Viscosity and Density of Water + Sodium Chloride + Potassium Chloride Solutions at 298.15 K

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The viscosity and density of water + sodium chloride + potassium chloride solutions were measured at 298.15 K from very dilute to saturated as well as supersaturated solutions. A 3.5th term in molarity was added to the extended Jones−Dole equation to produce a new equation. This extended Jones−Dole type equation can well represent the viscosities of the systems studied to saturated concentrations. In low concentrations, the calculated viscosity values by simple additivity are close to the experimental values. Above a certain concentration, the calculated viscosities of NaCl + KCl mixtures are lower than the experimental values and the difference becomes greater with increasing concentration.

1. Introduction

The viscosities of electrolyte solutions are usually given by the Jones−Dole equation (Jones and Dole, 1929):

$$\eta_r = \eta/\eta^o = 1 + Ac^{1/2} + Bc \qquad (1)$$

where η and η^o are the viscosity of the solution and of the solvent, respectively, and c is the concentration in molarity. This equation was found to be suitable for aqueous single strong electrolyte solutions in the rather dilute region (Stokes and Mills, 1965). The A coefficient is a measure of ion−ion interactions and may be calculated from equilibrium theory as demonstrated by Falkenhagen (1971). The B coefficient, also called the Jones−Dole coefficient, is an empirical constant, qualitatively correlating ion−solvent interactions characteristic for each electrolyte and solvent. Assuming $B_{K^+} = B_{Cl^-}$, the B coefficient can be divided into ionic contributions. A positive B coefficient indicates "structure making", while a negative B coefficient indicates "structure breaking".

Equation 1 is only valid in the dilute region (not more than 0.3 mol·L^{-1}). For application to higher concentrations, an extended Jones−Dole equation has been used by many authors (Kaminsky, 1957):

$$\eta_r = \eta/\eta^o = 1 + Ac^{1/2} + Bc + Dc^2 \qquad (2)$$

The D coefficient, which can be related to solute−solute interactions, is not well understood. The equation still cannot fit data at very high concentrations. Equations and theories have been developed to represent the relation of viscosity to concentrations up to saturation (Horvath, 1985). Among them, Goldsack's two-parameter equation could be considered as the best with more advantages. Although Goldsack's two-parameter equation (Goldsack and Franchetto, 1977; Nowlan et al., 1980) could be used to represent viscosities of not only single but also mixed electrolyte solutions to rather high concentrations, the correlating standard deviations are still obvious from the viewpoint of application to accurate theoretical investigation. Certainly, the greatest advantage of Goldsack's equation is its predicting function and its two physically meaningful parameters. Jones−Dole type equations have not been further extended for higher concentrations. Above

all, the semi-empirical Jones−Dole equation has been widely used for dilute electrolyte solutions and accepted by many authors as a most fundamental equation for a long history. In this work the purpose has been designed to extend the Jones−Dole type equations to saturation not only for single electrolyte solutions but also for binary electrolyte solutions.

Many measurements have been reported on the viscosity of aqueous single electrolyte solutions, but there are few measurements on binary salt mixtures in water, especially in the concentrated region (Stokes and Mills, 1965; Nowlan et al., 1980; Horvath, 1985). Furthermore, the existing scarce viscosity values are not very accurate. The viscometric behavior of aqueous mixed electrolyte solutions can provide information on single electrolyte, solute−solute interactions and the interionic force in water.

2. Experimental Section

Ultrapure NaCl and KCl were dried at 150 °C in vacuum before being used for preparing solutions. Double-distilled deionized water was used. Solutions were prepared by mass with a precision of $\pm 5 \times 10^{-5}$ g. All weighing was corrected to vacuum. For single electrolyte solutions in the dilute region, solutions were made by diluting a stock solution by mass. In the concentrated region, solutions were prepared from a known mass of salt and water, respectively. For the mixed electrolyte solutions, a ratio of NaCl + KCl stock solution with concentration approaching saturation was prepared by mass. Then by dilution by mass, a series of concentrations of solutions were made. Solutions around saturation were prepared by weighing NaCl, KCl, and water, respectively. To test the method, several concentrations less than the stock solution were also made this way.

