Dicationic disiloxane liquids

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1. Introduction

Polar ionic liquids with very low volatility, low viscosity and wide operating temperature range are used in various fields of science and technology. Ionic liquids are used as polar solvents in organic synthesis [1,2], in the synthesis of metal nanoparticles [3], in electrochemistry [4,5] as electrolytes in lithium and solar batteries, in separation processes as liquid phases in capillary columns gas-liquid chromatography [6] and as extracting agents [7]. New application areas for ionic liquids are constantly emerging. The possibilities of their application as depolymerizing reagents in the processing of plastic waste [8,9], as the media for storing carbon dioxide [10], drying agents for industrial gases [11,12] and air conditioning systems [13,14] are also investigated. Ionic liquids can be used as working fluids in compressors to compress oxygen [15]. There are works on the use of ionic liquids as high-energy matrices [16]. In recent years, many papers have been published on the possibility of using ionic liquids as heat transfer fluids for heat transport in solar panels [17,18] and refrigeration plants [18-20]. There are some works on the estimation of possibility of use of ILs as heat transfer agents under conditions of dynamic vacuum [21-23].

The ionic interactions in ILs causes their low volatility and contribute to an increase in viscosity. The presence in the structure of an IL of polar groups and other heteroatoms generally reduces their thermal stability. To obtain an IL with low volatility, low viscosity and high thermal stability it is necessary to solve the optimization problem on the interrelated three parameters "viscosity-volatility-thermal stability". Generally, the most thermally stable ILs are imidazolium liquids with bis(trifluoromethylsulfonyl)imide anion (Tf$_2$N$^-$$^-$). This anion also allows obtaining ILs with low viscosities. Monocationic imidazolium ionic liquids with Tf$_2$N$^-$ anion, without polar substituents in the cation structure, are characterized by a volatility value of 20-30 mg/h · cm$^2$ in a vacuum of ~0.013 Pa [24]. The presence in the cation structure of hydroxyl groups capable of participating in intermolecular interactions leads to a decrease
in the volatility of ILs to ~10 mg/h·cm², but significantly increases their viscosity [24]. Introduction of a second ion pair into an IL structure (dicationic ILs) significantly reduces its volatility (up to ~0.1 mg/h·cm²), but often leads to an increase in the melting point of the IL above room temperature and/or to a significant increase in viscosity [25,26]. The rotational energy barriers of Si-O and C-C bonds are 0.8 and 11.3 kJ/mol, respectively, and ones for Si-CH₃ and C-CH₃ bonds are 6.7 and 15.1 kJ/mol [27,28]. Use of siloxane structural fragments characterized by greater mobility as a linker in dicationic ILs will lead to a decrease in the viscosity and the tendency to crystallization of the ILs [29,30]. The aim of this work is the synthesis of room-temperature dicationic imidazolium ionic liquids (RTDIL) with disiloxane linker with low viscosity, low volatility and high thermal stability.

2. Experimental

2.1. Materials and methods

The melting points and glass transition temperatures of ILs were determined via differential scanning calorimetry (DSC) using a DSC-822e instrument (Mettler-Toledo, Switzerland). The measurements were performed in the temperature range from −100 to 100°C at a sample heating rate of 10°C/min in an argon atmosphere. Thermogravimetric analysis was performed on a Derivatograph-C instrument (MOM, Hungary) in an argon atmosphere at a heating rate of 10°C/min (sample mass,~20 mg). Kinematic viscosity was measured using an Ostwald viscometer. The viscometer was calibrated at 25°C using ethylene glycol (Aldrich, 99.8%, water content < 0.01%) as the reference liquid. The viscosity of ethylene glycol was also checked against bidistilled water in another viscometer. The evaporation of ILs in vacuum was studied using a McBain quartz spring balance. Each sample (~0.2 g) was placed in a ceramic cup attached to the movable end of the spring of the balance. The surface area of the liquid layer was about 1.7 cm². The tube casings of the spirals with samples were placed in a thermostatted aluminum block. Spring elongation was determined from the change in the positions of reference marks using a KM-8 cathetometer with an accuracy of ±0.02 mm. The spring had a sensitivity of 0.3709 mm/mg. The setup was evacuated with a diffusion pump. Before measurements the samples were dried to constant weight (for ~15 h) in vacuum ~0.013 Pa at 100°C. ¹H and ¹³C NMR spectra were recorded on a Bruker AM300 spectrometer (300.13 and 75.47 MHz, respectively) in DMSO-d₆. IR ATR spectra were measured on a Nicolet iS50 IR spectrometer (built-in ATR attachment, with diamond crystal) with resolution of 4 cm⁻¹.

