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Model for Calculating the Density of Aqueous Electrolyte Solutions

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A new model for calculating the density of aqueous solutions of electrolytes has been developed. Parameters for 59 electrolytes were established on the basis of an extensive critical review of the published literature for solutions of one electrolyte in water, with over 10 700 points included. The average difference between the calculated and experimental density of solutions of water and one electrolyte is 0.10 kg m^{-3} with a standard deviation of 1.44 kg m^{-3}. The model was validated by predicting the density of systems of two or more electrolytes in water. The average difference between experimental and calculated values for over 1600 points is 0.003 kg m^{-3} with a standard deviation of 1.39 kg m^{-3}. The electrolytes studied are $AlCl_3$, $Al_2(SO_4)_3$, $BaCl_2$, $CaCl_2$, $CdCl_2$, $CdSO_4$, $CoCl_2$, $CoSO_4$, $CrCl_3$, $Cr_2(SO_4)_3$, $CuCl_2$, $CuSO_4$, $FeCl_2$, $FeSO_4$, $FeCl_3$, $Fe_2(SO_4)_3$, HCl, HCN, HNO_3, H_3PO_4, H_2SO_4, KCl, K_2CO_3, KNO_3, KOH, K_2SO_4, LiCl, Li_2SO_4, $MgCl_2$, $MgSO_4$, $MnCl_2$, $MnSO_4$, NaBr, NaCl, $NaClO_3$, Na_2CO_3, NaF, $NaHCO_3$, NaH_2PO_4, Na_2HPO_4, $NaHSO_3$, NaI, Na_2MoO_4, $NaNO_2$, $NaNO_3$, NaOH, Na_3PO_4, Na_2SO_3, $Na_2S_2O_3$, Na_2SO_4, NH_3, NH_4Cl, NH_4NO_3, $(NH_4)_2SO_4$, $NiCl_2$, $NiSO_4$, $SrCl_2$, $ZnCl_2$, and $ZnSO_4$.

Introduction

The density of aqueous electrolyte solutions is useful in the design and control of chemical processes. It is used in pipe sizing, pump calculations, heat transfer calculations, and other common problems.

Despite the importance of density data in engineering calculations, finding the relevant data can be frustrating. Perry's Chemical Engineers' Handbook[90] has a short section on density with good data for commercially important chemicals (H_2SO_4, HCl, HNO_3, NaOH, NH_3, etc.) and with fragmentary and often dated information for about 70 other electrolytes. There is no other practical reference available to engineers. This is surprising because chemists have been studying the density of electrolyte solutions for over a century and have measured the density of all common electrolyte solutions over a range of concentration and temperature.

One of the reasons for this discrepancy may be confusion regarding units. Chemists often use mole-based units for concentration (molality and molarity), but mass-based units are more practical for engineers (mass fraction and mass per volume are most common). Furthermore, published data are often reported as apparent molal volume instead of density.

The units of concentration used in this paper are mass based instead of mole based as is more traditional. This should help make the model more immediately useful for engineering calculations. More importantly, mole-based units, especially molality, are not very well suited for calculating the density of solutions containing a large number of electrolytes in water, the molality being by definition the number of moles of a solute in a kilogram of solvent excluding any other solute present in this solution. As will be demonstrated later in looking at data for multielectrolyte solutions, the other solutes, if present, will have an effect on the density of the solution, and ignoring this effect significantly decreases the accuracy of the model prediction.

Review of Available Data

The first step of the study was to assemble published data from the literature. Density data are readily available going back to the late 1800s. Measurements using modern tube vibration techniques are now common and are considered quite accurate and consistent.[34] The measurement of concentration is also more accurate because of the use of modern analytical techniques. Data from as far back as the early 1900s were reviewed: data from before 1970 might be less reliable, but some of the early literature data are still of excellent quality.

One secondary source that was used extensively is a compilation of data from 1900 to about 1985 by Lobo.[64] Additional searches were performed for electrolytes that are not well covered in Lobo, as well as for more recent data.

Fifty nine electrolytes were selected for this review. The electrolytes selected consist of the chloride and sulfate salts of most common metals plus a selection of common acids and bases and other electrolytes such as carbonates, nitrates, and bromides of alkali metals. The model proposed here works well for all selected electrolytes, and there is no reason to believe that it would not work for any other electrolyte.

Density Model

The first step in developing a density model was to develop a simple mixing rule that could be used for a solution containing an arbitrary number of components. We based our mixing rule on the well-known fact that the volume of a mixture of ideal liquids can be calculated with the following equation:

$$v_m = v_{H_2O} + \sum_i v_i \tag{1}$$

where v_{H_2O}, v_m, and v_i are the volumes of the water, the mixture, and ideal component i, respectively.

Equation 1 can be transformed to calculate density. For all ideal mixtures,

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$$\frac{1}{\rho_m} = \frac{w_{H_2O}}{\rho_{H_2O}} + \sum_i \frac{w_i}{\rho_i} \qquad (2)$$

where w_{H_2O} and ρ_{H_2O} are the mass fraction and the density of water, w_i is the mass fraction of component i, ρ_i is its density, and ρ_m is the density of the mixture. All densities are expressed in kg m^{-3}.

In the model presented here, it is assumed that the density (or the volume) of water is not a function of concentration but only of temperature. The density (or volume) of the electrolyte has been assumed to vary with both temperature and composition and is called "apparent" density or volume. (The pressure dependency of the density and volume of water and electrolytes is small and was not considered in this model. The limited data at high pressure in the literature were not used to calculate the model's coefficients.)

Equation 1 then becomes

$$v_m = v_{H_2O} + \sum_i v_{app,i} \qquad (3)$$

where v_{H_2O} is the volume of water in m^3 and $v_{app,i}$ is the apparent volume of electrolyte i, also in m^3.

Equation 3 can be rewritten using the specific volume, the volume occupied per unit of mass

$$v_m = w_{H_2O} v_{H_2O} + \sum_i w_i \bar{v}_{app,i} \qquad (4)$$

where $\bar{v}_{app,i}$ indicates the electrolyte i specific volume in m^3 kg^{-1}. This can be rewritten in terms of density

$$\rho_m = \frac{1}{\dfrac{w_{H_2O}}{\rho_{H_2O}} + \sum_i \dfrac{w_i}{\rho_{app,i}}} \qquad (5)$$

or, alternatively,

$$\rho_m = \frac{1}{w_{H_2O}\bar{v}_{H_2O} + \sum_i w_i \bar{v}_{app,i}} \qquad (6)$$

where $\rho_{app,i}$ is the apparent density of electrolyte i.

Equations 4−6 are mathematically equivalent, and any of them can be used. Because in some cases the apparent specific volume of an electrolyte tends to 0 and its apparent density tends to infinity, eq 5 can cause some numerical problems. Equation 6 was used hereafter, but this is mostly a matter of preference.

Solving eq 6 for $\bar{v}_{app,i}$ yields the following equation for calculating the apparent specific volume of one electrolyte in solution with water:

$$\bar{v}_{app,i} = \frac{1 - \dfrac{\rho_m(1 - w_i)}{\rho_{H_2O}}}{\rho_m w_i} \qquad (7)$$

The density of water instead of its apparent volume was used for convenience only. Either can be used. The density of water was calculated using a correlation from Kell (eq 8):[51] where t is the temperature in °C.

$$\rho_{H_2O} = \frac{(((((-2.8054253 \times 10^{-10} t + 1.0556302 \times 10^{-7})t - 4.6170461 \times 10^{-5})t - 0.0079870401)t + 16.945176)t + 999.83952)}{1 + 0.01687985t} \qquad (8)$$

At high concentration, the numerical value used for the density of water has little impact on the value of the apparent specific volume. At low concentration ($w_i \langle 0.01$), this is not the case.

The numerical values for the density of water predicted by eq 8 were compared to those in the Revised Supplementary Release on Saturation Properties of Ordinary Water Substance edited by the International Association for the Properties of Water and Steam[43] (IAPWS) and to those in Recommended Reference Materials for the Realization of Physicochemical Properties edited by Marsh.[68] Equation 8 was found to be in very close agreement with the values in Marsh (average deviation 0.003, maximum 0.005 kg m^{-3}), but those found by eq 8 are systematically higher than those in IAPWS at temperatures below about 110 °C by about 0.05 kg m^{-3} at 25 °C. This may be explained by the fact that the densities in Lobo and Marsh are at atmospheric pressure below 100 °C whereas those from the IAPWS are at saturation pressure. Because of the agreement between the values in Lobo and Marsh, the fact that most engineering calculations will be done for processes at atmospheric pressure, and that most experimental measurements of density were taken at that same pressure, eq 8 was used hereafter.

Figure 1 shows how the apparent specific volume, in this case, $MgSO_4$, can be either positive or negative. Apparent specific volume typically has a low value at low concentration and then increases toward a linear relationship with mass fraction at higher concentration. The inflection point where this relationship becomes linear, the slope of that linear relationship, and the influence of temperature on both of these factors, however, are difficult to predict.

Finding a mathematical model to represent the apparent specific volume suitably was a challenge. The following was found to adequately represent all electrolytes studied and is suitable for interpolation as well as extrapolation, as will be demonstrated later:

$$\bar{v}_{app,i} = \frac{w_i + c_2 + c_3 t}{(c_0 w_i + c_1)e^{(0.000001(t + c_4)^2)}} \qquad (9)$$

where c_0 to c_4 are empirical constants. c_0 and c_1 are in kg m^{-3}, c_2 is dimensionless, c_3 is in °C^{-1} and c_4 is in °C, and t is the temperature in °C. The fractional term of this equation was formulated by examining many sets of experimental data using residual plots of $\rho_{app,i}$. The original form of the equation included only terms c_0 to c_2. The exponential term with the c_4 constant was added for the temperature dependence and is based on the findings of Sangwal.[116] The term $c_3 t$ was added after looking at residual plots and noting that the point where the apparent specific volume switched from negative to positive changed slowly with temperature even with the exponential term included.

Calculation of Terms c_0 to c_4

To calculate terms c_0 to c_4, we calculated the apparent specific volume using eq 7 for all 10 700 data points studied. A nonlinear least-squares method was then used to estimate terms c_0 to c_4 from eq 9:

Initial values were entered for c_0 to c_4 (1, 1, 1, 0.0025, and 1500 are typical values).