Viscosities were measured with two Ubbelohde type viscosimeters. One was 12.2 cm long with a capillary diameter of 0.45 mm and with a capacity of 3.0 cm^3 (I). Another was 11.8 cm long with a capillary diameter of 0.39 mm and with a capacity of 2.1 cm^3 (II). The viscosity can be expressed (Stokes and Mills, 1965) as

$$\eta/\rho = at - b/t \qquad (3)$$

where ρ is the density of the liquid, t is the flow time, and a and b are constants for a given viscosimeter in a certain range of temperature. The a and b parameters for both the viscosimeters were obtained by the measurements on

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Table 1. Density ρ and Viscosity η at 298.15 K for Aqueous NaCl and KCl

m/mol·kg^{-1}	ρ/g·cm^{-3}	η/mPa·s	m/mol·kg^{-1}	ρ/g·cm^{-3}	η/mPa·s
		NaCl (I)			
0.0234	0.9980	0.8928	0.3495	1.0112	0.9190
0.0275	0.9982	0.8931	0.4057	1.0135	0.9237
0.0525	0.9992	0.8954	0.4478	1.0149	0.9272
0.0576	0.9994	0.8957	0.7023	1.0250	0.9488
0.0632	0.9996	0.8963	0.7244	1.0259	0.9506
0.0794	1.0003	0.8974	0.8636	1.0312	0.9626
0.0933	1.0008	0.8984	1.5854	1.0578	1.0312
0.1124	1.0017	0.9002	1.6654	1.0607	1.0397
0.1435	1.0030	0.9027	1.9610	1.0709	1.0715
0.1648	1.0038	0.9042	3.2579	1.1141	1.2368
0.2187	1.0059	0.9088	3.4321	1.1196	1.2621
0.3395	1.0108	0.9182	3.6813	1.1275	1.3005
		NaCl (II)			
0.0280	0.9982	0.8932	2.3156	1.0831	1.1129
0.0439	0.9988	0.8945	2.7186	1.0966	1.1632
0.1486	1.0032	0.9030	2.9405	1.1038	1.1930
0.1554	1.0033	0.9037	3.2249	1.1130	1.2328
0.1735	1.0041	0.9052	3.6736	1.1271	1.3000
0.2499	1.0073	0.9111	4.2179	1.1437	1.3902
0.4476	1.0150	0.9272	4.3397	1.1473	1.4117
0.5614	1.0196	0.9367	4.6368	1.1562	1.4658
0.7198	1.0257	0.9500	4.9288	1.1647	1.5218
0.9807	1.0355	0.9732	5.1160	1.1698	1.5591
1.0034	1.0364	0.9752	5.2593	1.1739	1.5887
1.3174	1.0480	1.0048	5.3460	1.1762	1.6068
1.6728	1.0609	1.0410	5.5426	1.1816	1.6490
1.8995	1.0689	1.0653	5.8345	1.1897	1.7145
2.0010	1.0723	1.0764	6.0216	1.1949	1.7585
		KCl			
0.0214	0.9981	0.8907	1.7032	1.0701	0.8917
0.0590	0.9999	0.8906	1.7218	1.0709	0.8915
0.0955	1.0015	0.8905	1.7758	1.0732	0.8923
0.1340	1.0033	0.8902	2.2846	1.0926	0.8987
0.1597	1.0046	0.8903	2.4240	1.0978	0.9007
0.3197	1.0118	0.8891	2.7977	1.1114	0.9076
0.4944	1.0197	0.8882	3.3554	1.1309	0.9204
0.5331	1.0213	0.8884	3.4934	1.1356	0.9239
0.9477	1.0393	0.8877	3.5485	1.1375	0.9251
1.2173	1.0507	0.8883	3.9487	1.1508	0.9368
1.2968	1.0539	0.8885	4.6030	1.1717	0.9582
1.3584	1.0564	0.8890	4.8181[a]	1.1782	0.9662

[a] Supersaturated (the saturated concentration is 4.76 mol·kg^{-1}).