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\text{Scheme 1. Synthesis of disiloxane dicationic IL 1-7.}
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Dimethyl(chloromethyl)chlorosilane (98%), dimethyl(3-chloropropyl)chlorosilane (97%) and diethyl(chloromethyl)chlorosilane (97%) were purchased from ABCR. 1-Methylimidazole (99%), 1,2-dimethylimidazole (98%), 1-(2-methoxyethyl)-2-methylimidazole (97%), lithium bis(trifluoromethylsulfonyl)imide (99%) were purchased from Acros and Sigma-Aldrich. Before addition of chloroalkylsiloxanes, the solutions of imidazoles were dried by azeotropic distillation of acetonitrile. All organic solvents used in the synthesis were previously dried over CaH₂ and distilled.

2.2. Methods for the synthesis of ionic liquids.

Synthesis of the ionic liquids was carried out in three stages [23,31]. At the first step, a disiloxane linker with chloralkyl end groups was obtained by hydrolytic condensation of the corresponding chlorosilane in water. At the second stage, alkylimidazole was quaternized with equimolar amount of siloxane linker in acetonitrile, and in the third stage Cl⁻ anion was exchanged for Tf₂N⁻ anion with lithium bis(trifluoromethylsulfonyl)imide (10% excess) in acetonitrile (Scheme 1). Lithium salts were removed by washing with water.

2.2.1. 1,1,3,3-Tetramethyl-1,3-di[1,2-dimethylimidazolium-3-yl]methyl)disiloxane bis(trifluoromethylsulfonyl)imide (1):

First stage of the synthesis (Scheme 1).

Dimethyl(chloromethyl)chlorosilane (100 mL, 108.6 g) was added dropwise to 300 mL of distilled water with stirring on a magnetic stirrer. Then the reaction mixture was stirred for 1 hour, followed by addition of 200 mL of hexane. The acidic water layer was removed, and the organic layer was washed with water until neutral pH. Hexane was removed by distillation, and then in vacuum at room temperature. Yield of 1,1,3,3-tetramethyl-1,3-di(chloromethyl)disiloxane was 85.6 g (97.5 %).

Second stage of the synthesis.

1,1,3,3-Tetramethyl-1,3-di(chloromethyl)disiloxane (3.15 g, 0.0136 mol) was added to a solution of 2.61 g (0.0272 mol) of 1,2-dimethylimidazole in 6 mL of acetonitrile under argon atmosphere. The reaction mixture was stirred at reflux temperature for 72 hours. After cooling, the product was collected by filtration and dried in a vacuum. Yield 5.07 g, 88 %.

Third stage of the synthesis.
To 5 g (0.0118 mol) of chloride salt a solution of 7.45 g (0.0260 mol) of lithium bis(trifluoromethylsulfonyl)imide (LiNTf₂) in 15 mL of acetonitrile was added under argon atmosphere. The reaction mixture was stirred at room temperature for 3 hours. The precipitate of lithium chloride was filtered off, acetonitrile was removed from the filtrate by rotary evaporation, and the residue was dissolved in 50 mL of dichloromethane. The solution was repeatedly washed with water to remove lithium chloride until no chloride can be detected in wash waters with silver nitrate. The target ionic liquid was dried by azeotropic distillation of dry dichloromethane. Tf₂N-IL 1 was obtained with yield of 10.02 g (93%). ¹H NMR (DMSO-d₆, 300.13 MHz), δ, ppm: 0.16, s (12H, CH₃-Si), 2.52, s (6H, CH₃-C), 3.75, s (6H, CH₃-N), 3.82, s (4H, CH₂-N), 7.41, m (2H, CH=), 7.62, m (2H, CH =). ¹³C NMR (DMSO-d₆, 75.47 MHz), δ, ppm: 0.48, 9.74, 35.26, 40.21, 113.45, 11.70, 121.83, 122, 07, 122.81, 126.37, 143.97. Gross formula: C₂₀H₃₂N₆O₉F₁₂S₄Si₂, molecular weight: 912.92. Calculated, %: C 26.31, H 3.53, N 9.21, F 24.97, S 14.05, Si 6.15. Found, %: C 26.23, H 3.63, N 9.16, F 24.94, S 13.91, Si 6.26.