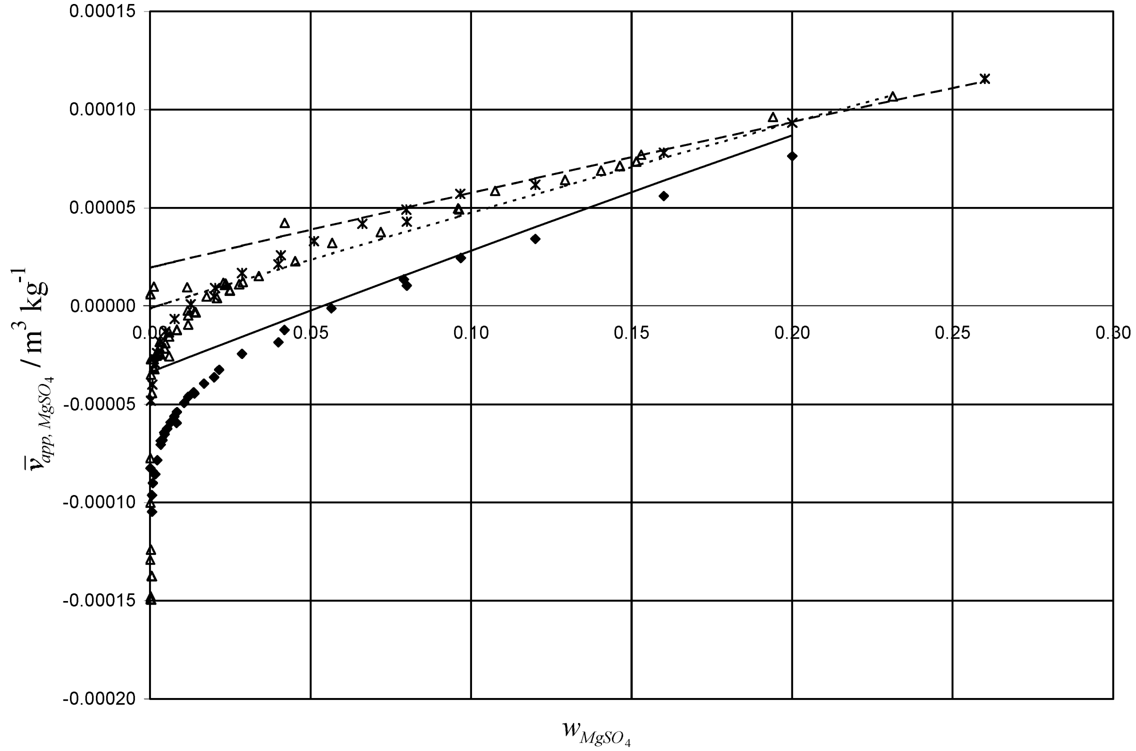

Figure 1. Specific volume of $MgSO_4$ in solution with water: ♦, exptl data at 0 °C; −, calcd data at 0 °C; Δ, exptl data at 25 °C; - - -, calcd data at 25 °C; *, exptl data at 50 °C; — — —, calcd data at 50 °C.

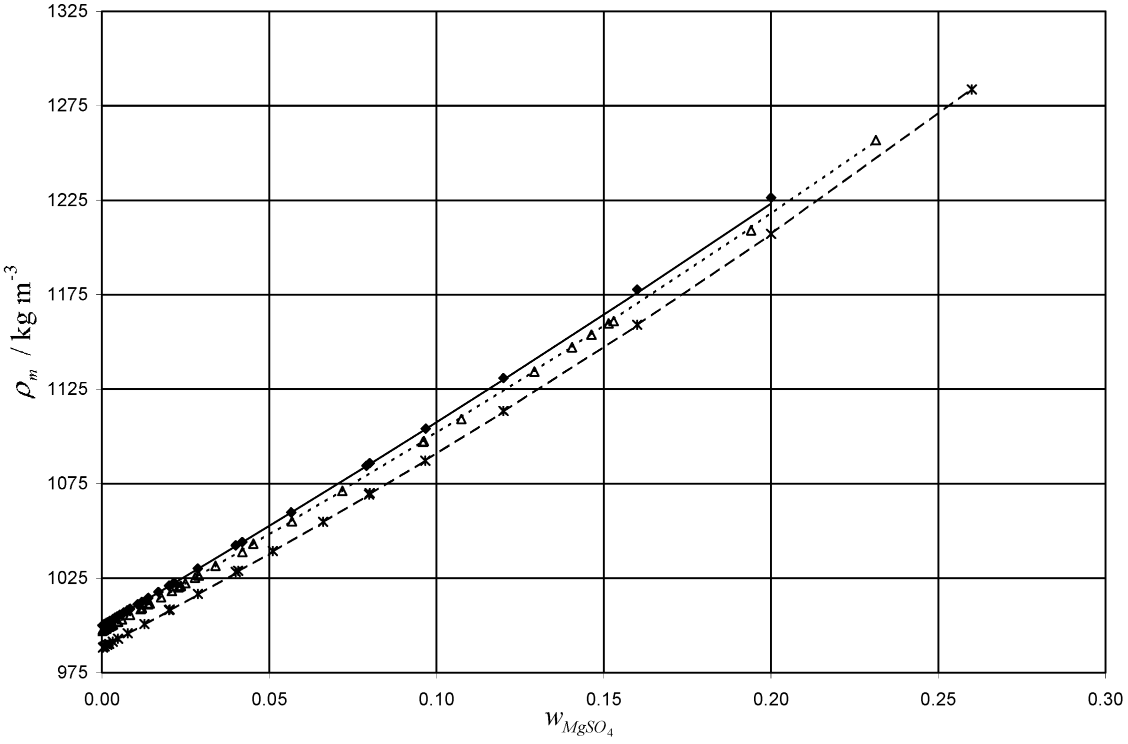

Figure 2. Density of solutions of $MgSO_4$ and water: ♦, exptl data at 0 °C; −, calcd data at 0 °C; Δ, exptl data at 25 °C; - - -, calcd data at 25 °C; *, exptl data at 50 °C; — — —, calcd data at 50 °C.

A residual was calculated by subtracting the calculated solution density from its experimental value.

The sum of the square of the residuals was calculated, and this value was minimized by varying c_0 to c_4. It was found that alternating between the conjugate gradient and the Newton methods of seeking the minimum value significantly increased the quality of the fit.

The data were checked for consistency (see below). If an inconsistent datum was found, then it was removed and steps 2 and 3 were repeated. This was repeated until there were no more inconsistent data.

Because the constant c_4 can sometimes be negative and the solver program does not always converge to the absolute minimum square of the residuals, especially if c_4

Table 1. Values of Constants c_0 to c_4 from Equation 9

	c_0/kg/m^3	c_1/kg/m^3	c_2/dimensionless	c_3/1/°C	c_4/°C	$\bar{v}_{app,i}$ at $w =$ 0.01 and $t =$ 25 °C/m^3/kg	references
$AlCl_3$	221.68	160.90	0.15125	0.002500	1500.0	0.0001340	23, 70
$Al_2(SO_4)_3$	−0.0017202	0.0018967	−0.030904	0.004087	3804.2	0.0000185	18, 90, 121
$BaCl_2$	−0.0030518	0.00526670	4.1785	0.068274	3971.9	0.0001299	45, 67, 87, 90, 129
$CaCl_2$	−0.63254	0.93995	4.2785	0.048319	3180.9	0.0002025	28, 45, 57, 87, 90, 113, 123, 133, 136
$CdCl_2$	−0.090879	0.29116	7.3827	−0.031855	−3477.5	0.0001513	9, 23, 37, 104, 107
$CdSO_4$	-1.0440×10^{-7}	6.1070×10^{-8}	−0.003761	0.004108	5007.7	0.0000182	6, 7, 117
$CoCl_2$	-8.0924×10^{-8}	8.0261×10^{-8}	410.24	9.1808	5619.8	0.0001169	37, 93, 99, 123
$CoSO_4$	−118.36	1368.1	0.01304	−0.000145	−294.02	0.0000132	7, 117
$CrCl_3$	3.1469	232.160	0.20191	0.002500	1500.0	0.0001155	90
$Cr_2(SO_4)_3$	1.0045	1.7697	−0.085017	0.002500	1500.0	−0.0006873	6
$CuCl_2$	1868.5	1137.20	0.07185	0.002565	575.7	0.0000880	23, 26, 90, 97
$CuSO_4$	-1.9827×10^{-7}	1.0883×10^{-7}	−0.12506	0.003831	4936.8	−0.0000037	84, 80, 95, 101, 125
$FeCl_2$	98.654	199.51	0.33639	0.0038444	1650.1	0.0001334	48, 99
$FeSO_4$	-3.6737×10^{-6}	1.2465×10^{-4}	−0.062861	0.0015696	3943.0	−0.0000159	7, 21, 90
$FeCl_3$	−1333.8	4369.2	1.5298	0.007099	829.21	0.0001901	90
$Fe_2(SO_4)_3$	0.47444	−0.64624	−713.10	−25.569	4023.2	0.0001610	14, 75, 90
HCl	−80.061	255.42	118.42	1.0164	2619.5	0.0005186	3, 30, 39, 90, 98, 128
HCN	255.82	283.11	0.66888	0.0062057	891.0	0.0012616	53, 90
HNO_3	12.993	−23.579	−3.6070	0.0079416	−2427.1	0.0004521	35, 82, 90
H_3PO_4	1358.3	−4327.7	−4.5950	0.0043831	−912.45	0.0004720	17, 25, 90
H_2SO_4	89.891	224.48	0.82285	0.0068422	1571.5	0.0003482	35, 90, 103
KCl	−0.46782	4.30800	2.3780	0.022044	2714.0	0.0003769	20, 28, 31, 32, 44, 49, 52, 62, 65, 73, 79−81, 90, 114, 135
K_2CO_3	−1.4313	2.49170	1.1028	0.013116	2836.0	0.0001621	29, 41, 73, 90
KNO_3	7.5436	26.38800	1.2396	0.011656	2214.0	0.0003872	7, 22, 45, 73, 79, 82, 90, 110
KOH	194.85	407.31	0.14542	0.002040	1180.9	0.0001178	4, 41, 69, 81, 90, 109, 127
K_2SO_4	-2.6681×10^{-5}	3.0412×10^{-5}	0.97118	0.019816	4366.1	0.0002071	20, 49, 72, 78, 88, 90, 114
$LiCl$	17.807	32.011	1.3951	−0.006234	−2131.6	0.0004588	28, 45, 62, 73, 80, 130, 133
Li_2SO_4	0.0014730	0.0026934	0.17699	0.0041319	3640.7	0.0001565	12, 48, 85, 134
$MgCl_2$	−0.00051500	0.0013444	0.58358	0.0085832	3843.6	0.0001910	5, 13, 28, 45, 49, 72, 87, 90, 113, 129
$MgSO_4$	3.9412×10^{-7}	1.4425×10^{-6}	−0.05372	0.002062	4563.3	0.0000039	6, 13, 27, 45, 49, 52, 72, 74, 88, 90
$MnCl_2$	0.000001869	0.00004545	1.5758	−0.010776	−4369.9	0.0001832	37, 40, 92, 97, 104, 128
$MnSO_4$	0.0032447	0.057246	0.05136	0.002146	3287.8	0.0000344	6, 7, 19, 40, 75, 103, 117
$NaBr$	109.770	513.04	1.54540	0.011019	1618.1	0.0002394	24, 28, 32, 45, 73, 90, 118, 119, 130
$NaCl$	−0.00433	0.06471	1.01660	0.014624	3315.6	0.0003065	13, 20, 27, 28, 31, 32, 44, 48, 52, 62, 67, 73, 74, 79, 80, 90, 135
$NaClO_3$	0.014763	0.024913	1.2924	−0.0076175	−3454.3	0.0003465	11, 90, 108
Na_2CO_3	0.012755	0.014217	−0.091456	0.0021342	3342.4	−0.0000233	38, 41, 73, 88
NaF	2.8191×10^{-6}	2.1777×10^{-7}	−0.041483	0.00021765	4586.9	−0.0000613	55, 72, 73, 86, 114
$NaHCO_3$	-9.4794×10^{-8}	1.5657×10^{-7}	0.9912	0.022644	4900.2	0.0002939	38, 73, 88, 106
NaH_2PO_4	208.77	641.05	0.78893	0.0045520	1198.4	0.0003177	71, 122
Na_2HPO_4	1096.7	937.57	0.01424	−0.0005595	−860.20	0.0000054	122
$NaHSO_3$	6.1384×10^{-6}	1.3029×10^{-6}	0.13635	−0.0014624	−4472.5	0.0002066	16
NaI	626.15	1858.2	1.7387	0.010500	1203.3	0.0002386	62, 65, 73, 112, 118, 119, 130
Na_2MoO_4	−2.0813	4.8446	4.4342	−0.020815	−2942.3	0.0001638	78, 122
$NaNO_2$	78.365	298.00	0.96246	0.0021999	1500.0	0.0003360	33, 90
$NaNO_3$	49.209	94.737	0.77927	0.0075451	1819.2	0.0003423	8, 22, 45, 50, 73, 82, 90, 102, 110
$NaOH$	385.55	753.47	−0.10938	0.0006953	542.88	−0.0000784	3, 39, 41, 54, 66, 73, 81, 88, 90, 109
Na_3PO_4	1015.6	1533.7	−0.15180	0.00013660	173.71	−0.0000862	122
Na_2SO_3	1.5197×10^{-5}	4.3766×10^{-7}	0.10296	−0.0015271	−4500.9	0.0002528	90, 122, 131
$Na_2S_2O_3$	0.84462	−1.5142	−42.949	0.19335	−3425.9	0.0002400	78, 90, 122
Na_2SO_4	-1.2095×10^{-7}	4.3474×10^{-7}	0.15364	0.0072514	4731.5	0.0001189	13, 20, 27, 45, 47, 52, 72, 88, 90, 114, 134
NH_3	0.12693	0.10470	1.0302	−0.0050803	−2973.7	0.0014430	90, 106
NH_4Cl	6.56150	89.772	4.9024	−0.016574	−2089.3	0.0007061	40, 45, 47, 73, 74, 84, 90, 106
NH_4NO_3	1379.3	1124.4	0.65598	0.0014106	176.41	0.0005916	1, 10, 90, 108, 110, 120
$(NH_4)_2SO_4$	−123.22	452.59	3.2898	0.016292	1692.4	0.0004301	30, 46, 90
$NiCl_2$	-1.3900×10^{-6}	4.1879×10^{-6}	0.77734	−0.0066936	−4638.1	0.0000851	23, 37, 83, 90, 91, 97, 105, 117, 123, 124
$NiSO_4$	−0.03894	0.22109	−0.14443	0.0009867	3073.8	−0.0000336	44, 90, 94, 117
$SrCl_2$	1.3534×10^{-6}	-7.4877×10^{-7}	−1.9356	0.010704	−4882.1	0.0001281	40, 45, 73, 87, 96, 113
$ZnCl_2$	1943.6	304.34	−0.013753	0.0011543	573.79	0.0000542	37, 90, 100, 104, 132
$ZnSO_4$	18.378	35.927	−0.089193	0.0010773	2066.3	−0.0000182	5, 7, 44, 90, 101, 126
median	0.00324470	0.9400	0.33639	0.0025646	1500.0		