water at 20, 25, and 30 °C. The viscosities and densities of water at different temperatures were obtained from the literature (Stokes and Mills, 1965). At 25 °C, the viscosity and density of water are 0.8903 mPa·s and 0.997 07 g·cm^{-3}, respectively. The temperature of the thermostat was controlled to ±0.002 K. The experimental temperature was accurate to (298.15 ± 0.01) K. An electrical stopwatch with a precision of 0.01 s was used. The repeatability for reading was ±0.05 s. At least three time recordings reproducible to 0.05 s were obtained, and the average value was used. It could be expected that the measurement of viscosity has a precision of 0.025%. The accuracy could reach up to ±0.02% in the dilute region and ±0.05% in the concentrated region.

The densities of solutions were measured by an Anton Paar 45 densimeter with a precision of ±5 × 10^{-5} g·cm^{-3} and an accuracy of 0.005%. It was calibrated by double-distilled water and dry air.

3. Results

The viscosities of all the solutions were measured with viscosimeter I, except that one group of NaCl solutions (I) was measured with viscosimeter II. The densities and viscosities of NaCl and KCl are given in Table 1. The densities and viscosities of mixtures of NaCl + KCl are given in Table 2. The mole ratios of NaCl/KCl studied were

3/1, 1/1, and 1/3. Two sets of measurements were made on the solutions with a NaCl/KCl ratio of 1/3.

For the NaCl solution, the maximum concentration eq 2 can fit to is 2 mol·kg^{-1}. It has been empirically found that when a 3.5th term in molarity, $Ec^{3.5}$, was added to eq 2, the experimental viscosity for group I can be well represented over all concentrations. The extended equation is

$$\eta_r = \eta/\eta^0 = 1 + Ac^{1/2} + Bc + Dc^2 + Ec^{3.5} \qquad (4)$$

All parameters were obtained by equally-weighting least-squares regression by using the theoretical A values. For the group II NaCl solution, the maximum experimental concentration approaches saturation. Equation 4 could still well represent the viscosity data over the all concentrations.

For aqueous KCl solution, the maximum experimental concentration is 4.82 mol·kg^{-1}, being supersaturated. Equation 2 represents the experimental viscosity data valid up to 3.95 mol·kg^{-1} and eq 4 valid up to the supersaturation. Equation 4 can represent the experimental viscosity data of a mixed NaCl + KCl solution in different mole ratios very well over the entire concentration range.

All the coefficients of eqs 2 and 4 obtained by least-squares regression are listed in Table 3, together with standard deviation $\sigma(\eta)$ and theoretical A values calculated by the Falkenhagen theory. Some authors concluded that the Jones–Dole B coefficient is additive (Wu, 1968; Dordick, 1981), i.e.

$$B = x_1 B_1 + x_2 B_2 \qquad (5)$$

where x_i ($i = 1, 2$) is the mole fraction of one electrolyte in the mixed electrolyte and B_1 and B_2 are the B coefficients of individual electrolyte 1 and 2, respectively. The calculated B coefficients are also listed in Table 3.

The simple additivity rule has been used to examine our results. The simple additivity equation is

$$\Delta\eta_{mix} = \Delta\eta_1 + \Delta\eta_2 \qquad (6)$$

$$\eta_{mix} = \eta^0(1 + \Delta\eta_{mix}) \qquad (7)$$

where

$$\Delta\eta_1 = A_1 c_1^{1/2} + B_1 c_1 + D_1 c_1^2 + E_1 c_1^{3.5} \qquad (8\text{-}1)$$

$$\Delta\eta_2 = A_2 c_2^{1/2} + B_2 c_2 + D_2 c_2^2 + E_2 c_2^{3.5} \qquad (8\text{-}2)$$

The viscosities of mixed NaCl + KCl have been calculated using the obtained parameters for NaCl and KCl. The calculated values are also listed in Table 2 for comparison with the experimental viscosities.

