling, J.M. Prausnitz, J.P. O'Connell, *The Properties of Gases And Liquids*, 5th ed., McGraw-Hill, New York, 2001.
- [86] J.L. Shereshefsky, *J. Phys. Chem.* 35 (1931) 1712–1720.
- [87] E.A. Guggenheim, *J. Chem. Phys.* 13 (1945) 253–261.
- [88] K.S. Birdi, *Handbook of Surface and Colloid Chemistry*, 1st ed., CRC Press, 1997.