2.2.2. 1,1,3,3-Tetraethyl-1,3-bis{[1,2-dimethylimidazolium-3-yl]methyl}disiloxane bis(trifluoromethylsulfonyl)imide (2):

IL 2 was synthesized a method similar to the method of obtaining IL 1. Yield 90%. ¹H NMR (DMSO-d₆, 300.13 MHz), δ, ppm: 0.63 m (8H, CH₂CH₃), 0.86 m (12H, CH₂CH₃), 2.53 s (6H, C-CH₃), 3.74 s (6H, N-CH₃), 3.87 m (4H, N-CH₂), 7.38 m (2H, =CH), 7.62 m (2H, =CH). ¹³C NMR (DMSO-d₆, 75.47 MHz), δ, ppm: 5.54, 6.25, 9.68, 35.25, 37.80, 113.60, 117.80, 121.90, 121.96, 122.94, 126.40, 144.04. Gross formula: C₂₀H₄₀N₁₀O₁₂F₂₄S₄Si₂, molecular weight: 969.03. Calculated, %: C 30.69, H 4.16, N 8.67, F 23.53, S 13.23, Si 5.80. Found, %: C 29.71, H 4.22, N 8.63, F 23.51, S 13.27, Si 5.85.

2.2.3. 1,1,3,3-Tetramethyl-1,3-bis{3-[1,2-dimethylimidazolium-3-yl]propyl}disiloxane bis(trifluoromethylsulfonyl)imide (3):

IL 3 was synthesized a method similar to the method of obtaining IL 1. Yield 95%. ¹H NMR spectrum (DMSO-d₆, 300.13 MHz), δ, ppm: 0.04, s (12H, CH₃-Si), 0.49, m (4H, CH₂CH₂CH₂Si), 1.67, m (4H, CH₂CH₂CH₂Si), 2.55, s (6H, CH₃-C), 3.74, s (6H, CH₂-N), 4.06, m (4H, NCH₂CH₂CH₂Si), 7.61, m (4H, CH=). ¹³C NMR spectrum (DMSO-d₆, 75.47 MHz), δ, ppm: 0.33, 9.43, 13.50, 23.90, 34.97, 50.51, 113.52, 117.79, 121.16, 122.05, 122.70, 126.32, 144.54. Gross formula: C₂₄H₄₀F₁₂N₁₀O₁₂S₄Si₂, molecular weight: 969.03. Calculated, %: C 29.75, H 4.16, N 8.67, F 23.53, S 13.23, Si 5.80. Found, %: C 29.66, H 4.27, N 8.60, F 23.50, S 13.19, Si 5.87.

2.2.4. 1,1,3,3-tetramethyl-1-([1,2-dimethylimidazolium]-methyl)-3-[3-[1,2-dimethylimidazolium-3-yl]propyl]disiloxane bis(trifluoromethylsulfonyl)imide (4):

IL 4 was synthesized a method similar to the method described for IL 1. Yield 89%. ¹H NMR (DMSO-d₆, 300.13 MHz), δ, ppm: 0.05, s (6H, CH₃-Si), 0.17, s (6H, CH₃-Si), 0.49, m (2H, CH₂CH₂CH₂Si), 1.67, m (2H, CH₂CH₂CH₂Si), 2.53, s (3H, CH₃-C), 2.58, s (3H, CH₃-C), 3.76, s (6H, CH₃-N), 3.80, s (2H, CH₂-N), 4.07, m (2H, NCH₂CH₂CH₂Si), 7.41, m (1H, CH=), 7.62, m (3H, CH=). ¹³C NMR (DMSO-d₆, 75.47 MHz), δ, ppm: -0.51, 0.09, 9.45, 9.61, 14.31, 23.75, 34.99, 35.13, 40.45, 50.58, 113.55, 117.81, 121.18, 121.81, 122.08, 122.64, 122.74, 126.34, 143.86, 144.58. Gross formula: C₂₂H₃₆N₆O₁₆F₁₂S₄Si₂, molecular weight: 940.98. Calculated, %: C 28.08, H 3.86, N 8.93, F 24.23, S 13.63, Si 5.97. Found, %: C 27.96, H 3.91, N 8.85, F 24.43, S 13.33, Si 6.04.
2.2.5. 1,1,3,3-Tetramethyl-1,3-bis(1-methylimidazolium-3-yl)methyl)disiloxane bis(trifluoromethylsulfonyl)imide (5):