crosses 0, results from step 4 were saved, and steps 1 to 4 were repeated with new initial values, this time using −1500 as an initial guess for c_4.

If the solver found different values for constants c_0 to c_4 after step 5, then the ones with the lowest sum of the square of residuals was used.

As mentioned above, the value minimized was the square of the solution density residual. The square of the electrolyte apparent specific volume residual could have been used instead. This would have given a better fit for the apparent specific volume at low mass fraction at the expense of the fit at high mass fraction. However, the accuracy of the calculated solution density would not have been significantly improved at low electrolyte concentration because the water density is the most important term in eq 6 in this situation. At high electrolyte concentration, however, the additional error in determining the electrolyte apparent specific volume would have caused a significantly worse estimation of the solution density.

Figure 2 shows the experimental and calculated density of $MgSO_4$ solutions at the same temperatures as in Figure 1. The fit is excellent, even at low concentration where there is a significant difference between the experimental and calculated apparent specific volumes.

Table 2. Statistical Results for Fit of Constants c_0 to c_4 from Equation 9

	t min/°C	*t* max/°C	*wi* min	*wi* max	average solution density residual/ kg/m^3	standard deviation of solution density residual/ kg/m^3	average electrolyte specific volume residual/ l/kg	standard deviation of electrolyte specific volume residual/ l/kg	number of points used in the correlation	number of inconsistent point
$AlCl_3$	25	25	0.00230	0.19356	0.08084	0.27545	−0.01943	0.04774	21	2
$Al_2(SO_4)_3$	15	95	0.00972	0.39800	0.06667	0.65002	−0.00255	0.00586	64	4
$BaCl_2$	0	140	0.00081	0.26000	0.03801	0.49239	−0.00186	0.00482	140	1
$CaCl_2$	0	100	0.00139	0.51320	0.20714	1.03856	−0.00841	0.01250	357	2
$CdCl_2$	25	75	0.00190	0.53833	0.10512	0.41154	−0.00280	0.01455	88	90
$CdSO_4$	25	75	0.00001	0.29671	0.08388	0.54655	−0.01114	0.02463	45	24
$CoCl_2$	15	75	0.00131	0.34452	0.11563	0.69019	−0.00610	0.00861	171	1
$CoSO_4$	25	75	0.00008	0.33050	−0.03259	1.68202	−0.01342	0.11682	34	7
$CrCl_3$	18	18	0.01000	0.12000	−0.06859	0.13855	0.00313	0.00281	5	0
$Cr_2(SO_4)_3$	25	25	0.00001	0.00149	0.00515	0.01167	−0.10673	0.19405	16	0
$CuCl_2$	0	55	0.00135	0.42036	0.00418	0.62217	−0.00092	0.01241	116	3
$CuSO_4$	0	60	0.00161	0.28440	0.03240	0.98107	−0.00382	0.01693	232	3
$FeCl_2$	15	45	0.00012	0.20968	0.01412	0.13982	−0.00864	0.01622	93	0
$FeSO_4$	15	75	0.00200	0.27401	−0.34048	4.95152	0.01509	0.03989	72	5
$FeCl_3$	0	30	0.01000	0.50000	0.21341	1.24076	−0.00832	0.01396	47	0
$Fe_2(SO_4)_3$	15	25	0.01000	0.60000	0.08538	9.26838	−0.00123	0.03505	67	0
HCl	−5	100	0.00037	0.40000	0.08895	0.84965	−0.00566	0.01024	331	0
HCN	0	15	0.01000	1.00000	0.15182	2.12717	−0.00933	0.02463	18	0
HNO_3	−10	100	0.00104	0.80110	−0.04043	2.29532	0.00331	0.00963	476	2
H_3PO_4	15.85	81.4	0.00100	0.85000	0.10601	0.37553	−0.00518	0.00971	196	0
H_2SO_4	0	100	0.00005	0.77060	0.08914	1.14088	−0.01912	0.06636	332	6
KCl	0	125	0.00007	0.28000	0.06154	0.22885	−0.00971	0.02848	688	5
K_2CO_3	0	100	0.01000	0.58240	0.50966	2.75832	−0.00978	0.01984	170	1
KNO_3	0	100	0.00105	0.24000	0.03281	0.21962	−0.00279	0.00458	206	27
KOH	0	100	0.00084	0.59460	0.15383	1.51866	−0.00991	0.01879	421	9
K_2SO_4	0	98.67	0.00035	0.10970	0.03750	0.15534	−0.00915	0.01927	230	7
$LiCl$	5	95	0.00212	0.45390	0.34210	0.92901	−0.01654	0.01959	332	0
Li_2SO_4	0	65	0.00009	0.26021	0.04565	0.35769	−0.01014	0.01923	145	1
$MgCl_2$	0	100	0.00024	0.32748	0.23446	0.85186	−0.02122	0.02081	400	6
$MgSO_4$	0	125	0.00006	0.26000	0.16889	0.75475	−0.02575	0.05259	331	17
$MnCl_2$	15	75	0.00122	0.43468	0.08571	0.61832	−0.00496	0.00867	186	0
$MnSO_4$	0	45	0.00001	0.36398	0.01826	0.94715	−0.01108	0.02885	114	36
$NaBr$	15	91.95	0.00512	0.54816	0.03090	0.32130	−0.00182	0.00386	139	20
$NaCl$	0	140	0.00006	0.26031	0.07133	0.33349	−0.00568	0.01129	630	7
$NaClO_3$	18	35	0.00053	0.50097	0.06097	0.79294	−0.01679	0.06039	79	1
Na_2CO_3	0	45	0.00042	0.30824	0.06081	0.84564	−0.00819	0.01590	147	0
NaF	0	98.67	0.00041	0.03744	0.02489	0.29430	−0.01375	0.07657	85	6
$NaHCO_3$	0	45	0.00025	0.07810	0.01642	0.12809	−0.00381	0.00745	91	176
NaH_2PO_4	5	80	0.00012	0.60000	0.47090	2.35507	−0.07216	0.09928	38	3
Na_2HPO_4	40	80	0.05000	0.30000	−0.00875	0.62112	0.00038	0.00355	12	0
$NaHSO_3$	10	40	0.00103	0.24298	−0.00850	1.14795	−0.01228	0.05942	91	1
NaI	0	99.96	0.00656	0.75037	0.05082	0.80436	−0.00171	0.00400	92	3
Na_2MoO_4	25	80	0.00611	0.35000	0.09456	0.28754	−0.00540	0.00753	30	0
$NaNO_2$	15	20	0.01000	0.20000	0.00892	0.17519	−0.00086	0.00259	11	0
$NaNO_3$	0	100	0.00128	0.46820	0.04938	0.60805	−0.00306	0.00716	252	29
$NaOH$	0	120	0.00050	0.70000	0.17220	2.71593	−0.01094	0.02659	623	12
Na_3PO_4	40	80	0.05000	0.30000	−0.02280	0.83275	0.00075	0.00388	14	0
Na_2SO_3	19	80	0.01000	0.20000	−0.02610	3.08175	−0.00230	0.06546	43	0
Na_2S2O_3	20	80	0.00399	0.60000	0.84240	1.83868	−0.02573	0.02516	50	0
Na_2SO_4	0	125	0.00032	0.24000	0.16611	0.51522	−0.01924	0.04224	340	9
NH_3	0	100	0.01000	0.30000	0.05431	0.73499	−0.00363	0.01578	172	4
NH_4Cl	0	100	0.00005	0.40000	0.10373	0.59267	−0.00599	0.01778	387	2
NH_4NO_3	0	95	0.00448	0.78740	−0.00268	1.35067	0.00037	0.00426	162	26
$(NH4)_2SO_4$	0	100	0.00656	0.50000	0.27713	1.03004	−0.01061	0.01354	174	0
$NiCl_2$	15	75	0.00045	0.39244	0.12238	0.56366	−0.00722	0.01108	224	6
$NiSO_4$	15	60	0.00005	0.35329	0.04764	0.35323	−0.00456	0.01012	107	8
$SrCl_2$	15	98.81	0.00059	0.28382	−0.00564	1.25027	−0.00131	0.00738	98	6
$ZnCl_2$	0	100	0.00138	0.70000	−0.02405	0.85636	0.00357	0.01414	240	7
$ZnSO_4$	15	60	0.00165	0.36772	0.03498	0.96533	−0.00401	0.00990	227	33
average					0.10438		−0.00866			

