doi: 10.15407/ujpe60.12.1196

S. ODINAEV,[1] R.S. MAKHMADBEGOV[2]

[1] Academy of Sciences of Republic of Tajikistan
(33, Rudaki Ave., Dushanbe 734025, Republic of Tajikistan; e-mail: odbs42@mail.ru)
[2] Tajik National University
(17, Rudaki Ave., Dushanbe 734025, Tajikistan; e-mail: Mah86Rashid@mail.ru)

PACS 77.22.-d, 77.22.Gm

FREQUENCY DISPERSION OF DIELECTRIC PERMITTIVITY AND DIELECTRIC LOSSES IN AQUEOUS KCl AND CsCl SOLUTIONS DEPENDING ON THEIR STATE PARAMETERS

The frequency spectra of the coefficients of dielectric permittivity, $\varepsilon_1(\omega)$, and dielectric losses, $\varepsilon_2(\omega)$, have been studied for aqueous KCl and CsCl solutions in wide intervals of the density ρ, concentration C, and temperature T. The research is carried out on the basis of the analytical expressions obtained for those parameters, by using the method of kinetic equations. Numerical calculations of $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ at various ρ, C, and T are carried out with a certain choice of the solution model, the potential interaction energy $\Phi_{ab}(|\mathbf{r}|)$, and the radial distribution function $g_{ab}(|\mathbf{r}|)$ for ions of sorts a and b in the solutions concerned. The obtained results are in satisfactory quantitative agreement with experimental data.

Keywords: dielectric permittivity coefficient, coefficient of dielectric losses, potential of intermolecular interaction, radial distribution function, fluid friction coefficient, relaxation times.

A preliminary knowledge about the physical and chemical properties of dielectric substances is required for their successful application in industry and electronics, as well as for searching the new dielectric materials and the optimal sphere of their application. The electric properties of dielectric media are described by the dielectric permittivity coefficient. At weak and constant electric fields, the latter does not depend on the external field strength and remains constant in time. However, if the applied electric field $E(t)$ periodically varies in time, the electric induction $D(t)$ also changes periodically in time with a certain phase shift. In this case, the relation between those field characteristics is determined with the help of a frequency-dependent complex dielectric permittivity coefficient $\tilde{\varepsilon}(\omega)$, whose real part is the dielectric permittivity coefficient $\varepsilon_1(\omega)$ and the imaginary one is the coefficient of dielectric losses $\varepsilon_2(\omega)$. A lot of works were devoted to experimental and theoretical researches of those coefficients in electrolyte solutions [1–8].

Onsager [1] developed a theory for the electric conductivity in aqueous electrolyte solutions in the case of weak stationary electric fields. He showed that, in this approximation, there is no correlation between the specific conductance of a solution and its dielectric permittivity.

Debye and Falkenhagen [1, 2] studied the influence of a high frequency on the conductivity and the dielectric permittivity of electrolyte solutions in the presence of an external electric field varying in time. The obtained analytical expressions for the dynamic coefficients of conductivity and dielectric permittivity corresponded to the exponential law of damping (of

---

© S. ODINAEV, R.S. MAKHMADBEGOV , 2015

periodic fields), and they did not contain contributions associated with the variations in the solution structure, i.e. the structural relaxation was not taken into account.

There is an important phenomenon in electrolyte solutions known as the Wien effect [1, 2]. If the electrolyte solution is subjected to the action of a strong electric field, the ions will be extracted by this field from their atmospheres. This phenomenon results in an increase of the ionic conductivity coefficient, because the ions do not entrain their ionic atmosphere. It should be noted that the time evolution of the conductivity on the basis of this effect gives rise to the frequency dispersion of the dielectric permittivity coefficient in electrolyte solutions, the theoretical research of which is of a large interest.

In work [3], a theory for the dielectric permittivity and the dielectric losses in a homogeneous dielectric media under the action of both static and time-dependent external electric fields, independent of spatial coordinates, was described in detail. The Debye formulas for the complex dielectric permittivity coefficient $\tilde{\varepsilon}(\omega)$ in various models were derived, and analytical expressions for the coefficients of dielectric permittivity $\varepsilon_1(\omega)$ and dielectric losses $\varepsilon_2(\omega)$ were obtained. In their integrands, those coefficients contain an unknown function $y(\tau)$, which describes the distribution of relaxation times. Hence, the explicit form of this function and its relation to the structure of dielectric media, i.e. to the radial distribution function, is required. The Debye theory is based on the hypothesis that the system evolves to the equilibrium state following the exponential law.