IL 5 was synthesized by a method similar to the method described for IL 1. Yield 88%. $^1$H NMR (DMSO-d$_6$, 300.13 MHz), δ, ppm: 0.16 s (12H, CH$_3$-Si), 3.87 s (6H, CH$_3$-N), 3.89 s (4H, CH$_2$-N), 7.52 m (2H, =CH), 7.69 m (2H, =CH), 8.90 s (2H, NCHN), $^{13}$C NMR (DMSO-d$_6$, 75.47 MHz), δ, ppm: 0.96, 36.16, 41.37, 113.42, 117.81, 122.07, 123.54, 124.15, 126.31, 136.25. Gross formula: C$_{16}$H$_{28}$N$_6$O$_9$F$_{12}$S$_6$Si$_2$, molecular weight: 884.87. Calculated, %: C 24.43, H 3.20, N 9.50, F 25.77, S 14.49, Si 6.45.

2.2.6. 1,1,3,3-Tetramethyl-1,3-bis(3-[1-methylimidazolium-3-yl]propyl)disiloxane bis(trifluoromethylsulfonyl)imide (6):

IL 6 was synthesized by a method similar to the method described for IL 1. Yield 96%. $^1$H NMR (DMSO-d$_6$, 300.13 MHz), δ, ppm: 0.06, s (12H, CH$_3$-Si), 0.45, m (4H, CH$_2$CH$_2$CH$_2$Si), 1.78, m (4H, CH$_3$CH$_2$CH$_3$Si), 3.86, s (6H, CH$_3$-N), 4.13, m (4H, NCH$_3$CH$_2$CH$_3$Si), 7.69, m (4CH=), 7.73, (4CH=), 9.08, s (2H, NCHN). $^{13}$C NMR ((DMSO-d$_6$, 75.47 MHz), δ, ppm: 0.47, 14.53, 24.27, 36.13, 51.88, 113.54, 117.80, 122.07, 122.59, 124.05, 126.33, 136.94. Gross formula: C$_{22}$H$_{36}$F$_{12}$N$_6$O$_9$S$_6$Si$_2$, molecular weight: 940.98. Calculated, %: C 28.08, H 3.86, N 8.93, F 24.23, S 13.63, Si 5.97. Found, % C 27.99, H 3.95, N 8.90, F 24.20, S 13.51, Si 6.07.

2.2.7. 1,1,3,3-Tetramethyl-1,3-bis(3-[1-(2-methoxyethyl)-2-methylimidazolium-3-yl]propyl)disiloxane bis(trifluoromethylsulfonyl)imide (7):

IL 7 was synthesized by a method similar to the method described for IL 1. Yield 94%. $^1$H NMR (DMSO-d$_6$, 300.13 MHz), δ, ppm: 0.05, s (12H, CH$_3$-Si), 0.49, m (4H, CH$_2$CH$_2$CH$_2$Si), 1.71, m (4H, CH$_2$CH$_2$CH$_3$Si), 2.61, s (6H, CH$_3$-C), 3.25, s (6H, CH$_3$-N), 3.66, m (4H, CH$_2$-O), 4.09, m (4H, NCH$_3$CH$_2$CH$_3$Si), 4.32, m (4H, CH$_2$-N), 7.65, m (4H, CH=). $^{13}$C NMR (DMSO-d$_6$, 75.47 MHz), δ, ppm: 0.42, 9.76, 14.51, 23.85, 47.91, 50.51, 58.59, 70.29, 113.55, 117.81, 121.55, 122.08, 126.34, 144.70. Gross formula: C$_{25}$H$_{48}$F$_{12}$N$_6$O$_{11}$S$_6$Si$_2$, molecular weight: 1057.14. Calculated, %: C 31.81, H 4.58, N 7.95, F 21.57, S 12.13, Si 5.31. Found, %: C 28.67, H 4.66, N 7.88, F 21.62, S 12.02, Si 5.40.