Experimental data points with significant error were removed from the calculation of the constants but are included for reference. Significant error here is defined as a point where the residual is greater than the average residual plus or minus 4 times the standard deviation of the residuals. This was tested for both the density residual and the apparent specific volume residual. This rule was not blindly followed, however. If the residual could be seen as being part of a pattern of residuals going steadily worse, typically as the electrolyte mass fraction was going toward a minimum or a maximum, then the point was kept. However, if the residual was found to be significantly different from similar data points, then it was removed. This is usually a sign of a measurement or a transcription error. All inconsistent data points have been kept in the Supporting Information for further study and

Table 3. Interpolating and Extrapolating Density Data for NH_4NO_3 over Mass Fraction

	all data: constants c_0 to c_4 fitted over the entire data/kg m^{-3}		interpolation: constants c_0 to c_4 fitted only where $w_i \leq 0.25$ or $w_i \rangle 0.55$/kg m^{-3}		extrapolation: constants c_0 to c_4 fitted only where $w_i \leq 0.4$/kgm^{-3}	
range	residual	standard deviation	residual	standard deviation	residual	standard deviation
$w_i \leq 0.1$	−0.0126	0.3134	−0.0800	0.3219	0.0545	0.2168
$0.1 \langle w_i \leq 0.2$	−0.0247	0.9325	−0.1546	0.9315	−0.0107	0.8179
$0.2 \langle w_i \leq 0.3$	−0.0053	1.1657	−0.0839	1.1982	0.0443	0.5680
$0.3 \langle w_i \leq 0.4$	−0.1505	1.0908	−0.1394	1.1334	−0.2966	0.6659
$0.4 \langle w_i \leq 0.5$	−0.0845	1.2968	−0.0007	1.3734	0.3383	0.3960
$0.5 \langle w_i \leq 0.6$	0.7051	1.7808	0.7975	1.8365	3.9139	2.8375
$0.6 \langle w_i \leq 0.7$	−0.6898	2.0528	−0.6531	1.9793	5.4216	4.0500
$0.7 \langle w_i \leq 0.8$	0.1778	1.3411	0.1352	1.3466	9.3939	2.4608

Table 4. Interpolating and Extrapolating Density Data for NH_4NO_3 over Temperature

	all data: constants c_0 to c_4 fitted over the entire data/kg m^{-3}		interpolation: constants c_0 to c_4 fitted only where $t \leq 30$ °C or 70 °C$\langle t$/kg m^{-3}		extrapolation: constants c_0 to c_4 fitted only where $t \leq 55$ °C/kg m^{-3}	
range	residual	standard deviation	residual	standard deviation	residual	standard deviation
$t \langle 10$ °C	1.3701	0.7059	1.1927	0.5773	0.5837	0.3488
10 °C $\leq t \langle 20$ °C	0.1487	0.1458	0.0025	0.1237	−0.1210	0.3108
20 °C $\leq t \langle 30$ °C	−0.7216	0.9689	−0.6451	0.9487	−0.4019	0.8846
30 °C $\leq t \langle 40$ °C	0.1736	1.1701	1.3485	0.7956	0.7904	1.1278
40 °C $\leq t \langle 50$ °C	−0.3461	1.1309	0.2488	1.6369	0.1297	1.0129
50 °C $\leq t \langle 60$ °C	0.3468	1.3913	1.6458	1.4481	−0.1526	1.5924
60 °C $\leq t \langle 70$ °C	0.0034	1.1681	0.5982	1.5558	−0.4191	1.6686
70 °C $\leq t \langle 80$ °C	0.3847	1.8403	1.4270	1.7511	−1.9591	2.5133
80 °C $\leq t \langle 90$ °C	0.4964	0.5605	0.2839	0.4698	1.3804	1.1177
90 °C $\leq t \langle 100$ °C	−0.1185	2.7742	−0.2839	2.5867	−0.8945	4.5935

are identified by an exclamation point "!" to the right of the residuals.

Although the occasional single experimental point had to be removed, sometimes an entire data set was inconsistent with several others. If the data set was from an older publication, then it was usually ignored and is not necessarily presented in the Supporting Information, especially if the electrolyte has been well studied and many other data are available. However, if the inconsistent data set was from a more recent publication, then it was not used in the estimation of constants c_0 to c_4 but was kept in the Supporting Information for reference.

A good example is $CdCl_2$, where the set of data from Call[9] and the three sets from Herrington,[37] Rard,[104] and Reilly[107] are mutually inconsistent. The densities measured by Call are systematically higher than those measured by Herrington, Rard, and Reilly. (The densities from Dolian[23] could be interpreted as being consistent with any of these sets.) In this case, we have used the densities from Herrington, Rard, and Reilly, reasoning that three sets of data were less likely to be wrong than one. We have also kept Dolian's set. It is perhaps significant that Call did not check the purity of the $CdCl_2$ he used in his experiments but trusted the certificate of analysis provided by his supplier. In the same paper, Call reported measurements on $MgCl_2$ that are consistent with other data sets for this electrolyte.

Results and Discussion

The values of constants c_0 to c_4 from eq 9 are given in Table 1. Also included in Table 1 is the calculated specific volume $\bar{v}_{app,i}$ of the electrolyte at $w_i = 0.01$ and $t = 25$ °C. This value can be used to determine whether the constants were properly entered when recalculating specific volume. Statistical results, including the average residual and standard deviation for both the solution density and the electrolyte apparent specific volume, are given in Table 2. The apparent specific volume residual is on average −0.0087 l kg^{-1} with a standard deviation of 0.028 l kg^{-1}. When using these apparent specific volumes in eq 6, the average solution density residual is 0.10 kg m^{-3} with a standard deviation of 1.44 kg m^{-3}. These values are calculated over all consistent points and are not an average of the average value for each electrolyte.

Equations 6 and 9 were tested for their usefulness in predicting density outside the range used in estimating their coefficients, both for extrapolation and interpolation. NH_4NO_3 was chosen as the test case because its density residual standard deviation is 1.35 kg m^{-3}, close to the average value for all data sets, and because data are available for it over a wide range of concentration and temperature.

Equations 6 and 9 were first tested for extrapolation and interpolation over the mass fraction. The data were split by slices of 0.1 mass fraction, and the model predictions were compared for the full data set, fitting the data only where the mass fraction is below 0.25 or above 0.55 (interpolation) or fitting the data only where the mass fraction is below 0.4 (extrapolation). Results are found in Table 3.

There is no significant difference when comparing the results over the entire data set and when interpolating over the mass fraction. Results when extrapolating over the mass fraction are different. When extrapolating by less than a mass fraction of 0.1, the fit is still quite good. With an extrapolation of 0.2 mass fraction, there is some degradation in the fit quality, and above this value the degradation becomes significant both in terms of the average residual and in terms of the standard deviation. The density of solutions of NH_4NO_3 of a mass fraction of 0.7 is on the order of 1350 kg m^{-3}, however, and an average residual of 9 kg m^{-3} with a standard deviation of 2.5 kg m^{-3} might still be acceptable for many calculations.

Table 5. Statistical Results for Solutions of More than One Electrolyte in Water (Part 1)

electrolyte 1	electrolyte 2	electrolyte 3	electrolyte 4	average density residual kg/m^3 (eqs 6 and 9)	std dev of density residual kg/m^3 (eqs 6 and 9)	average density residual kg/m^3 (eqs 6 and 10)	std dev of density residual kg/m^3 (eqs 6 and 10)	number of points used	number of inconsistent points
$BaCl_2$	NaCl			−1.03	1.80	0.27	0.69	288	0
$CaCl_2$	KCl			−1.76	2.83	0.26	0.67	162	0
$CaCl_2$	KCl	$MgCl_2$	NaCl	−14.41	0.96	−3.64	0.97	75	0
$CaCl_2$	$MgCl_2$			−0.42	1.85	0.88	1.48	72	0
$CaCl_2$	NaCl			−2.75	3.29	−0.11	1.38	222	0
$CdCl_2$	HCl			−9.68	8.19	−3.91	3.86	19	0
$CuCl_2$	HCl			−8.07	7.26	−1.30	1.82	20	0
$CuSO_4$	H_2SO_4			−6.90	5.37	−2.10	1.33	36	0
$Fe_2(SO_4)_3$	Na_2SO_4			−2.81	3.39	0.87	2.47	9	3
$Fe_2(SO_4)_3$	NaBr			1.21	0.99	3.03	1.43	16	0
$Fe_2(SO_4)_3$	NaCl			0.84	2.28	4.20	1.81	12	0
$Fe_2(SO_4)_3$	$NaNO_3$			1.82	0.93	3.84	1.75	16	0
HCl	$MnCl_2$			−5.85	4.05	3.94	3.71	76	0
KCl	K_2SO_4			−1.61	0.62	−0.26	0.28	30	0
KCl	$MgCl_2$			−1.97	2.37	−0.61	0.80	36	0
KCl	NaBr			−1.73	1.65	0.23	0.25	31	0
KCl	NaCl			−2.50	2.48	−0.16	0.70	145	0
KCl	Na_2SO_4			−1.44	0.80	−0.28	0.41	30	0
KCl	$(NH_4)_2SO_4$			−2.10	1.30	−0.27	0.48	6	0
K_2SO_4	NaCl			−1.66	0.68	−0.45	0.36	32	0
K_2SO_4	Na_2SO_4			−1.99	3.95	−0.80	3.80	28	0
$MgCl_2$	NaCl			−1.35	1.72	0.72	0.98	72	0
$MgSO_4$	NaCl			0.34	1.36	1.10	1.15	66	0
$MgSO_4$	Na_2SO_4			0.71	0.97	0.80	0.95	54	61
NaCl	Na_2SO_4			−0.38	1.01	0.12	0.78	81	0
NaCl	NH_4NO_3			−6.12	6.64	−0.44	0.83	17	0
Na_2SO_4	$(NH_4)_2SO_4$			−10.87	5.79	−0.91	1.67	6	0
average				−0.050		0.003			
std dev					2.750		1.393		
number								1657	64
inconsistent	data sets								
$FeSO_4$	H_2SO_4			−8.07	11.74	16.65	13.89	0	26
$Fe_2(SO_4)_3$	$FeSO_4$	H_2SO_4		−32.64	40.53	−14.58	40.31	0	112
H_2SO_4	$MnSO_4$			−32.17	34.45	−16.57	34.61	0	38
$MnSO_4$	Na_2SO_4			−40.59	16.79	−26.75	13.64	0	13
number									189

The same method was used to evaluate the usefulness of eqs 6 and 9 when interpolating or extrapolating over temperature. Refer to Table 4.

Once again this proves that there is no significant degradation of the fit quality when interpolating data. When extrapolating, there is a significant increase in the standard deviation as the temperature difference increases to 40 °C or more, but this increase is less pronounced than when extrapolating over mass fraction. It should also be noted that restricting the range of mass fraction or temperature used in calculating constants c_0 to c_4 does slightly increase the accuracy of the fit over that range, as indicated by the decrease in the standard deviation.