In works [4–8], the transfer phenomena in electrolyte solutions and the related dielectric properties were studied using both experimental and theoretical methods. Besides the phenomenological theory, the methods of temporal autocorrelation functions, collective variables, and kinetic theory were widely applied in the physics of insulators. In the cited works, both the static and frequency-dependent dielectric permittivity coefficients of dielectric media were determined. The Cole–Cole, Davidson–Cole, Havriliak–Negami, Williams–Watts, and Fuoss–Kirkwood equations for $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ were obtained in various approximations. The latter equation is rather simple for the explanation of experimental results, and its parameters are related to the parameters of the Cole–Cole and Davidson–Cole equations. In some approximations, those equations transform into the Debye one.

The dielectric properties of aqueous electrolyte solutions have also been studied recently in works [9–14]. A detailed analysis of experimental data for the dielectric parameters of a concentrated sodium chloride solution [9] showed that the dielectric parameters are described by the Cole–Cole relaxation model, rather than the pure relaxation Debye one, as was supposed earlier. The Debye type of a polar liquid is known to be a special case of the more general Cole–Cole relaxation model. Using the method of dielectric spectroscopy, the formation of ionic complexes in an aqueous zinc chloride solution was researched in work [10]. It was shown that the second Debye region is easily distinguished in the Cole–Cole diagrams and in the frequency coefficients of dielectric permittivity and dielectric losses.

In works [11–13], the dielectric properties and relaxations of aqueous electrolyte solutions were studied. The frequency spectra of the coefficients of dielectric permittivity and dielectric losses of solutions, as well as their dependences on the temperature and the concentration, were analyzed. According to work [14], the research of dielectric characteristics of electrolyte solutions has been complicated for a long time owing to their high conductivity and high ionic losses. In particular, the attention was paid to difficulties associated with the impossibility to separate losses connected with the ionic and dipole components. A direct measurement of the static dielectric permittivity is also impossible, so that the data obtained in the microwave frequency interval has to be extrapolated to the zero frequency.

The results of researches dealing with the dielectric relaxation in aqueous KCl and CsCl solutions were reported in work [15]. The experiments were carried out at a temperature of 25°C. The measurements were performed on a vector analyzer in the frequency interval $0.2\ \text{GHz} \leqslant \nu \leqslant 20\ \text{GHz}$ and with the help of wave-guide interferometers in the interval $27\ \text{GHz} \leqslant \nu \leqslant 89\ \text{GHz}$. The spectra of both salts are well described by the Cole–Cole equation. The influence of a solute on the water structure manifests itself in a reduction of the relaxation time in the water bulk, as the electrolyte concentration grows. The effect decreases along the series NaCl → KCl → CsCl, being probably proportional to the cation surface charge density.

A regular study of the frequency spectra for the dielectric relaxation in aqueous LiCl and Li_2SO_4 solutions was carried out in work [16]. The researches were fulfilled at a temperature of 25 °C, in the solute concentration intervals $0.05\ \text{mol/l} \leq C \leq 1\ \text{mol/l}$ for LiCl and $0.05\ \text{mol/l} \leq C \leq 2\ \text{mol/l}$ for Li_2SO_4, and in the wide frequency range $0.2\ \text{GHz} \leq \nu \leq 89\ \text{GHz}$. The spectra obtained describe a superposition of four Debye relaxation processes: two of them are known as the regions of water relaxation with the times 0.5 and 8 ps, and the other two are ionic-pair contributions corresponding to characteristic relaxation times of 20 and 200 ps. According to the spectroscopic researches, no non-contact ion pairs were revealed in the examined concentration interval.

In work [17], the anomalous behavior of the glycerol–water solution was studied. The density of an aqueous glycerol solution was measured along the coexistence curve in the temperature interval $293\ \text{K} \leqslant T \leqslant 363\ \text{K}$ and the glycerol concentrations $0.225\ \text{mol/l} \leqslant C \leqslant 0.552\ \text{mol/l}$ within the pycnometer method. The growth of the solution density was shown to depend on the concentration. The maximum of this curve was observed at $C = 0.33$ mol/l. In addition, this concentration was found to be characterized by the largest isobaric expansion coefficient.