To examine the accuracy and precision of our density and viscosity measurements, we have checked our results with available literature values. Our densities for NaCl and KCl solutions are in agreement with literature values within 0.01% (Lengyel et al., 1964; Zhang, 1989). The densities for NaCl and KCl from Zhang (Zhang, 1989) were measured by an Anton Paar DMA 602 densimeter from the very dilute to the saturated, covering many concentrations, from which a precise density expression was obtained. It has also been found that Goncalves' (Goncalves and Kestin, 1977) densities for NaCl at $m = 5.243\ 24$ and $m = 5.822\ 67$ were apparently lower than ours and those of the literature (Lengyel et al., 1964; Zhang, 1989). Parameters for viscosity equations were used to calculate the viscosity of all concentrations of NaCl and KCl solutions for comparison with the literature values (Lengyel, 1964; Goncalves and

Table 2. Density ρ, Viscosity η, and Calculated Viscosity η (Eq 7) at 298.15 K for Aqueous Mixed NaCl + KCl at Total Molality m

m/mol·kg^{-1}	ρ/g·cm^{-3}	η/mPa·s	η (eq 7)/mPa·s	m/mol·kg^{-1}	ρ/g·cm^{-3}	η/mPa·s	η (eq 7)/mPa·s
			$n_{NaCl}/n_{KCl} = 2.9867$				
0.0586	0.9994	0.8945	0.8949	2.9004	1.1056	1.1067	1.0880
0.2808	1.0088	0.9077	0.9083	3.4102	1.1223	1.1595	1.1312
0.4231	1.0147	0.9161	0.9166	3.5286	1.1260	1.1723	1.1416
0.4520	1.0158	0.9176	0.9183	3.8441	1.1360	1.2083	1.1702
0.7189	1.0265	0.9337	0.9343	4.0701	1.1432	1.2352	1.1915
0.9221	1.0345	0.9469	0.9467	4.1038	1.1440	1.2388	1.1947
1.3241	1.0497	0.9741	0.9724	4.3503	1.1515	1.2694	1.2186
1.4542	1.0547	0.9836	0.9810	4.5098	1.1562	1.2897	1.2345
1.9247	1.0719	1.0195	1.0135	4.6956	1.1621	1.3143	1.2536
2.3760	1.0877	1.0576	1.0467	5.0687	1.1728	1.3662	1.2929
2.6567	1.0970	1.0835	1.0684	5.6813	1.1903	1.4588	1.3614
			$n_{NaCl}/n_{KCl} = 1.0010$				
0.0466	0.9990	0.8927	0.8932	2.5015	1.0949	1.0087	0.9923
0.1285	1.0027	0.8956	0.8965	3.0357	1.1131	1.0445	1.0175
0.2217	1.0067	0.8989	0.9001	3.3475	1.1236	1.0671	1.0329
0.2475	1.0077	0.9000	0.9011	3.5450	1.1300	1.0820	1.0428
0.4228	1.0152	0.9060	0.9075	3.8533	1.1400	1.1064	1.0588
0.5299	1.0196	0.9101	0.9115	4.3164	1.1546	1.1455	1.0836
0.6927	1.0259	0.9166	0.9175	4.4450	1.1583	1.1564	1.0906
0.8222	1.0317	0.9217	0.9224	4.6241	1.1639	1.1724	1.1006
1.3009	1.0506	0.9429	0.9409	4.7350	1.1672	1.1829	1.1069
1.6958	1.0656	0.9622	0.9570	5.0739	1.1773	1.2147	1.1263
2.4674	1.0937	1.0068	0.9908	5.2630	1.1828	1.2328	1.1374
			$n_{NaCl}/n_{KCl} = 1/2.9890$ (I)				
0.0483	0.9993	0.8916	0.8921	1.7524	1.0700	0.9294	0.9236
0.0766	1.0006	0.8921	0.8927	2.0316	1.0806	0.9384	0.9301
0.1021	1.0017	0.8927	0.8932	2.9347	1.1131	0.9732	0.9540
0.1612	1.0043	0.8936	0.8943	3.2594	1.1243	0.9875	0.9637
0.2529	1.0084	0.8949	0.8958	3.6775	1.1382	1.0075	0.9768
0.5561	1.0217	0.9003	0.9007	3.9172	1.1462	1.0200	0.9848
0.6335	1.0249	0.9014	0.9019	4.1238	1.1527	1.0312	0.9918
0.8357	1.0334	0.9054	0.9054	4.4892	1.1644	1.0515	1.0047
1.2147	1.0488	0.9146	0.9123	5.1139	1.1825	1.0877	1.0279
1.6251	1.0650	0.9254	0.9208				
			$n_{NaCl}/n_{KCl} = 1/3.0075$ (II)				
0.0529	0.9996	0.8916	0.8922	2.7760	1.1075	0.9648	0.9493
0.1282	1.0029	0.8929	0.8937	3.0188	1.1159	0.9748	0.9562
0.2004	1.0061	0.8941	0.8949	3.0970	1.1184	0.9783	0.9585
0.2649	1.0089	0.8947	0.8960	3.5691	1.1345	1.0002	0.9730
0.3559	1.0131	0.8965	0.8974	3.5807	1.1349	1.0006	0.9734
0.5386	1.0207	0.8993	0.9003	3.7278	1.1398	1.0083	0.9782
0.6869	1.0271	0.9020	0.9027	3.9943	1.1483	1.0218	0.9870
0.7935	1.0315	0.9040	0.9045	4.1894	1.1546	1.0325	0.9937
1.0492	1.0421	0.9096	0.9091	4.2183	1.1552	1.0338	0.9947
1.3409	1.0538	0.9166	0.9147	4.2780	1.1570	1.0371	0.9968
1.8747	1.0745	0.9318	0.9263	4.9316	1.1774	1.0741	1.0207
2.1933	1.0865	0.9427	0.9339	5.0843	1.1826	1.0829	1.0266