Prediction of the Density of Solutions of More Than One Electrolyte in Water

Equations 6 and 9 were tested to determine if they could accurately predict data for solutions of more than one electrolyte in water. Data for these solutions are limited, but measurements for 29 different systems of 2 electrolytes in water, 1 system of 3 electrolytes in water, and 1 system of 5 electrolytes in water were found, close to 2000 data points. Not all of these data points were consistent, however; see below.

During the course of this validation, it was found that eqs 6 and 9 were adequate for multielectrolyte solutions at low concentrations. However, at higher concentrations, the error in the calculated density was higher than desired. It was found that a subtle modification of eq 9 decreased this error significantly. By using the total electrolyte concentration $(1 - w_{H_2O})$ instead of the concentration of just the electrolyte in question (w_i) to calculate the electrolyte apparent specific volume, the model was found to be significantly more accurate. The modified form of eq 9 is

$$\bar{v}_{app,i} = \frac{(1 - w_{H_2O}) + c_2 + c_3 t}{(c_0(1 - w_{H_2O}) + c_1)e^{(0.000001(t+c_4)^2)}} \qquad (10)$$

This equation reduces to eq 9 for a solution of just one electrolyte in water. Using eq 10 to calculate the apparent specific volume and eq 6 to calculate the solution density yielded excellent results. Tables 5 and 6 show the results; with eqs 6 and 9, the average solution density residual is −0.05 kg m^{-3} with a standard deviation of 2.75 kg m^{-3}. Using eq 6 and 10 gives an average solution density residual of 0.003 kg m^{-3} with a standard deviation of 1.39 kg m^{-3}. This standard deviation compares favorably with the standard deviation of 1.44 kg m^{-3} for systems of one electrolyte in water.

Four data sets have a much higher standard deviation: solutions of $FeSO_4$ and H_2SO_4, of $FeSO_4$, $Fe_2(SO_4)_3$, and H_2SO_4, of H_2SO_4 and $MnSO_4$, and finally of $MnSO_4$ and Na_2SO_4. For all of these data sets, no recent references were found (except data from Przepiera,[103] which date from 2000). For these four systems, the standard deviation is

Table 6. Statistical Results for Solutions of More than One Electrolyte in Water (Part 2)

electrolyte 1	electrolyte 2	electrolyte 3	electrolyte 4	*t* min °C	*t* max °C	*w* min electrolyte 1	*w* max electrolyte 1	*w* min electrolyte 2	*w* max electrolyte 2	*w* min electrolyte 3	*w* max electrolyte 3	*w* min electrolyte 4	*w* max electrolyte 4	refs
$BaCl_2$	NaCl			25	140	0.003	0.215	0.003	0.187	0.000	0.000	0.000	0.000	67
$CaCl_2$	KCl			25	25	0.000	0.267	0.000	0.251	0.000	0.000	0.000	0.000	59, 136
$CaCl_2$	KCl	$MgCl_2$	NaCl	20	40	0.036	0.040	0.010	0.012	0.117	0.141	0.079	0.083	56
$CaCl_2$	$MgCl_2$			22.87	98.67	0.009	0.136	0.008	0.109	0.000	0.000	0.000	0.000	115
$CaCl_2$	NaCl			5	98.67	0.001	0.259	0.000	0.203	0.000	0.000	0.000	0.000	58, 77, 115, 136
$CdCl_2$	HCl			25	25	0.000	0.379	0.000	0.267	0.000	0.000	0.000	0.000	128
$CuCl_2$	HCl			25	25	0.000	0.309	0.000	0.267	0.000	0.000	0.000	0.000	128
$CuSO_4$	H_2SO_4			25	40	0.032	0.128	0.000	0.200	0.000	0.000	0.000	0.000	42
$Fe_2(SO_4)_3$	Na_2SO_4			25	25	0.043	0.168	0.030	0.123	0.000	0.000	0.000	0.000	14
$Fe_2(SO_4)_3$	NaBr			25	25	0.045	0.169	0.022	0.093	0.000	0.000	0.000	0.000	15
$Fe_2(SO_4)_3$	NaCl			25	25	0.045	0.169	0.025	0.105	0.000	0.000	0.000	0.000	14
$Fe_2(SO_4)_3$	$NaNO_3$			25	25	0.046	0.170	0.018	0.078	0.000	0.000	0.000	0.000	15
HCl	$MnCl_2$			25	25	0.001	0.335	0.005	0.412	0.000	0.000	0.000	0.000	128
KCl	K_2SO_4			5	95	0.012	0.115	0.010	0.092	0.000	0.000	0.000	0.000	20
KCl	$MgCl_2$			25	25	0.004	0.220	0.003	0.113	0.000	0.000	0.000	0.000	60
KCl	NaBr			25	25	0.007	0.200	0.008	0.263	0.000	0.000	0.000	0.000	61
KCl	NaCl			5	95	0.001	0.210	0.001	0.184	0.000	0.000	0.000	0.000	20, 30, 77, 135
KCl	Na_2SO_4			5	95	0.012	0.115	0.008	0.076	0.000	0.000	0.000	0.000	20
KCl	$(NH_4)_2SO_4$			25	25	0.032	0.062	0.059	0.113	0.000	0.000	0.000	0.000	30
K_2SO_4	NaCl			5	95	0.011	0.092	0.010	0.092	0.000	0.000	0.000	0.000	20
K_2SO_4	Na_2SO_4			5	95	0.002	0.092	0.008	0.083	0.000	0.000	0.000	0.000	20
$MgCl_2$	NaCl			22.87	98.67	0.009	0.107	0.015	0.203	0.000	0.000	0.000	0.000	115
$MgSO_4$	NaCl			25	125	0.001	0.152	0.006	0.127	0.000	0.000	0.000	0.000	27, 77
$MgSO_4$	Na_2SO_4			25	125	0.001	0.035	0.001	0.021	0.000	0.000	0.000	0.000	27, 63
NaCl	Na_2SO_4			5	125	0.006	0.127	0.001	0.076	0.000	0.000	0.000	0.000	20, 27
NaCl	NH_4NO_3			25	25	0.007	0.218	0.010	0.386	0.000	0.000	0.000	0.000	77
Na_2SO_4	$(NH_4)_2SO_4$			25	25	0.051	0.101	0.058	0.236	0.000	0.000	0.000	0.000	30
average														
std dev														
number														
inconsistent	data sets													
$FeSO_4$	H_2SO_4			−10	25	0.024	0.207	0.014	0.250	0.000	0.000	0.000	0.000	63
$Fe_2(SO_4)_3$	$FeSO_4$	H_2SO_4		25	80	0.000	0.220	0.000	0.152	0.001	0.067	0.000	0.000	76
H_2SO_4	$MnSO_4$			12.6	45	0.058	0.991	0.001	0.297	0.000	0.000	0.000	0.000	63, 103
$MnSO_4$	Na_2SO_4			97	97	0.007	0.265	0.022	0.295	0.000	0.000	0.000	0.000	63
number														

more than 6 times the standard deviation of all of the other data. This makes the data for these systems highly suspect, and the data sets have been excluded from the calculation of the average and standard deviation. They have been included for reference in the supplementary data.

Conclusions

An empirical model has been developed that can predict the density of aqueous solutions of one or more electrolytes. Experimental data from 59 electrolytes have been fit to the model over a wide range of temperature and concentration. The model has been tested by calculating the difference between the experimental and predicted density of solutions of more than one electrolyte in water. The average difference was found to be 0.10 with a standard deviation of 1.42 kg m^{-3} over a wide range of temperature and concentration.

Further Work

As explained above, one of the main sources of inaccuracy in the model presented here is the lack of consistency between different data sets. This is particularly the case for many metal sulfates, where there is very little published information and what has been published is often of poor quality. The data for $CoSO_4$, $FeSO_4$, and $Fe_2(SO_4)_3$ are especially poor. Additional experimental data for these electrolytes, perhaps also as mixtures with H_2SO_4, over a wide range of concentration and temperature would definitely be helpful.

For some electrolytes such as NaOH and HNO_3, there is a lot of consistent information available, but eqs 6 and 9 do not represent the data perfectly. In addition to the expected apparent volume residual at low concentration, the model tends to over or underestimate the density at various mass fractions, and this over or underestimation varies with temperature. We are reasonably confident that this effect is real and is not caused by inconsistent data, but there is no obvious modification to eq 9 that could represent this behavior easily.

List of Symbols

c_0, empirical constant in eqs 9 and 10, kg m^{-3}
c_1, empirical constant in eqs 9 and 10, kg m^{-3}
c_2, empirical constant in eqs 9 and 10, dimensionless
c_3, empirical constant in eqs 9 and 10, $°C^{-1}$
c_4, empirical constant in eqs 9 and 10, °C
t, temperature, °C
$v_{\mathrm{app},i}$, apparent volume of component i, m^3
$\bar{v}v_{\mathrm{app},i}$, specific volume of component i, m^3 kg^{-1}
v_i, volume of ideal component i, m^3
v_{H_2O}, volume of water, m^3
v_{m}, volume of the mixture, m^3
w_{H_2O}, mass fraction of water
w_i, mass fraction of component i
$\rho_{\mathrm{app},i}$, apparent density of component i, kg m^{-3}
ρ_{H_2O}, density of water, kg m^{-3}
ρ_i, density of ideal component i, kg m^{-3}
ρ_{m}, density of the mixture, kg m^{-3}

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Supporting Information Available:

Calculation spreadsheets for all of the electrolyte solutions presented in Tables 1, 2, and 5. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Adams, L. H. Equilibrium in Binary Systems Under Pressure. III. The Influence of Pressure on the Solubility of Ammonium Nitrate in Water at 25 °C. *J. Am. Chem. Soc.* **1932**, *54*, 4520−4537.

(2) Akerlof, G.; Teare, J. A Note on the Density of Aqueous Solutions of Hydrochloric Acid. *J. Am. Chem. Soc.* **1938**, *60*, 1226−1228

(3) Akerlof, G.; Kegeles, G. The Density of Aqueous Solutions of Sodium Hydroxide. *J. Am. Chem.* **1939**, *61*, 1027−1032

(4) Akerlof, G.; Bender, P. The Density of Aqueous Solutions of Potassium Hydroxide. *J. Am. Chem. Soc.* **1941**, *63*, 1085−1088.

(5) Albright, J. G.; Miller, D. G. Mutual Diffusion Coefficient of $ZnSO_4$ at 25 °C. *J. Solution Chem.* **1975**, *4*, 809−816.

(6) Asmus, A. The Viscosities of Aqueous Solutions of Strong Electrolytes of High Valence Type. *Ann. Phys.* **1939**, *35*, 1−22.

(7) Bakeev, M. I.; Zharmenov, A. A.; Andamasov, R. S.; Baikenova, N. A.; Abdygalimova, S. Sh. Electrical Conductivity and Viscosity of the Binary Systems $MeSO_4-H_2O$ ($Me = Mn^{2+}$, Fe^{2+}, Co^{2+}, Zn^{2+}, Cd^{2+}) at 25−75 Degree and the Structure of Electrolyte Solutions. *Izv. Nats. Akad. Nauk, Resp. Kaz., Ser. Khim.* **1994**, *6*, 25−30.