In work [18], it was shown that the resistance dependence of a cell filled with an aqueous NaCl solution on the ac current frequency cannot be explained as a result of the polarization phenomena taking place only in the region near the electrode-electrolyte interface. A physical mechanism, which explains a monotonic increase of the solution conductivity at frequencies below 10^4 Hz and its constant value in the frequency interval 10^4–10^5 Hz, was proposed. The temperature dependences for the diffusion coefficients of Na^+ and Cl^- ions in NaCl aqueous solutions and for the size of the corresponding physically infinitesimal volume, i.e. a region, where the local equilibrium in this electrolyte is established, were calculated. The space-time hierarchies in an aqueous NaCl solution were analyzed. A relation of the ac period to certain time characteristics and its correlation with the frequency dependence of the conductivity in this electrolyte solution were demonstrated.

In work [19], an approach was developed to describe the influence of the ionic association on the solvent and the dielectric permittivity in an electrolyte solution on the basis of the mass action law in the mean spherical approximation. The dependences of the dielectric constant on the electrolyte concentration, ion size, and ion association degree were analyzed. The results obtained turned out in satisfactory agreement with the recent experimental data for the aqueous solutions of nitrates and formates.

Using the method of kinetic equations, the analytical expressions were obtained in work [20] for the coefficients of dielectric permittivity $\varepsilon_1(\omega)$ and dielectric losses $\varepsilon_2(\omega)$ in electrolyte solutions. Those expressions contain the potential energy of interaction $\Phi_{ab}(|\mathbf{r}|)$ and the radial distribution function $g_{ab}(|\mathbf{r}|)$, i.e. the relation to the solution structure, in relevant integrands. In works [21, 22], the frequency dispersion of those coefficients was studied for the aqueous LiCl and NaCl solutions in wide temperature and concentration intervals.

This work was aimed at studying the frequency spectra $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ for aqueous KCl and CsCl solutions in wide intervals of the temperature, density, concentration, and frequency. For this purpose, we present the analytical expressions obtained in work [20] for $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$, chosen solution model, expressions for the friction coefficients β_a and β_b, potential energy of interaction $\Phi_{ab}(|\mathbf{r}|)$, and radial distribution function $g_{ab}(|\mathbf{r}|)$ for ions of sorts a and b, which were used in works [21, 22]:

$$\varepsilon_1(\omega) = \varepsilon_\infty + \sum_a \frac{\sigma_a^0 \tau_a}{\varepsilon_0[1 + (\omega\tau_a)^2]} \times$$
$$\times \left[1 + \sum_b \left(\frac{1 - (\omega\tau_a)^2 \frac{\tau_{ab}}{\tau_a}}{1 + (\omega\tau_a)^2 \left(\frac{\tau_{ab}}{\tau_a}\right)^2} A_{ab}(0) \right)\right], \tag{1}$$

$$\varepsilon_2(\omega) = \sum_a \frac{(\omega\tau_a)\sigma_a^0 \tau_a}{\varepsilon_0[1 + (\omega\tau_a)^2]} \times$$
$$\times \left[1 + \sum_b \left(\frac{\left(1 + \frac{\tau_{ab}}{\tau_a}\right)}{1 + (\omega\tau_a)^2 \left(\frac{\tau_{ab}}{\tau_a}\right)^2} A_{ab}(0) \right)\right], \tag{2}$$

where

$$A_{ab}(0) = 6\pi \overset{*}{n}_b\, q_{ab} \int \frac{\partial^2 \overset{*}{\Phi}_{ab}(r)}{\partial r^2} g_{ab}(r) r^2 dr, \tag{3}$$

$\sigma_a^0 = \frac{n_a e_a^2}{\beta_a}$; $\tau_a = \frac{m_a}{2\beta_a}$; $\tau_b = \frac{m_b}{2\beta_b}$; $\tau_{ab} = \frac{d_{ab}^2}{kT} \frac{\beta_a\beta_b}{\beta_a+\beta_b}$; $d_{ab} = \frac{1}{2}(d_a + d_b)$; $n_b^* = \frac{\pi}{6} n_b d_{ab}^3$; $q_{ab} = \frac{4}{\pi} \frac{e_b\beta_a - e_a\beta_b}{e_a(\beta_a+\beta_b)}$;