Table 3. Experimental, Literature, and Calculated Coefficients in Extended Jones−Dole Equations for NaCl, KCl, and Their Mixtures and the Standard Deviation $\sigma(\eta)$

mole ratios of NaCl/KCl	exptl					calcd		lit.			
	B	D	$10^4 E$	m_{max}^a	$10^4\sigma$/mPa·s	A^b	B^c	A	B	D	m_{max}
1/0 (I)	0.0799	0.010 40	7.56	3.7	2.7	0.0061		0.0060	0.079		0.5^d
	0.0797	0.011 76		1.7	3.6			0.0062	0.0793	0.008	0.5^d
								0.0062	0.0802		0.15^e
1/0 (II)	0.0794	0.011 42	6.19	6.0	2.5	0.0061		0.0061	0.078	0.013	1.2^d
	0.0791	0.012 31		2.0	5.3						
	−0.0152	0.007 25	0.80	4.8	1.6			0.0052	−0.0140	0.001	0.5^d
0/1						0.0051		0.0052	−0.0161	0.00808	3.3^e
	−0.0155	0.007 72		4.0	4.4			0.0057	−0.0147		0.13^e
								0.0051	−0.0141	0.007	1^d
3/1	0.0561	0.009 02	4.38	5.7	4.3	0.0058	0.0557				
1/1	0.0304	0.008 87	2.12	5.3	2.8	0.0056	0.0322	0.0057	0.0313		0.2^f
1/3 (I)	0.0077	0.008 69	0.20	5.1	4.3	0.0053	0.0088				
(II)	0.0069	0.008 78	0.18	5.1	4.0	0.0053	0.0087				

^{a} The maximum concentration for regression. ^{b} A is calculated by Falkenhagen theory. ^{c} B is calculated by eq 5. ^{d} Out and Los (1980). ^{e} Dordick et al. (1979). ^{f} Dordick and Drost-Hansen (1981).