(8) Berchiesi, M. A.; Berchiesi, G.; Lobbia, G. G. Apparent Molal Volumes of Alkali Metal Nitrates at 30 °C. *J. Chem. Eng. Data* **1974**, *19*, 326−328.

(9) Call, T. G.; Ballerat-Busserolles, K.; Origlia, M. L.; Ford, T. D.; Woolley, E. M. Apparent Molar Volumes and Heat Capacities of Aqueous Magnesium Chloride and Cadmium Chloride at Temperatures from 278.15 K to 393.15 K at the Pressure 0.35 MPa: A Comparison of Ion−Ion Interactions. *J. Chem. Thermodyn.* **2000**, *32*, 1525−1538.

(10) Campbell, A. N.; Kartzmark, E. M. The Conductances of Strong Solutions of Strong Electrolytes at 95 °C. *Can. J. Chem.* **1952**, *30*, 128−134.

(11) Campbell, A. N.; Kartzmark, E. M.; Oliver, B. G. The Electrolytic Conductances of Sodium Chlorate and of Lithium Chlorate in Water and in Water−Dioxane. *Can. J. Chem.* **1966**, *44*, 925−934.

(12) Cartón, A.; Sobrón, F.; Bolado, S.; Gerbolés, J. I. Density, Viscosity, and Electrical Conductivity of Aqueous Solutions of Lithium Sulfate. *J. Chem. Eng. Data* **1995**, *40*, 987−991.

(13) Chen, C.-T. A.; Chen, J. H.; Millero, F. J. Densities of NaCl, $MgCl_2$, Na_2SO_4, and $MgSO_4$ Aqueous Solutions at 1 atm from 0 to 50 °C and from 0.001 to 1.5 *m*. *J. Chem. Eng. Data* **1980**, *25*, 307−310.

(14) Chenlo, F.; Moreira, R.; Pereira, G.; Vazquez, J.; Viscosidad de Disoluciones Acusas de $Fe_2(SO_4)_3$, $Fe_2(SO_4)_3-Na_2SO_4$ y $Fe_2(SO_4)_3-$NaCl a Diferentes Concentrationes y Temperaturas. *Afinidad* **1997**, *54*, 126−128.

(15) Chenlo, F.; Moreira, R.; Pereira, G.; Vazquez, M. J. Viscosities of Aqueous Solutions of $Fe_2(SO_4)_3$ Containing $NaNO_3$, KNO_3, NaBr, or KBr from 293.1 to 323.1 K. *J. Chem. Eng. Data* **1998**, *43*, 325−328.

(16) Choudary, N. V.; Jasra, R. V. Densities of Aqueous Solutions of Sodium Bisulfite and Sodium 2-Methalallyl Sulfate. *J. Chem. Eng. Data* **1994**, *39*, 9, 181−183.

(17) Christensen, J. H.; Reed, R. B. Density of Aqueous Solutions of Phosphoric Acid. Measurements at 25 °C. *Ind. Eng. Chem.* **1955**, *47*, 1277−1279.

(18) Cupples, H. L. Surface Tension of Aluminium Sulfate Solutions. *J. Phys. Chem.* **1946**, *50*, 256−260.

(19) Deckwer, W. D. Density, Viscosity, Vapor Pressure, and Hydrogen Solubility of Aqueous $MnSO_4$ Solutions. *J. Chem. Eng. Data* **1980,** *25*, 75−76.

(20) Dedick, E. A.; Hershey, J. P.; Sotolongo, S.; Stade, D. J.; Millero, F. J. The PVT Properties of Concentrated Aqueous Electrolytes IX. The Volume Properties of KCl and K_2SO_4 and their Mixtures with NaCl and Na_2SO_4 as a Function of Temperature. *J. Solution Chem.* **1990**, *19*, 353−374.

(21) *Degrémont, Mémento Technique de l'eau*; Paris, 1989.

(22) Doan, T. H.; Sangster, J. Viscosities of Concentrated Aqueous Solutions of Some 1:1, 2:1, and 3:1 Nitrates at 25 °C. *J. Chem. Eng. Data* **1981**, *26*, 141−144.

(23) Dolian, F. E. The Viscosities of Solutions of Chlorides in Certain Solvents. *J. Phys. Chem.* **1937**, *41*, 1129−1138.

(24) Doménech, J.; Rivera, S. Viscosity B-Coefficient for Sodium Bromide in Formamide−Water Mixtures. *Z. Phys. Chem. N. F.* **1983**, *136*, 153−161.

(25) Egan, E. P.; Luff, B. B. Density of Aqueous Solutions of Phosphoric Acid. Measurements at 15° to 80 °C. *Ind. Eng. Chem.* **1955**, *47*, 1280−1280.

(26) Ellis, R. N.; Stokes, R. H.; Wright, A. C.; Spiro, M. Transference Numbers and Conductance in Concentrated Copper(II) Chloride Solutions at 25 °C. *Aust. J. Chem.* **1983**, *36*, 1913−1921.

(27) Fabuss, B. M.; Korosi, A.; Huq, A. K. M. S. Densities of Binary and Ternary Aqueous Solutions of NaCl, Na_2SO_4, and $MgSO_4$, of Seawaters, and Seawater Concentrates. *J. Chem. Eng. Data* **1966**, *3*, 325−331

(28) Gates, J. A.; Wood, R. H. Densities of Aqueous Solutions of NaCl, $MgCl_2$, KCl, NaBr, LiCl, and $CaCl_2$ from 0.05 to 5.0 mol kg^{-1} and 0.1013 to 40 MPa at 298.15 K. *J. Chem. Eng. Data* **1985**, *30*, 44−49.

(29) Ginzburg, D. M.; Pikulina, N. S.; Litvin, V. P. Density of Potassium Carbonate Solutions. *J. Appl. Chem. USSR* **1964**, *37*, 2353−2357.

(30) Goldsack, D. E.; Franchetto, A. A. The Viscosity of Concentrated Electrolyte Solutions. III. A Mixture Law. *Electrochim. Acta* **1977**, *22*, 1287−1294.

(31) Gonçalves, F. Kestin, J. The Viscosity of NaCl and KCl Solutions in the Range 25−50 °C. *Ber. Bunsen-Ges. Phys. Chem.* **1977**, *81*, 1156−1161.

(32) Gucker, F. T.; Stubley, D.; Hill, D. J. The Isentropic Compressibilities of Aqueous Solutions of Some Alkali Halides at 298.15 K. *J. Chem. Thermodyn.* **1975**, *7*, 865−869.

(33) Gunther, P.; Perschke, W.; Comparison of Some Physical Constants of Thyocyanate, Azide and Nitrite Solutions. *J. Chem. Soc.* **1930**, 100−104.

(34) Gupta, S. V. *Practical Density Measurement and Hydrometry*; Institute of Physics Publishing: Bristol, U.K., 2002.

(35) Haase, R.; Saurmann, P.-F.; Dücker, K.-H. Conductivities of Concentrated Electrolyte Solutions. II. Nitric Acid. *Z. Phys. Chem. N. F.* **1965**, *46*, 129−139.

(36) Haase, R.; Saurmann, P.-F.; Dücker, K.-H. Conductivity of Concentrated Electrolyte Solutions. V. Sulfuric Acid. *Z. Phys. Chem. N. F.* **1966**, *48*, 206−212.

(37) Herrington, T. M.; Roffey, M. G.; Smith, D. P. Densities of Aqueous Electrolytes $MnCl_2$, $CoCl_2$, $NiCl_2$, $ZnCl_2$, and $CdCl_2$ from 25 to 72 °C at 1 atm. *J. Chem. Eng. Data*, **1986**, *31*, 221−225.

(38) Hershey, J. P.; Sotolongo, S.; Millero, F. J. Densities and Compressibilities of Aqueous Sodium Carbonate and Bicarbonate from 0 to 45 °C. *J. Solution Chem.* **1983**, *12*, 233−254.

(39) Hershey, J. P.; Sotolongo, S.; Millero, F. J. Densities and Compressiblities of Aqueous HCl and NaOH from 0 to 45 °C. The Effect of Pressure on the Ionization of Water. *J. Solution Chem.* **1984**, *13*, 825−848.

(40) Herz, W. Internal Friction of Salt Solutions (C. A. Trans. from German). *Z. Anorg. Chem.* **1914**, *89*, 393−396.

(41) Hitchcock, L. B.; McIlhenny, J. S. Viscosity and Density of Pure Alkaline Solutions and their Mixtures. *Ind. Eng. Chem.* **1935**, *27*, 461−466.

(42) Holler, H. D.; Peffer, E. L. The Density of Aqueous Solutions of Copper Sulfate and Sulfuric Acid. *J. Am. Chem. Soc.* **1916**, *38*, 1021−1029.

(43) *Revised Supplementary Release on Saturation Properties of Ordinary Water Substance*; International Association for the Properties of Water and Steam: St. Petersburg, Russia, 1992.

(44) Isono, T. Measurements of Density, Viscosity, and Electrolytic Conductivity of Concentrated Aqueous Electrolyte Solutions. *Rikagaku Kenkyusho Hokoku* **1980**, *56*, 103−114.

(45) Isono, T. Densities, Viscosities, and Electrolytic Conductivity of Concentrated Aqueous Electrolyte Solutions at Several Temperatures. Alkaline-Earth Chlorides, $LaCl_3$, Na_2SO_4, $NaNO_3$, NaBr, KNO_3, KBr, and $Cd(NO_3)_2$. *J. Chem. Eng. Data* **1984**, *29*, 45−52.

(46) Isono, T. Densities, Viscosities, and Electrolytic Conductivities of Concentrated Aqueous Electrolyte Solutions of 31 Solutes in the Temperature Range 15−55 °C and Empirical Equations for the Relative Viscosity. *Rikagaku Kenkyusho Hokoku* **1985**, *61*, 53−79

(47) Kaminsky, M. Experimental Investigations of the Concentration and Temperature Dependence of the Viscosity of Aqueous Solutions of Strong Electrolytes. I. Potassium Iodide, Ammonium Chloride, and Sodium Sulphate Solutions. *Z. Phys. Chem. N. F.* **1955**, *5*, 154−191.

(48) Kaminsky, M. Concentration and Temperature Dependence of the Viscosity of Aqueous Solutions of Strong Electrolytes. II. NaCl, Li_2SO_4, $FeCl_2$, and $CeCl_3$ Solutions. *Z. Phys. Chem. N. F.* **1956**, *8*, 173−191.

(49) Kaminsky, M, Concentration and Temperature Dependence of the Viscosity of Aqueous Solutions of Strong Electrolytes. III. KCl, K_2SO_4, $MgCl_2$, $BeSO_4$, and $MgSO_4$ Solutions. *Z. Phys. Chem. N. F.* **1957**, *12*, 206−231.

(50) Kartzmark, E. M. Conductances, Densities, and Viscosities of Solutions of Sodium Nitrate in Water and in Dioxane−Water at 25 °C. *Can. J. Chem.* **1972**, *50*, 2845−2850.

(51) Kell, G. S. Density, Thermal Expansitivity, and Compressibility of Liquid Water from 0 to 150 °C: Correlations and Tables for Atmospheric Pressure and Saturation Reviewed and Expressed on 1968 Temperature Scale. *J. Chem. Eng. Data*, **1975**, *20*, 97−105.