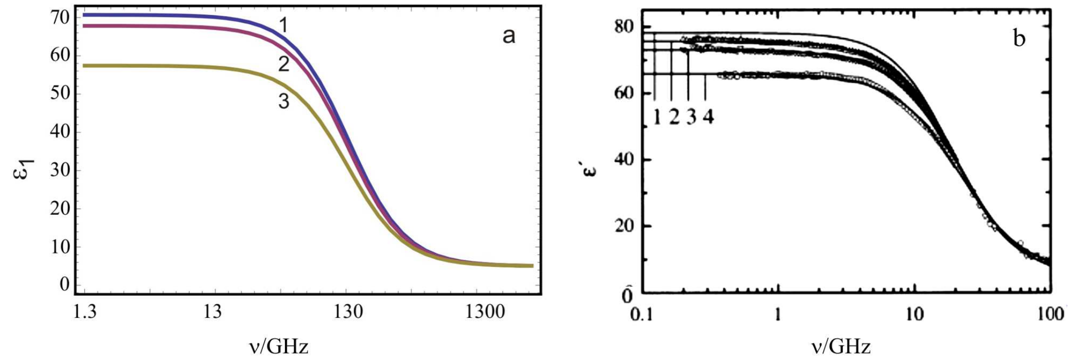

Fig. 1. Frequency dispersion $\varepsilon_1(\nu)$ for an aqueous KCl solution at $T = 298$ K: calculated by formula (1) for concentrations of 0.15 (*1*), 0.60 (*2*), and 1.42 mol/l (*3*) (*a*); experimental results [15] for concentrations 0 (*1*, pure water), 0.15 (*2*), 0.60 (*3*), and 1.42 mol/l (*4*) (*b*)

Table 1. **Dependence of ε_1 for aqueous KCl and CsCl solutions on ρ, C, and ν at $T = 298$ K**

C, mol/l	ρ, kg/m^2	ν, GHz									
		[15]	0.0135	0.135	1.35	13.5	67.5	135	675	1350	[15]
					KCl						
0.1504	1003.4	76.94	70.66	70.66	70.65	70.06	58.43	39.31	7.77	5.71	5.21
0.2497	1006.5	76.15	65.84	65.84	65.83	65.28	54.38	36.59	7.53	5.65	5.04
0.3153	1009.7	75.63	63.64	63.64	63.63	63.09	52.52	35.32	7.42	5.62	4.85
0.4408	1016.1	74.52	61.66	61.66	61.66	61.13	50.84	34.17	7.32	5.60	4.47
0.6008	1022.5	72.97	60.71	60.71	60.71	60.19	50.03	33.62	7.27	5.59	4.31
0.7931	1035.4	71.23	59.51	59.51	59.51	59.00	49.03	32.97	7.22	5.57	7.79
1.104	1048.5	68.20	58.48	58.48	58.48	57.97	48.18	32.44	7.17	5.56	5.08
1.423	1061.6	65.93	57.47	57.47	57.46	56.97	47.35	31.92	7.13	5.55	5.66
					CsCl						
0.2499	1033	76.54	77.64	77.64	77.63	76.39	56.88	34.88	8.52	6.02	4.73
0.4016	1052	75.48	73.19	73.19	73.18	71.89	52.34	32.40	8.55	5.97	5.33
0.6009	1082	73.87	68.47	68.47	68.45	67.06	47.46	30.93	8.48	5.92	5.34
0.7964	1111	72.33	64.40	64.40	64.39	62.89	43.84	30.74	8.36	5.88	4.32
1.106	1152	70.23	59.17	59.17	59.15	57.56	40.51	31.06	8.20	5.83	5.65
1.506	1205	67.20	52.77	52.77	52.75	51.14	38.30	31.27	8.01	5.77	6.33
1.760	1239	65.49	48.91	48.90	48.89	47.38	37.62	31.14	7.89	5.74	5.77

$\Phi^*_{ab}(r) = \frac{\Phi_{ab}(r)}{kT}$; $\Phi_{ab}(r)$ is the potential energy of interaction between structural units in the electrolyte solution; $g_{ab}(r)$ the radial distribution function; m_a, m_b, e_a, e_b, n_a, n_b, d_a, d_b, β_a, and β_b are the masses, charges, numerical densities, diameters, and friction coefficients of ions of sorts a and b; τ_a, τ_b and τ_{ab} are the relaxation times in the momentum and configuration spaces; $\mathbf{r}_{ab} = \mathbf{q}_b - \mathbf{q}_a$ is the relative distance; $\mathbf{r} = \mathbf{r}_{ab}/d_{ab}$ is the reduced distance between the ions of sorts a and b; ε_0 the electric constant, k the Boltzmann constant, T the absolute temperature, $\omega = 2\pi\nu$ is the cyclic frequency, ν the frequency of process, and ε_∞ the value of dielectric permittivity coefficient at $\omega \to \infty$.