Kestin, 1977; Out and Los, 1980). Some results are listed in Table 4. The results are rather satisfactory. The Goncalves' (Goncalves, 1977) viscosities for NaCl at 5.2432 mol·kg^{-1} and 5.82267 mol·kg^{-1} are obviously lower than

ours and Lengyel's (Lengyel et al., 1964). This may be ascribed to the lower densities of the two concentrations mentioned above. Lengyel's (Lengyel et al., 1964) viscosities for NaCl solutions are slightly lower than ours and

Table 4. Comparison of Literature Viscosity η_l with Calculated Viscosity η_c Using the Parameters in This Work for Aqueous NaCl and KCl at 298.15 K

m/mol·kg^{-1}	η_l/mPa·s	$\eta_c - \eta_l$/mPa·s	m/mol·kg^{-1}	η_l/mPa·s	$\eta_c - \eta_l$/mPa·s
	NaCl[a]			KCl[a]	
0.1000	0.8994	−0.0003	0.0400	0.8908	−0.0001
0.2000	0.9065	0.0007	0.0900	0.8907	−0.0002
0.3200	0.9164	0.0004	0.1600	0.8911	−0.0010
0.5000	0.9319	−0.0003	0.2500	0.8895	0.0001
0.8000	0.9571	0.0001	0.4000	0.8891	−0.0003
1.2000	0.9928	0.0010	0.7000	0.8885	−0.0006
			1.0000	0.8882	−0.0004
	NaCl[b]			KCl[b]	
0.0986	0.8987	0.0003	0.5041	0.8872	0.0012
0.4971	0.9288	0.0025	0.9910	0.8881	−0.0003
0.9865	0.9709	0.0030	2.0476	0.8969	−0.0017
1.9930	1.0733	0.0024	2.4968	0.9033	−0.0014
2.9296	1.1886	0.0025	3.0013	0.9130	−0.0012
3.4865	1.2683	0.0026	3.5327	0.9251	−0.0003
3.9873	1.3455	0.0049	3.9618	0.9386	−0.0015
5.4952	1.6326	0.0064	4.6934	0.9613	0.0004
5.8023	1.7000	0.0076			
	NaCl[c]			KCl[c]	
0.00784	0.8910	0.0003	0.32974	0.8895	−0.0003
0.01285	0.8921	0.0003	0.51841	0.8886	−0.0003
0.01598	0.8920	0.0001	1.02409	0.8882	−0.0003
0.02027	0.8923	0.0002	1.54691	0.8910	−0.0008
0.06177	0.8960	0.0000	2.10665	0.8972	−0.0012
0.11094	0.9002	−0.0002	2.72517	0.9079	−0.0018
0.23631	0.9097	0.0004	3.42161	0.9238	−0.0020
0.56874	0.9361	0.0012	3.93033	0.9377	−0.0016
0.85382	0.9607	0.0013	4.55469	0.9576	−0.0009
1.47458	1.0185	0.0021			
2.51393	1.1335	0.0036			
3.09392	1.2104	0.0033			
5.24324	1.5752	0.0098			
5.82267	1.7008	0.0109			

[a] Out and Los (1980). [b] Lengyel et al. (1964). [c] Goncalves and Kestin (1977).

Table 5. Comparison of Experimental Viscosity η_e with Calculated Viscosity η_c at 298.15 K for Aqueous Mixed NaCl + KCl at Total Molarity

c/mol·L^{-1}	η_e/mPa·s	$\eta_c - \eta_e$/mPa·s	c/mol·L^{-1}	η_e/mPa·s	$\eta_c - \eta_e$/mPa·s
		$n_{NaCl}/n_{KCl} = 1$[a]			
0.0464	0.8927	−0.0000	0.2199	0.8989	−0.0001
0.1277	0.8956	0.0001	0.2455	0.9000	−0.0003
		$n_{NaCl}/n_{KCl} = 1$[b]			
0.98	0.9268	0.0026	3.62	1.1289	−0.0107
1.90	0.9795	−0.0004	4.41	1.2001	0.0082
2.78	1.0472	−0.0053			
		$n_{NaCl}/n_{KCl} = 3$[c]			
0.5	0.9209	0.0001	2.5	1.0830	0.0003
1.0	0.9525	0.0013	3.0	1.1372	0.0025
1.5	0.9893	0.0020	3.5	1.1931	0.0115
2.0	1.0315	0.0026	4.0	1.2693	0.0096
		$n_{NaCl}/n_{KCl} = 1$[c]			
0.5	0.9072	0.0022	2.5	1.0169	0.0031
1.0	0.9276	0.0029	3.0	1.0570	0.0032
1.5	0.9535	0.0021	3.5	1.1052	0.0011
2.0	0.9855	−0.0002	4.0	1.1551	0.0041
		$n_{NaCl}/n_{KCl} = 1/3$[c]			
0.5	0.8968	0.0018	2.5	0.9588	0.0031
1.0	0.9065	0.0023	3.0	0.9802	0.0071
1.5	0.9216	0.0010	3.5	1.0108	0.0062
2.0	0.9362	0.0041	4.0	1.0445	0.0060