(52) Korosi, A.; Fabuss, B. M. Viscosities of Binary Aqueous Solutions of NaCl, KCl, Na_2SO_4, and $MgSO_4$ at Concentrations and Temperatures of Interest in Desalination Processes. *J. Chem. Eng. Data* **1968**, *13*, 548–552.

(53) Kortüm, G.; Reber, H. Density, Viscosity, and Dielectric Constant of Pure Hydrocyanic Acid and of Hydrocyanic Acid–Water Mixtures at 0°. *Z. Elektrochem.* **1961**, *65*, 809

(54) Krey, J. Vapour Pressure and Density of the System Water–Sodium Hydroxide. *Z. Phys. Chem. N. F.* **1972**, *81*, 252–273.

(55) Krishnamurty, B. Ultrasonic Studies in Electrolytes: Part I – Alkali Halides. *Ind. Res. (India)* **1950**, *9B*, 215–219.

(56) Krumgalz, B. S.; Millero, F. J. Physico-Chemical Study of Dead Sea Waters II. Density Measurements and Equation of State of Dead Sea Waters at 1 atm. *Mar. Chem.* **1982**, *11*, 477–492.

(57) Kumar, A.; Atkinson, G.; Howell, R. D. Thermodynamics of Concentrated Electrolyte Mixtures. II. Densities and Compressibilities of Aqueous NaCl–$CaCl_2$ at 25 °C. *J. Solution Chem.* **1982**, *11*, 857–870.

(58) Kumar, A.; Atkinson, G. Thermodynamics of Concentrated Electrolyte Mixtures. 3. Apparent Molal Volume, Compressibilities, and Expansibilities of NaCl–$CaCl_2$ Mixtures from 5 to 35 °C. *J. Phys. Chem.* **1983**, *87*, 5504–5507.

(59) Kumar, A. Densities and Apparent Molal Volumes of Aqueous KCl–$CaCl_2$ Mixtures at 298.15 K. *J. Chem. Eng. Data.* **1986**, *31*, 21–23.

(60) Kumar, A. Mixture Densities and Volumes of Aqueous KCl–$MgCl_2$ up to Ionic Strength of 4.5 mol kg^{-1} and at 298.15 K. *J. Chem. Eng. Data* **1989**, *34*, 87–89.

(61) Kumar, A. Densities and Excess Volumes of Aqueous KCl–NaBr up to Ionic Strength of 4 mol kg^{-1}. *J. Chem. Eng. Data* **1989**, *34*, 446–447.

(62) Lengyel, S.; Tamás, J.; Giber, J.; Holderith, J. Study of Viscosity of Aqueous Alkali Halide Solutions. *Acta Chim. Acad. Sci. Hung.* **1964**, *40*, 125–143.

(63) Linke, W. F. *Solubilities: Inorganic and Metal-Organic Compounds*, 4th ed.; American Chemical Society: Washington, DC, 1965.

(64) Lobo, V. M. M. *Handbook of Electrolyte Solutions.*; Elsevier Science: New York, 1989.

(65) MacInnes, D. A.; Dayhoff, M. O. The Partial Molal Volumes of Potassium Chloride, Potassium and Sodium Iodides and Iodine in Aqueous Solution at 25 °C. *J. Am. Chem. Soc.* **1952**, *74*, 1017–1020.

(66) Maksimova, I. N.; Yushkevich, V. F. Electrical Conductivity of Sodium Hydroxide Solutions at High Temperatures. *Z. Fiz. Khim.* **1963**, *37*, 903–907.

(67) Manohar, S.; Pulchaska, D.; Atkinson, G.; Pressure–Volume–Temperature Properties of Aqueous Mixed Electrolyte Solutions: NaCl + $BaCl_2$ from 25 to 140 ° C. *J. Chem. Eng. Data*, **1994**, *39*, 150–154

(68) *Recommended Reference Materials for the Realization of Physicochemical Properties*; Marsh, K. N., Ed.; Blackwell Scientific Publishing: Oxford, U.K., 1987.

(69) Mashovets, V. P.; Dibrov, I. A.; Krumgal'z, B. S.; Mateeva, R. P. Density of Aqueous KOH Solutions at High Temperatures over a Wide Range of Concentrations. *J. Appl. Chem. USSR* **1965**, *38*, 2344–2347.

(70) Mason, C. M. The Activity and Osmotic Coefficient of Trivalent Metal Chlorides in Aqueous Solution from Vapor Pressure Measurements at 25 °C. *J. Am. Chem. Soc.* **1938**, *60*, 1638–1647.

(71) Mason, C. M.; Culvern, J. B. Electrical Conductivity of Orthophosphoric Acid and of Sodium and Potassium Dihydrogen Phosphates at 25 °C. *J. Am. Chem. Soc.* **1949**, *71*, 2387–2393.

(72) Millero, F. J.; Knox, J. H. Apparent Molal Volumes of Aqueous NaF, Na_2SO_4, KCl, K_2SO_4, $MgCl_2$, and $MgSO_4$ Solutions at 0° and 50 °C. *J. Chem. Eng. Data* **1973**, *18*, 407–411.

(73) Millero, F. J.; Ward, G. K.; Chetirkin, P. V. Relative Sound Velocities of Sea Salts at 25 °C. *J. Acoust. Soc. Am.* **1977**, *61*, 1492–1498.

(74) Motin, M. A. Temperature and Concentration Dependence of Apparent Molar Volumes and Viscosities of NaCl, NH_4Cl, $CuCl_2$, and $MgSO_4$ in Pure Water and Water + Urea Mixtures. *J. Chem. Eng. Data.* **2004**, *49*, 94–98.

(75) National Research Council. *International Critical Tables of Physical and Numerical Data, Physics, Chemistry, and Technology*; McGraw-Hill: New York, 1928.

(76) Novikov, S. G.; Rud'ko, P. K.; Klepatskii, P. M.; Brazovskii, P. M. Density and Viscosity of Sulfuric Acid Solutions of Iron(II) and Iron(III) Sulfates. *Vestsi Akad. Navuk BSSR, Ser. Khim. Navuk* **1991**, 52–54.

(77) Nowlan, M.-F.; Doan, T. H.; Sangster, J. Prediction of the Viscosity of Mixed Electrolyte Solutions from Single-Salt Data. *Can. J. Chem. Eng.* **1980**, *58*, 637–642.

(78) Olofsson, I. V.; Spitzer, J. J.; Hepler, L. G. Apparent Molar Heat Capacities and Volumes of Aqueous Electrolytes at 25 °C: Na_2SO_4, K_2SO_4, $Na_2S_2O_3$, $Na_2S_2O_8$, $K_2S_2O_8$, K_2CrO_4, Na_2MoO_4, and Na_2WO_4. *Can. J. Chem.* **1978**, *56*, 1871–1873.

(79) Olofsson, I. V. Apparent Molar Heat Capacities and Volumes of Aqueous NaCl, KCl, and KNO_3 at 298.15 K. Comparison of Picker Flow Calorimeter with Other Calorimeters. *J. Chem. Thermodyn.* **1979**, *11*, 1005–1014.

(80) Out, D. J. P.; Los, J. M. Viscosity of Aqueous Solutions of Univalent Electrolytes from 5 to 95 °C. *J. Solution Chem.* **1980**, *9*, 19–35.

(81) Patterson, B. A.; Call, T. G.; Jardine, J. J.; Origlia-Luster, M. L.; Woolley, E. M. Thermodynamics for Ionization of Water at Temperatures from 278.15 K to 393.15 K and at the Pressure 0.35 MPa: Apparent Molar Volumes of Aqueous KCl, KOH, and NaOH and Apparent Molar Heat Capacities of Aqueous HCl, KCl, KOH, and NaOH. *J. Chem. Thermodyn.* **2001**, *33*, 1237–1262.

(82) Patterson, B. A.; Woolley, E. M. Thermodynamics for Ionization of Water at Temperatures from 278.15 K to 393.15 K and at the Pressure 0.35 MPa: Apparent Molar Volumes and Apparent Molar Heat Capacities of Aqueous Solutions of Potassium and Sodium Nitrates and Nitric Acid. *J. Chem. Thermodyn.* **2002**, *34*, 535–556.

(83) Pearce, J. N.; Eckstrom, H. C. The Vapor Pressure and Some Thermodynamic Properties of Aqueous Solutions of Nickel Chloride at 25 °C. *J. Phys. Chem.* **1937**, *41*, 563–565.

(84) Pearce, J. N.; Pumplin, G. G. The Apparent and Partial Molal Volume of Ammonium Chloride and of Cupric Sulfate in Aqueous Solutions at 25 °C. *J. Am. Chem. Soc.* **1937**, *59*, 1221–1222.

(85) Pearce, J. N.; Eckstrom, H. C. Vapor Pressures and Partial Molal Volumes of Aqueous Solutions of the Alkali Sulfates at 25 °C. *J. Am. Chem. Soc.* **1937**, *59*, 2689–2691.

(86) Pedersen, T. G.; Dethlefsen, C.; Hvidt, A. Volumetric Properties of Aqueous Solutions of Alkali Halides. *Carlsberg Res. Commun.* **1984**, *49*, 445–455.

(87) Perron, G.; Desnoyers, J. E.; Millero, F. J. Apparent Molal Volumes and Heat Capacities of Alkaline Earth Chlorides in Water at 25 °C. *Can. J. Chem.* **1974**, *52*, 3738–3741.

(88) Perron, G.; Desnoyers, J. E.; Millero, F. J. Apparent Molal Volumes and Heat Capacities of Some Sulfates and Carbonates in Water at 25 °C. *Can. J. Chem.* **1975**, *53*, 1134–1138.

(89) Perron, G.; Fortier, J.-L.; Desnoyers, J. E. Apparent Molar Heat Capacities and Volumes of Aqueous NaCl from 0.01 to 3 mol kg^{-1} in the Temperature Range 274.65 to 318.15 K. *J. Chem. Thermodyn.* **1975**, *7*, 1177–1184.

(90) Perry, R. H.; Green, D. W. *Perry's Chemical Engineers' Handbook*, 7th ed.; McGraw-Hill: New York, 1997.

(91) Phang, S. Viscosity and Transference Number Measurements of Concentrated Nickel Chloride Solutions at 298.15 K. *Aust. J. Chem.* **1979**, *32*, 1149–1153.

(92) Phang, S. The Density, Viscosity, and Transference Number of Aqueous Manganese Chloride at 298.15 K. *Aust. J. Chem.* **1980**, *33*, 413–417.

(93) Phang, S. The Density, Viscosity and Transference Number of Aqueous Cobalt Chloride at 298.15 K. *Aust. J. Chem.* **1980**, *33*, 641–645.

(94) Phillips, V. R. Specific Gravity, Viscosity, and Solubility for Aqueous Nickel Sulfate Solutions. *J. Chem. Eng. Data* **1972**, *17*, 357–360.

(95) Demichowicz-Pigoniowa, J. Dependence of Density, Viscosity and Electric Conductivity of Aqueous $CuSO_4$ Solutions on Temperature and Concentration. *Ann. Soc. Chim. Pol.* **1973**, *47*, 2183–2190.