The coefficients $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ in formulas (1) and (2) consist of the kinetic and potential components, which, in accordance with Eq. (3), depend on the potential energy of interaction between the structural units of the solution, $\Phi_{ab}(r)$, and the radial distribution function $g_{ab}(r)$. We select the semiphenomenological osmotic model of a solution [6, 23], which is described in the framework of the McMillan–Mayer theory.

In order to determine the friction coefficients β_a and β_b and the relaxation times τ_a, τ_b, and τ_{ab}, let us take advantage of the analytical expressions presented in work [24]:

$$\begin{aligned} \beta_a^2 &= \sum_a \frac{4\pi}{3}\rho_a \sum_b d_{ab} \int\limits_0^\infty \nabla^2\, \Phi_{ab}(r) g_{ab}(r) r^2 dr, \\ \beta_b^2 &= \sum_b \frac{4\pi}{3}\rho_b \sum_a d_{ab} \int\limits_0^\infty \nabla^2\, \Phi_{ab}(r) g_{ab}(r) r^2 dr, \end{aligned} \tag{4}$$

where $\nabla^2 = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \frac{\partial}{\partial r})$ is the radial part of Laplace operator, and $\rho_a = m_a n_a$ and $\rho_b = m_b n_b$ are the mass density of particles of sorts a and b, respectively.

According to work [24], the potential energy of interaction Φ_{ab} can be taken in the form

$$\Phi_{ab} = 4\varepsilon_{ab}(r^{-12} - r^{-6})/\varepsilon_{ss} + R_{ab} e^{-\overset{*}{\kappa} r}/r, \tag{5}$$

where $d_{ab} = (d_{aa} + d_{\,bb})/2$, $R_{ab} = f z_a z_b e^2 e^{\kappa^*}/[kT\varepsilon_{ss} d_{ab}(1+\kappa^*)]$, $\varepsilon_{ab} = (\varepsilon_{aa}\varepsilon_{\,bb})^{1/2}$ is the depth of the potential well in the energy of particle-to-particle interaction, $f = (4\pi\varepsilon_0)^{-1} = 9 \times 10^9$ F/m, ε_{ss} the dielectric permittivity coefficient of the solvent, e the elementary charge, d_{aa}, d_{bb} and z_a, z_b are the diameters and the valency, respectively, of ions of sorts a and b, $\kappa^* = \kappa_a d_{ab}$ is the reduced inverse Debye screening radius, in which, according to work [25], κ is determined in the form $\kappa^2 = \sum_a n_a e_a^2/(\varepsilon_r \varepsilon_0 kT)$.

Following work [6], the radial distribution function $g_{ab}(r)$ for the ionic subsystem is taken in the form

$$g_{ab}(r) = y(r, \rho^*) \exp\{-\Phi_{ab}(r)/kT\}, \tag{6}$$

where $y(r, \rho^*)$ is the binary distribution function for two cavities. We confine the consideration to its contact value $y(r, \rho^*) \approx y(\rho^*)$ at the distance $r = 1 (r_{ab} = d_{ab})$ obtained by Carnahan and Starling in the form

$$y(\rho^*) = (2 - \rho^*)/2(1 - \rho^*)^3, \tag{7}$$

where $\rho^* = \pi n d_{ab}^3/6 = \pi \rho d_{ab}^3 N_0/(6M)$ is the reduced density, ρ the solution density, N the Avogadro constant, and M the molar mass.