3. Results and Discussion

3.1. Aggregate state of IL at RT

IL 1 (Table 1) obtained from 1,2-dimethylimidazole, despite the presence of a bulky fluorine-containing Tf$_2$N-anion, is a solid with $T_m = 69$°C. At the first stage of the study, an attempt was made to reduce $T_m$ by introducing more bulky substituents at the silicon atom of the linker, i.e., to increase the steric effect. Replacement methyl for ethyl substituents at the silicon atom (IL 2, Table 1) changes the melting point by only 1°C, and the replacement of the methylene spacer between imidazole and the silicon atom with propylene (IL 3) reduces the $T_m$ by 10° (Table 1). From the obtained data it is concluded that the increase in the steric effect with an increase in the size of substituents in the silicon atom in the linker has a weak effect on the crystallization ability of IL. Thus, increasing the steric effect in the linker and using an asymmetric linker does not result in RTDIL.
Table 1. Melting point/glass transition temperature, decomposition temperature and volatility of disiloxane ILs.

| № IL | Structure of IL (Scheme 1) | $T_m$, °C | $T_d$, °C | Volatility, mg/h cm$^2$ * in vacuo *~0.013 Pa at 150°C/190°C/220°C |
|------|--------------------------|---------|----------|-------------------------------------------------------------------|
| 1    | $R_1=R_2=R_3=\text{Me}, n=m=1$ | 69      | 437      | 0.00/0.03/0.04                                                   |
| 2    | $R_1=\text{Et}, R_2=R_3=\text{Me}, n=m=1$ | 68      | 432      | 0.02/0.05/0.07                                                  |
| 3    | $R_1=R_2=R_3=\text{Me}, n=m=3$ | 59      | 419      | 0.01/0.02/0.17                                                   |
| 4    | $R_1=R_2=R_3=\text{Me}, n=1, m=3$ | 42      | 420      | 0.02/0.11/0.40                                                   |
| 5    | $R_1=R_2=\text{Me}, R_3=\text{H}, n=m=1$ | -52*    | 435      | 0.02/0.08/0.22                                                  |
| 6    | $R_1=R_2=\text{Me}, R_3=\text{H}, n=m=3$ | -58*    | 402      | 0.03/0.33/0.95                                                  |
| 7    | $R_1=R_3=\text{Me}, n=m=3, R_2=\text{CH}_2\text{CH}_2\text{OCH}_3$ | -48*    | 416      | 0.02/0.22/0.94                                                  |

*It is known that the presence of polar groups in the cation reduces the tendency of IL to crystallization [24]. The use of 1-methylimidazole having a rather mobile hydrogen atom in the position 2, instead of 1,2-dimethylimidazole, results in ILs 5 and 6, which are liquid at room temperature (RTDIL). The absence of crystallization for ILs 5 and 6 ($T_g = -52$ and -58°C, respectively, table 1) is explained by the interaction of the mobile hydrogen atom in imidazole and $\text{Tf}_2\text{N}$-anion, which prevents the crystallization of an IL [33]. The introduction of an oxygen-containing polar substituent - 2-methoxyethyl group into the imidazole cation also prevents the crystallization of IL 7 ($T_g = -48°C$, table 1). However, the use of hydroxyl substituents in the cation (in particular, 2-hydroxyethyl groups) leads to protolysis of the linker with methylene spacer during quaternization reaction [31].

Thus, the presence of polar groups in the cation, capable of additional intermolecular interaction with the formation of hydrogen bonds, prevents the crystallization of dicationic disiloxane liquids. It is interesting to assess the effect of such substituents on other properties of IL: thermal stability, viscosity and volatility.

*3.2. Thermal stability of ILs

The use of 1,2-dimethylimidazole moiety together with $\text{Tf}_2\text{N}$ anion are expected to provide high thermal stability of the resulting ILs. For IL 1-4, with different substituents at the silicon atom, the thermal destruction temperature ($T_d$) varies within 437-419°C. $T_d$ of an IL decreases when the length of the substituents at the silicon atom is increased, and the presence of a propyl group in the linker has a greater influence on thermal stability (Figure 1 and 2).
The presence of a mobile hydrogen atom in the position 2 of imidazole has an unusual effect on the thermal stability of ILs. Use of 1-methylimidazole instead of 1,2-dimethylimidazole in the synthesis of ILs with a methylene spacer (ILs 1 and 5, Fig.3) practically does not affect their thermal stability ($T_d$ 437 and 435°C, respectively), but an increase in the spacer length in such ionic liquids leads to a significant decrease in thermal stability – from 437 to 402°C (IL 1, 5 and 6, table.1, Fig. 3).