(96) Pilar Peña, M.; Vercher, E.; Martínez-Andreu, A. Apparent Molar Volumes of Strontium Chloride in Ethanol + Water at 298.15 K. *J. Chem. Eng. Data* **1997**, *42*, 187–189.

(97) Pogue, R. F.; Atkinson, G. Solution Thermodynamics of First-Row Transition Elements. 1. Apparent Molal Volumes of Aqueous $NiCl_2$, $Ni(ClO_4)_2$, $CuCl_2$, and $Cu(ClO_4)_2$, from 15 to 55 °C. *J. Chem. Eng. Data* **1988**, *33*, 370–376.

(98) Pogue, R.; Atkinson, G. Apparent Molal Volumes and Heat Capacities of Aqueous HCl and $HClO_4$ at 15–55 °C. *J. Chem. Eng. Data* **1988**, *33*, 495–499.

(99) Pogue, R. F.; Atkinson, G. Solution Thermodynamics of First-Row Transition Elements. 2. Apparent Molal Volumes of Aqueous $MnCl_2$, $Mn(ClO_4)_2$, $CoCl_2$, $Co(ClO_4)_2$, $FeCl_2$, and $Fe(ClO_4)_2$, from 15 to 55 °C. *J. Chem. Eng. Data* **1989**, *34*, 227–232.

(100) Pogue, R. F.; Atkinson, G. Solution Thermodynamics of First-Row Transition Elements. 3. Apparent Molal Volumes of Aqueous $ZnCl_2$ and $Zn(ClO_4)_2$ from 15 to 55 °C and an Examination of Solute–Solute and Solute–Solvent Interactions. *J. Solution Chem.* **1989**, *18*, 249–264.

(101) Puchalska, D.; Atkinson, G.; Routh, S. Solution Thermodynamics of First-Row Transition Elements. 4. Apparent Molal Volumes of Aqueous $ZnSO_4$ and $CuSO_4$ Solutions from 15 to 55 °C. *J. Solution Chem.* **1993**, *22*, 625–639.

(102) Puchkov, L. V.; Matashkin, V. G. Densities of $LiNO_3$–H_2O and $NaNO_3$–H_2O Solutions at Temperatures in the Range 25–300 °C. *J. Appl. Chem. USSR* **1970**, *43*, 1848–1851.

(103) Przepiera, A.; Zielenkiewicz, A. Apparent Molar Volumes of Aqueous Solution in the $MnSO_4$ + H_2SO_4 System. *Bull. Pol. Acad. Sci. Chem.* **2000**, *48*, 267–272.

(104) Rard, J. A.; Miller, D. G. Densities and Apparent Molal Volumes of Aqueous Manganese, Cadmium, and Zinc Chlorides at 25 °C. *J. Chem. Eng. Data* **1984**, *29*, 151–156.

(105) Rard, J. A. Densities and Apparent Molal Volumes of Aqueous Nickel Chloride at 25 °C. *J. Chem. Eng. Data* **1986**, *31*, 183−185.

(106) Rashkovskaya, E. A.; Chernen'kaya, E. I. Densities of Solutions of NH_4HCO_3, $NaHCO_3$, NH_4Cl and Ammonia in the 20−100° Range. *J. Appl. Chem. USSR* **1967**, *40*, 301−308.

(107) Reilly, P. J.; Stokes, R. H. The Diffusion Coefficients of Cadmium Chloride and Cadmium Perchlorate in Water at 25 °C. *Aust. J. Chem.* **1971**, *24*, 1361−1367.

(108) Roux, A.; Musbally, G. M.; Perron, G.; Singh, P. P.; Woolley, E. M.; Hepler, L. G. Apparent Molal Heat Capacities and Volumes of Aqueous Electrolytes at 25 °C: $NaClO_3$, $NaClO_4$, $NaNO_3$, $NaBrO_3$, $NaIO_3$, $KClO_3$, $KBrO_3$, KIO_3, NH_4NO_3, NH_4Cl, and NH_4ClO_4. *Can. J. Chem.* **1978**, *56*, 24−28.

(109) Roux, A. H.; Perron, G.; Desnoyers, J. E. Heat Capacities, Volumes, Expansibilities, and Compressibilities of Concentrated Aqueous Solutions of LiOH, NaOH, and KOH. *Can. J. Chem.* **1984**, *62*, 878−885.

(110) Roy, M. N.; Jha, A.; Choudhury, A. Densities, Viscosities and Adiabatic Compressibilities of Some Mineral Salts in Water at Different Temperatures. *J. Chem. Eng. Data* **2004**, *49*, 291−296.

(111) Salavera, D.; Esteve, X.; Patil, K. R.; Mainair, A. M.; Coronas, A. Solubility, Heat Capacity, and Density of Lithium Bromide + Lithium Iodide + Lithium Nitrate + Lithium Chloride Aqueous Solutions at Several Compositions and Temperatures. *J. Chem. Eng. Data*, **2004**, *49*, 613−619.

(112) Saluja, P. P. S.; LeBlanc, J. C.; Hume, H. B. Apparent Molar Heat Capacities and Volumes of Aqueous Solutions of Several 1:1 Electrolytes at Elevated Temperatures. *Can. J. Chem.* **1986**, *64*, 926−931.

(113) Saluja, P. P. S.; LeBlanc, J. C. Apparent Molar Heat Capacities and Volumes of Aqueous Solutions of $MgCl_2$, $CaCl_2$, and $SrCl_2$ at Elevated Temperatures. *J. Chem. Eng. Data* **1987**, *32*, 72−76.

(114) Saluja, P. P. S.; Lemire, R. J.; LeBlanc, J. C. High-Temperature Thermodynamics of Aqueous Alkali-Metal Salts. *J. Chem. Thermodyn.* **1992**, *24*, 181−203.

(115) Saluja, P. P. S.; Jobe, D. J.; LeBlanc, J. C.; Lemire, R. J. Apparent Molar Heat Capacities and Volumes of Mixed Electrolytes: [NaCl(aq) + $CaCl_2$(aq)], [NaCl(aq) + $MgCl_2$(aq)], and [$CaCl_2$(aq) + $MgCl_2$(aq)]. *J. Chem. Eng. Data* **1995**, *40*, 398−406.

(116) Sangwal, K. A New Equation for the Temperature Dependence of Density of Saturated Aqueous Solutions of Electrolytes. *Cryst. Res. Technol.* **1987**, *22*, 789−792.

(117) Schmelzer, N.; Einfeldt, J. Density Measurements in Some Aqueous and Non-Aqueous Electrolyte Solutions at 25 °C. *Wiss. Z. Uni. Rostock* **1989**, *38*, 81−82.

(118) Scott, A. F.; Durham, E. J. Studies in the Solubilities of the sOluble Electrolytes. *J. Phys. Chem.* **1930**, *34*, 1424−1438.

(119) Scott, A. F.; Obenhaus, V. M.; Wilson, R. W. The Compressibility Coefficients of Solutions of Eight Alkali Halides. *J. Phys. Chem.* **1934,** *38*, 931−940.

(120) Sharma, R. C.; Gaur, H. C. Densities and Molar Volumes of the Ammonium Nitrate−Water System. *J. Chem. Eng. Data* **1977**, *22*, 41−44.

(121) Silva, J. W.; Chenevey, J. E. Specific Gravity of Aluminum Sulfate Solutions. *Ind. Eng. Chem.* **1945**, *37*, 1016−1018.

(122) Soehnel, P.; Novotny, P.; Solc, Z. Densities of Aqueous Solutions of 18 Inorganic Substances. *J. Chem. Eng. Data.* **1984**, *29*, 379−382.

(123) Spitzer, J. J.; Singh, P. P.; McCurdy, K. G.; Hepler, L. G. Apparent Molar Heat Capacities and Volumes of Aqueous Electrolytes: $CaCl_2$, $Cd(NO_3)_2$, $CoCl_2$, $Cu(ClO_4)_2$, $Mg(ClO_4)_2$, and $NiCl_2$. *J. Solution Chem.* **1978**, *7*, 81−86.

(124) Stokes, R. H.; Phang, S.; Mills, R. Density, Conductance, Transference Numbers, and Diffusion Measurements in Concentrated Solutions of Nickel Chloride. *J. Solution Chem.* **1979**, *8*, 489−500.

(125) Suryanarayana, C. V.; Alamelu, S. Electrical Conductance of Concentrated Aqueous Solutions of Copper Sulfate. *Bull. Chem. Soc. Jpn.* **1959**, *32*, 333−339.

(126) Suryanarayana, C. V.; Alamelu, S. Electrical Conductance of Concentrated Aqueous Solutions of Zinc Sulphate. *Acta Chim. Hung.* **1959**, *20*, 91−102.

(127) Tham, M. K.; Gubbins, K. E.; Walker, R. D., Jr. Densities of Potassium Hydroxide Solutions. *J. Chem. Eng. Data* **1967**, *12*, 525−526.

(128) Torók, T. I.; Berecz, E. Volumetric Properties and Electrolytic Conductances of Aqueous Ternary Mixtures of Hydrogen Chloride and Some Transition Metal Chlorides at 25 °C. *J. Solution Chem.* **1989**, *18*, 1117−1131.

(129) Vasilev, Y. A.; Fedyainov, N. V.; Kurenkov, V. V. Specific Heats and Specific Volumes of Isopiestic Aqueous Solutions of Beryllium-Subgroup Metal Chlorides. *Russ. J. Phys. Chem.* **1973**, *47*, 2799−2803.

(130) Vaslow, F. The Apparent Molal Volumes of the Lithium and Sodium Halides. Critical Type Transitions in Aqueous Solution. *J. Phys. Chem.* **1969**, *73*, 3745−3750.

(131) Vázquez, G.; Alvarez, E.; Cancela, A.; Navaza, J. M.; Density, Viscosity, and Surface Tension of Aqueous Solutions of Sodium Sulfite and Sodium Sulfite + Sucrose from 25 to 40 °C. *J. Chem. Eng. Data.* **1995**, *40*, 1101−1105

(132) Weingärtner, H.; Müller, K. J.; Hertz, H. G.; Edge, A. V. J.; Mills, R. Unusual Behavior of Transport Coefficients in Aqueous Solutions of Zinc Chloride. *J. Phys. Chem.* **1984**, *88*, 2173−2178.

(133) Wimby, J. M.; Berntsson, T. S. Viscosity and Density of Aqueous Solutions of LiBr, LiCl, $ZnBr_2$, $CaCl_2$, and $LiNO_3$. 1. Single Salt Solutions. *J. Chem. Eng. Data* **1994**, *39*, 68−72.

(134) Wirth, H. E.; Lo Surdo, A. Temperature Dependence of Volume Changes of Aqueous Solutions of Ammonium Chloride and Ammonium Nitrate at 25 °C. *J. Chem. Eng. Data* **1968**, *13*, 226−231.

(135) Zhang, H.-L.; Han, S.-J. Viscosity and Density of Water + Sodium Chloride + Potassium Chloride Solutions at 298.15 K. *J. Chem. Eng. Data* **1996**, *41*, 516−520.

(136) Zhang, H.-L.; Chen, G.-H.; Han, S.-J. Viscosity and Density of H_2O + NaCl + $CaCl_2$ and H_2O + KCl + $CaCl_2$ at 298.15 K. *J. Chem. Eng. Data* **1997**, *42*, 526−530.

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