On the basis of formulas (1) and (2) and with regard for Eqs. (4)–(7), let us numerically calculate the coefficients of dielectric permittivity $\varepsilon_1(\nu)$ and dielectric losses $\varepsilon_2(\nu)$ for aqueous KCl and CsCl solutions as functions of ρ, C, T, and ν. In Table 1, the results of calculations obtained for $\varepsilon_1(\nu)$ of the solutions concerned at a temperature of 298 K, in the frequency interval 13.5×10^6 Hz $\leqslant \nu \leqslant 13.5 \times 10^{11}$ Hz, and at various densities and concentrations are presented and compared with the experimental data of work [15]. In Table 2, the same is done for the coefficient of dielectric losses $\varepsilon_2(\nu)$ in those solutions. One can see that the values of $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$ decrease with the the growth of the density and the concentration, which agrees with the experimental data. According to Table 1, the theoretical results obtained for $\varepsilon_1(\nu)$, e.g., at low and high frequencies, are in satisfactory agreement with the experimental data of work [15].

In Fig. 1, the frequency dispersion of the dielectric permittivity coefficient $\varepsilon_1(\nu)$ for the aqueous KCl solution at a temperature of 298 K is shown. Panel *a* exhibits the calculation results obtained by formula (1) for three concentrations: 0.15 (*1*), 0.60 (*2*), and 1.42 mol/l (*3*). Panel *b* illustrates the experimental results of work [15] for four concentrations: pure water (*1*), 0.15 (*2*), 0.60 (*3*), and 1.42 mol/l (*4*). Figure 2 demonstrates the frequency spectra of the coefficient of dielectric losses $\varepsilon_2(\nu)$ for the aqueous KCl solution at the same temperature, densities, concentrations, and frequencies: panel *a* illustrates the calculation results obtained by formula (2), and panel *b* the experimental results of work [15].

In Fig. 3, the frequency spectra of the coefficients of dielectric permittivity $\varepsilon_1(\nu)$ and dielectric losses $\varepsilon_2(\nu)$ for the aqueous CsCl solution at a temperature of 298 K are depicted. Panel *a* exhibits the results obtained by formulas (1) for $\varepsilon_1(\nu)$ (solid curves) and (2) for $\varepsilon_2(\nu)$ (dashed curves) for three concentrations: 0.25 (*1*), 0.80 (*2*), and 1.76 mol/l (*3*). Panel *b* shows the experimental results of work [15] obtained for $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$ at the concentration $C = 0.25$ mol/l. One can see that both the theoretical and experimental values of $\varepsilon_1(\nu)$ decrease, as the frequency grows, and tend to the high-frequency values of dielectric permittivity ε_∞. At the same time, the experimental and theoretical values of $\varepsilon_2(\nu)$ first grow to a maximum and then fall to the minimum value. It should be noted that the frequencies, at which $\varepsilon_2(\nu)$ has maxima can be used to determine the characteristic times of dielectric relaxation.