![Figure 3. TGA curve IL 1, 5 и 6.](image)

The presence of 2-methoxyethyl group in the cation changes the thermal stability of an IL to a much lesser extent – from 419 to 416°C (IL 3 and 7, table 1, Fig. 4), but the combined effect of spacer elongation and the presence of a polar group reduces the thermal stability of an IL by 21°C (ILs 1 and 7).

Thus, of the three RTDIL synthesized, only IL 5, obtained from 1-methylimidazole and having a methylene spacer, has almost the same thermal stability as IL 1. Elongation of the spacer in a disiloxane linker leads to a decrease in the thermal stability of the IL by 18°C. Combining a propyl spacer with an imidazole with unsubstituted position 2 causes a further decrease in thermal stability (IL 6).

![Figure 4. TGA curve IL 3, 5 и 7.](image)

Thus, of the three RTDIL synthesized, only IL 5, obtained from 1-methylimidazole and having a methylene spacer, has almost the same thermal stability as IL 1. Elongation of the spacer in a disiloxane linker leads to a decrease in the thermal stability of the IL by 18°C. Combining a propyl spacer with an imidazole with unsubstituted position 2 causes a further decrease in thermal stability (IL 6).

![Figure 5. Dependence of the kinematic viscosity of IL 5-7 on temperature.](image)
3.3. Viscosity of ILs
The kinematic viscosity values for RTDIL 5-7 are presented in Table 3. Ionic liquid 5 (Table 2), characterized by the highest T_d, has the lowest viscosity at 30°C among the obtained IL - 312 cSt. The increase in viscosity to 344 cSt for IL 6 is explained by the presence of a propyl spacer in its structure. The high viscosity value for IL 7 is most likely due to the additional intermolecular interactions of the oxygen-containing substituent in its cation.

The dependence of kinematic viscosity on temperature for ILs 5-7 (Fig. 5) is well approximated (R2>0.99) by the Vogel–Tamman–Fulcher (VTF) equation for melts [34]:

$$\ln\nu = \frac{a}{T-T_0} + b$$

The equation parameters are shown in Table 2.

| № IL | Viscosity, cSt (30°C) | Constants of the VTF equation |
|------|----------------------|-------------------------------|
| 5    | 312                  | a: 798, -b: 1.402, T_0: 191.5 |
| 6    | 344                  | a: 901.3, -b: 1.681, T_0: 183.3 |
| 7    | 555                  | a: 890.9, -b: 1.784, T_0: 193.3 |

3.4. Volatility of ILs
McBain quartz spring balance was used to measure the dynamic characteristics of volatility. Measurements were carried out at temperatures of 150, 190 and 220°C in vacuum of ~ 0.013 Pa. The synthesized dicationic ionic liquids practically do not evaporate at 150°C: the values of the mass loss rate of the IL samples are in the range of 0-0.03 mg/h·cm². When the temperature in the experiment increases to 190 and 220°C, the upper limits of the volatility range increase to 0.33 and 0.95 mg/h·cm², respectively.

4. Conclusions
In result of the above studies, dicationic imidazolium ionic liquids with disiloxane linkers were prepared. The steric effect of the substituents at the silicon atom practically does not affect the T_m of the ILs due to short length of the linker, and only the presence of polar groups in the cation structure significantly reduces the tendency of ILs to crystallization. Introducing polar groups into the cation leads to some decrease in thermal stability and a significant increase in the volatility of the resulting ILs in a vacuum.