[a] The experimental values are from this work, and the calculated values are obtained from parameters given by Dordick and Drost-Hansen (1981). [b] The experimental values are from Goldsack and Franchetto (1977), and the calculated values are obtained from the parameters in this work. [c] The experimental values are from Nowlan et al. (1980), and the calculated values are obtained from the parameters in this work.

some other literature values. At 3.9873 mol·kg^{-1}, the viscosity shows a relatively greater negative deviation of about 5×10^{-3} mPa·s. The viscosities for the two groups of NaCl solutions measured by two different viscosimeters

in this work agree within 0.03% indicating that the types of viscosimeters used in this work are suitable and reliable.

The viscosities for 1/1 NaCl + NaCl solutions agree with those calculated by Dordick's parameters (Dordick and

Drost-Hansen, 1981) within 0.02% in the dilute concentration range. The five experimental viscosity values of higher concentrations by Goldsack et al. (Goldsack and Franchetto, 1977) for 1/1 NaCl + KCl are in agreement with those calculated from our parameters within 0.5%. This may be due to the low requirement of their molalities. Viscosities for NaCl + KCl mixtures have also been compared with the literature (Nowlan et al., 1980). Solutions were prepared volumetrically by Nowlan (1980) at round total molarities. All the comparisons mentioned above are given in Table 5. The coefficients in eq 4 for the two groups of 1/3 NaCl + KCl solutions are very similar, which shows that the method for measuring the viscosity of mixed electrolyte solutions is realiable and accurate. The group II results have been used for comparison with the literature due to its ratio being close to 1/3.

4. Discussion

For NaCl solutions, the valid maximum concentration for eq 2 is about 2 mol·kg^{-1} and for KCl about 4 mol·kg^{-1}. A 3.5th term of molality is added to eq 2, then the obtained eq 4 can represent the viscosity of NaCl, KCl, and their mixtures in different mole ratios over all concentrations.

For NaCl and KCl, our B coefficients are in excellent agreement with both the literature and the calculated values. The D coefficients deviate obviously when using different maximum concentrations or different Jones−Dole type equations for regression. Out and Los (1980) reached similar conclusions for NaCl solutions. The accepted D coefficient for NaCl is (0.013 ± 0.0005) when eq 2 is used and the maximum concentration for regression is beyond 1 mol·L^{-1}. When the maximum concentration is low or eq 4 is used, the D coefficient is from 0.008 to 0.012. For KCl the D coefficient is about 0.007.

We also calculated the B coefficients in terms of the component additivity by eq 5 for the salt mixtures. Our experimental B coefficient for 3/1 or 1/1 NaCl + KCl is in excellent agreement with those calculated, whereas for 1/3 NaCl + KCl, the agreement is only good.

For the three mole ratios of NaCl + KCl, the calculated viscosity values by simple component additivity are slightly greater than the experimental values in low concentrations. They approach each other in the dilute concentration range. With increasing concentration, the calculated values deviate negatively from the experimental values. It is assumed that (1) at low concentrations, enough water molecules could be employed to hydrate ions and the interactions between ions can be neglected, whereas with increasing concentration, the interactions become stronger and stronger, so the calculated values get smaller than the experimental values; and (2) in concentrated solutions, the real concentration of each electrolyte in a mixed electrolyte should be higher than that when not considering the existence of another electrolyte due to the decreasing amount of solvent from the presence of another electrolyte.

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