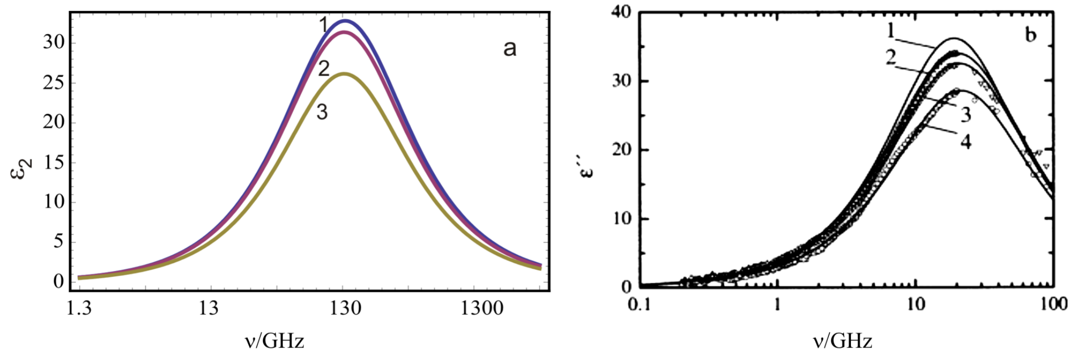

Fig. 2. The same as in Fig. 1, but for $\varepsilon_2(\nu)$

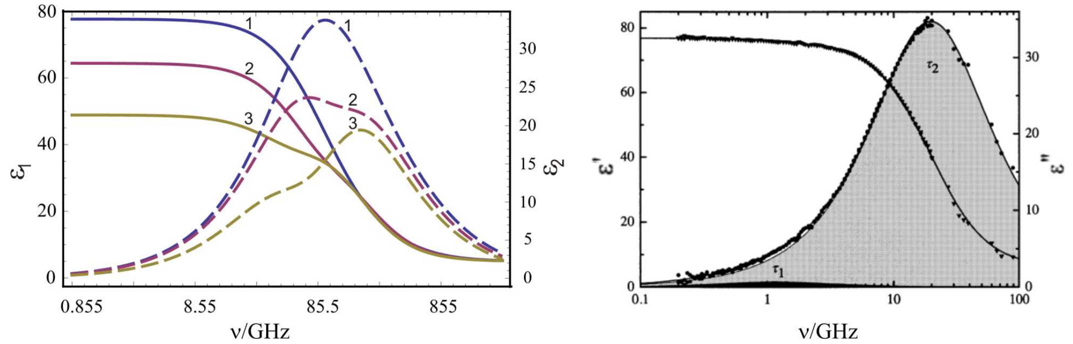

Fig. 3. Frequency spectra $\varepsilon_1(\nu)$ (solid curves) and $\varepsilon_2(\nu)$(dashed curves) for an aqueous CsCl solution at $T = 298$ K: calculated by formulas (1) and (2) for concentrations of 0.25 (*1*), 0.80 (*2*), and 1.76 mol/l (*3*) (*a*); experimental data [16] for $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$ at the concentration $C = 0.25$ mol/l (*b*)

Table 2. **Dependence of ε_2 for aqueous KCl and CsCl solutions on ρ, C, and ν at $T = 298$ K**

C, mol/l	ρ, kg/m^2	ν, GHz							
		0.0135	0.135	1.35	13.5	67.5	135	675	1350
					KCl				
0.1504	1003.4	0.0063	0.063	0.63	6.22	25.54	32.76	13.17	6.807
0.2497	1006.5	0.0059	0.058	0.59	5.81	23.77	30.37	12.13	6.26
0.3153	1009.7	0.0057	0.057	0.57	5.62	22.97	29.28	11.64	6.01
0.4408	1016.1	0.0055	0.055	0.55	5.45	22.26	28.30	11.21	5.78
0.6008	1022.5	0.0054	0.054	0.54	5.37	21.91	27.82	11.00	5.67
0.7931	1035.4	0.0053	0.053	0.53	5.27	21.45	27.21	10.75	5.55
1.104	1048.5	0.0052	0.052	0.52	5.17	21.04	26.68	10.55	5.44
1.423	1061.6	0.0051	0.051	0.51	5.08	20.63	26.16	10.35	5.34
					CsCl				
0.2499	1033	0.0092	0.092	0.92	9.06	31.04	32.98	12.87	6.89
0.4016	1052	0.0091	0.091	0.91	8.86	29.15	29.54	12.38	6.60
0.6009	1082	0.0089	0.089	0.89	8.66	26.47	25.50	11.98	6.34
0.7964	1111	0.0087	0.087	0.87	8.39	23.529	22.57	11.65	6.13
1.106	1152	0.0082	0.082	0.82	7.82	19.37	20.05	11.21	5.87
1.506	1205	0.0071	0.071	0.71	6.69	14.74	18.32	10.67	5.57
1.760	1239	0.0062	0.062	0.62	5.75	12.51	17.65	10.34	5.39

Hence, the adopted approximation in the choice of the model of a solution brought about a satisfactory agreement between the theoretical and experimental values of $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$. The slight numerical mismatches observed for $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$ in Tables 1 and 2 can be associated with the neglect of contributions from the ion-molecule and molecule-solvent molecule interactions in the potential $\Phi_{ab}(r)$. The frequency spectra $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$, depending on the density, concentration, and temperature, are a result of the dielectric relaxation in the aqueous KCl and CsCl solutions, i.e. the contribution of relaxation processes with characteristic times of ions in the momentum (τ_a and τ_b) and configuration (τ_{ab}) spaces.