5. References
[1] Zhao W, Sun J 2018 Chem Rev 118 10349–10392
[2] Itoh T 2017 Chem Rev 117 10567-10607
[3] Wegner S, Janiak C 2017 Top Curr Chem (Z) 375 65-72
[4] Azov V A, Egorova K S, Seitkalieva M M, Kashin A S, Ananikov V P 2018 Chem Soc Rev 47 1250—1284
[5] Watanabe M, Thomas M L, Zhang S, Ueno K, Yasuda T, Dokko K 2017 Chem Rev 1177190–7239
[6] Brown L, Earle M J, Gilea M A, Plechkova N V, Seddon K R 2017 Top Curr Chem (Z) 375 74-81
[7] Ventura S P M, e Silva F A, Quental M V, Mondal D, Freire M G, Coutinho J A P 2017 Chem Rev 117 6984–7052
[8] Kamimura A, Shiramatsu Y, Kawamoto T 2019 Green Energy & Environment 4 166–170
[9] Dutta T, Isern N G, Sun J, Wang E, Hull S, Cort J R, Simmons B A, Singh S 2017 ACS Sustainable Chem Eng 11 10116–10127
[10] Zeng S, Zhang X, Bai L, Zhang X, Wang H, Wang J, Bao D, Li M, Liu X, Zhang S 2017 Chem Rev 117 9625–9673
[11] Heym F, Haber J, Korth W, Etzold B J M, Jess A 2010 Chem Eng Technol 33 1625–1634
[12] Krannich M, Heym F, Jess A 2016 J Chem Eng Data 61 1162–1176
[13] Luo Y, Shao S, Qin F, Tian C, Yang H 2012 Solar Energy 86 2718–2724
[14] Watanabe H, Komura T, Matsumoto R, Ito K, Nakayama H, Nokami T, Itoh T 2019 Green Energy & Environment 4 139–145
[15] Predel T, Schlücker E 2009 Chem Eng Technol 32 1183–1188
[16] Zhang Q, Shreeve J M 2014 Chem Rev 114 10527–10574
[17] Van Valkenburg M, Vaughn R L, Williams M, Wilkes J S 2005 Thermochimica Acta 425, 181–188
[18] Paul T C, Morshed A K M M, Fox E B, Khan J A 2017 Appl Therm Eng 110 1–9
[19] Kühn A, Seiler M, Radspieler M, Kotenko O. Ionic liquids as new absorbents for absorption chillers and heat pumps. Chapter 6. Research on Working Pairs and Apparatus Technology in Book “Thermally driven heat pumps for heating and cooling”. Ed. A. Kühn – Berlin: Universitätverlag der TU Berlin, 2013, pp. 215-221
[20] Becker T M, Wang M, Kabra A, Jamali S H, Ramdin M, Dubbeldam D, Ferreira C A I, Vlugt T J H 2018 Ind Eng Chem Res 57 5442–5452
[21] Bondareva N V, Glukhov L M, Koroteev A A, Krasovskii V G, Kustov L M, Nagel’ Yu A, Safronov A A, Filatov N I, Chernikova E A, 2015 Izv Ross Akad Nauk Energ 4 130–142
[22] Chernikova E A, Glukhov L M, Krasovskiy V G, Kustov L M, Koroteev A A, 2014 Russ Chem Bull Int Ed 63 2702-2707
[23] Glukhov L M, Krasovskiy V G, Chernikova E A, Kapustin G I, Kustov L M, Koroteev A A. 2015 Russ J Phys Chem A 89 2204–2209
[24] Krasovskiy V G, Chernikova E A, Glukhov L M, Kapustin G I, Koroteev A A 2018 Russ J Phys Chem A 92 2379–2385
[25] Sun Y-X, Wang Y-Y, Shen B-B, Zhang B-X, Hu X-M S 2018 Royal Soc Open Sci 5 181230
[26] Mandai T, Imanari M, Nishikawa K 2012 Chem Phys Let 543 72–75
[27] Stark F O, Falendar J R, Wright A P. Comprehensive Organometallic Chemistry V2 Pergamon Press New York 1982 1020 p
[28] Liebau F. Structural Chemistry of Silicates: Structure, Bonding and Classification Springer-Verlag New York 1985 347 p
[29] Chernikova E A, Glukhov L M, Krasovskiy V G, Kustov L M, Koroteev A A 2014 Russ Chem Bull 63 2702-2706
[30] Niedermeyer H, Ab Rani M A, Lickiss P D, Hallett J P, Welton T, White A J P, Hunt P A 2010 Phys Chem Chem Phys 12 2018–2029
[31] Krasovskiy V G, Kapustin G I, Glukhov L M, Gorbatsevich O B, Chernikova E A, Koroteev A A, Kustov L M 2020 Mendeleev Commun 30 Is. 1.
[32] Krasovskiy V G, Glukhov L M, Chernikova E A, Kapustin G I, Gorbatsevich O B, Koroteev A A, Kustov L M 2017 Russ Chem Bull Int Ed 66 1269-1277
[33] Kempter V, Kirchner B 2010 J of Mol Struct 972 22–34
[34] Solution Chemistry Research Progress, ed. D. V. Bostrelli, Nova Science, New York, 2008. 185 p.