1. V.K. Semenchenko, *The Physical Theory of Solutions* (Gostekhteoretizat, Moscow,1941) (in Russian).
2. H.S. Harned and B.B. Owen, *The Physical Chemistry of Electrolyte Solutions* (Reingold, New York, 1958).
3. H. Fröhlich, *Theory of Dielectrics* (Clarendon Press, Oxford, 1958).
4. W.F. Brown, *Dielectrics* (Springer, Berlin, 1956).
5. T. Erdey-Grúz, *Transport Phenomena in Aqueous Solutions* (Hilger, London, 1974).
6. I.R. Yukhnovskii and M.F. Golovko, *Statistical Theory of Classical Equilibrium Systems* (Naukova Dumka, Kyiv, 1987) (in Russian).
7. A.A. Potapov and M.S. Metsyk, *Dielectric Polarization* (Irkutsk Univ., Irkutsk, 1986) (in Russian).
8. J.M.G. Barthel, H. Krienke, and W. Kunz, *Physical Chemistry of Electrolyte Solution. Modern Aspects* (Springer, New York, 1998).
9. E.A. Sharkov, Zh. Fiz. Khim. **58**, 1705, (1984).
10. U. Kaatze, V. Lonnecke, and R. Pottel, J. Chem. Phys. **91**, 2206 (1987).
11. J. Barthel, R. Buchner, and M. Münsterer, Electrolyte Data Collection, Part 2: Dielectric Properties of Water and Aqueous Electrolyte Solutions, (Dechema, Frankfurt-am-Main, 1995).
12. R. Buchner and J. Barthel, Annu. Rep. Prog. Chem. Sect. **97**, 349 (2001).
13. R. Buchner, P. Sipos, G. Hefter, and P.M. May, J. Phys. Chem. **106**, 6527 (2002).
14. A.S. Lileev, *Dielectric Relaxation and Molecular-Kinetic State of Water in Solutions,* Dr. Sci. thesis (Moscow, 2004) (in Russian).
15. T. Chen, G. Hefter, and R. Buchner, J. Phys. Chem. **107**, 4025 (2003).
16. W. Wachter, S. Fernandez, R. Buchner, and G. Hefter, J. Phys. Chem. **111**, 9010 (2007).
17. I.I. Adamenko, L.A. Bulavin, V. Ilyin, S.A. Zelinsky, and K.O. Moroz, J. Mol. Liq. **127**, 90 (2006).
18. L.A. Bulavin, A.N. Alekseev, Yu. F. Zabashta, and S.Yu. Tkachev, Ukr. J. Phys. **56**, 547 (2011).
19. M.F. Holovko and V. Kapko, Acta Chim. Slov. **56**, 203 (2009).
20. S. Odinaev and R.S. Makhmadbegov, Dokl. Akad Nauk Respub. Tajikistan **57**, 483 (2014).
21. S. Odinaev and R.S. Makhmadbegov, Dokl. Akad Nauk Respub. Tajikistan **57**, 692 (2014).
22. S. Odinaev and R.S. Makhmadbegov, Zh. Fiz. Khim. (to be published).
23. N.A. Smirnova, *Molecular Theories of Solutions* (Khimiya, Leningrad, 1987) (in Russian).
24. S. Odinaev and D.M. Akdodov, Zh. Fiz. Khim. **87**, 1154 (2013).
25. H. Krienke, G. Ahn-Ercan, and J. Barthel, J. Mol. Liq. **109**, 115 (2004).

Received 06.04.15.
Translated from Russian by O.I. Voitenko

С. Одінаєв, Р.С. Махмадбегов

ЧАСТОТНА ДИСПЕРСІЯ ДІЕЛЕКТРИЧНОЇ ПРОНИКНОСТІ І ДІЕЛЕКТРИЧНИХ ВТРАТ ВОДНИХ РОЗЧИНІВ KCl І CsCl ЗАЛЕЖНО ВІД ПАРАМЕТРІВ СТАНУ

Резюме

На основі аналітичних виразів коефіцієнтів діелектричної проникності $\varepsilon_1(\omega)$ і діелектричних втрат $\varepsilon_2(\omega)$, отриманих методом кінетичних рівнянь, досліджуються частотні спектри цих коефіцієнтів водних розчинів KCl і CsCl у широкому інтервалі зміни густини ρ, концентрації C і температури T. При певному виборі моделі розчину, потенціальної енергії взаємодії $\Phi_{ab}(|\mathbf{r}|)$ і радіальної функції розподілу $g_{ab}(|\mathbf{r}|)$ іонів сорту a і b, проведено чисельний розрахунок $\varepsilon_1(\omega)$ і $\varepsilon_2(\omega)$ для водних розчинів KCl і CsCl в залежності від ρ, C, T і ω. Отримані результати чисельних розрахунків цих коефіцієнтів наведено в двох таблицях і на трьох малюнках, а також порівняно з експериментальними даними, які знаходяться в кількісній задовільній злагоді.