

Viscosity and Density of the Nonelectrolyte System Mannitol + Sorbitol + Sucrose + H₂O and Its Binary and Ternary Subsystems at 298.15 K

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The densities and viscosities were measured at 298.15 K for the quaternary system mannitol + sorbitol + sucrose + H₂O and its binary and ternary subsystems (mannitol + H₂O, sucrose + H₂O, and sorbitol + H₂O) and (mannitol + sorbitol + H₂O, mannitol + sucrose + H₂O, and sorbitol + sucrose + H₂O). The results were used to test the applicability of simple equations for the density, kinematic viscosity, and viscosity of the multicomponent nonelectrolyte solutions. The predicted results are in good agreement with the measured values, indicating that the density, kinematic viscosity, and viscosity of the multicomponent nonelectrolyte solutions obeying the linear isopiestic relation can be related to those of their constituent binary solutions by the simple equations.

Introduction

The thermodynamic properties and transport properties of multicomponent aqueous solutions play a very important role in a variety of fields: chemistry and chemical engineering, separation process (crystallization, evaporation, desalination), wastewater treatment, pollution control, and oil recovery. However, while extensive data have been reported in the literature for the thermodynamic properties and transport properties of binary aqueous solutions, relatively few measurements have been made on ternary and multicomponent mixtures. Therefore, it is interesting and practically important to develop simple equations that can make full use of the available information on the binary solutions and provide sufficient accuracy to predict the properties of multicomponent solutions.^{1–3}

Recently, Hu et al.¹ presented an extended semi-ideal solution theory from which a new set of simple predictive equations have been developed for the thermodynamic properties of multicomponent solutions, including a novel linear isopiestic relation, activity coefficient of either solute in the multicomponent solutions, volumetric properties, and thermal properties. It has also been shown that the viscosities of multicomponent aqueous solutions obeying a linear isopiestic relation^{4–6} is very simple, and thus this relation has been used together with the thermodynamic equations and the Eyring's absolute rate theory⁷ to establish novel predictive equations for surface tension and viscosity⁸ of the multicomponent solutions. These simple equations are now among the most simple equations for prediction of the thermodynamic properties and viscosities of multicomponent solutions from the properties of their binary subsystems of equal water activity. The accuracy of these equations has been tested by the systematic comparisons with experimental data for the multicomponent electrolyte solutions, including strong electrolyte mixtures with and without common ions and the electrolyte mixtures containing the transition metal chlorides. The agreements between the measured and predicted properties are in general quite good.^{6,8,9}

The predictive equations for the thermodynamic properties and viscosity are expected to hold for different kinds of mixtures including aqueous and nonaqueous solutions of electrolytes, nonelectrolytes, (electrolyte + nonelectrolyte) mixtures, aqueous solutions of polyelectrolytes and water-soluble neutral polymers, and alloys.¹ However, its applicability to densities and viscosities of multicomponent nonelectrolyte solutions has not been tested. If these novel equations can be proven to be able to provide impressive predictions for the thermodynamic properties and viscosities of multicomponent solutions, then much complexity can be avoided in calculation of the properties of the multicomponent solutions. Therefore, in this study the densities and viscosities were measured for the quaternary nonelectrolyte system mannitol + sorbitol + sucrose + H₂O and its binary and ternary subsystems (mannitol + H₂O, sucrose + H₂O, and sorbitol + H₂O) and (mannitol + sorbitol + H₂O, mannitol + sucrose + H₂O, and sorbitol + sucrose + H₂O) at 298.15 K, and the results were used to check the applicability of the proposed equations. The measured data also play an important role in the fields of food engineering^{10,11} and fragile biological material processing¹² and in the study of inhibitor of the formation of gas hydrate because sugars and polyalcohols exhibit a substantial inhibiting effect on hydrate formation.¹³

Experimental Section

All the chemicals used were of reagent grade and were recrystallized twice from doubly distilled water. Mannitol, sorbitol, and sucrose were dehydrated at room temperature under vacuum over CaCl₂ to constant mass.^{1,14} Finally, all the chemicals were stored over P₂O₅ in a vacuum desiccator before use.

Solutions were prepared by mass using double-distilled deionized water and each of the solutes with a precision of $\pm 5 \times 10^{-5}$ g. All masses were corrected to vacuum. Dilute solutions were prepared by diluting a stock solution by mass. In the concentrated region, solutions were prepared from a known mass of solute and water, respectively. The ternary and quaternary solutions were prepared by mixing the binary solutions. All solutions were prepared immediately before use, and the uncertainty was $\pm 5 \times 10^{-5}$ kg·mol⁻¹. The densities of solutions were measured with a KEM oscillating-tube digital densimeter (DA-505) thermostated to better than ± 0.01 K. The

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temperature in the measuring cell was monitored with a digital thermometer. The densimeter was calibrated by double-distilled water and dry air. The densities of water at different temperatures were obtained from the literature.¹⁵ The densities of water and air at 298.15 K were taken as 0.99701 g·cm⁻³ and 1.18434 kg·m⁻³, respectively. In all the measured variables, the uncertainty in densities was $\pm 5 \times 10^{-5}$ g·cm⁻³.

The viscosities were measured using a modified Cannon-Ubbelohde suspended level capillary viscometer. A thoroughly cleaned and perfect dried viscometer filled with liquid was placed vertically in a glass-sided water thermostat. The temperature was maintained to (298.15 \pm 0.01) K. After attaining thermal equilibrium, the efflux times of flow of the liquids were recorded with a digital stop watch with a precision of \pm 0.01 s. Triplicate measurements were performed at each composition. At 298.15 K, the viscosity of water is 0.8903 mPa·s,¹⁵ and the uncertainty in viscosity was $\delta_{\eta, \text{water}} = (\eta_{\text{exp, water}} - 0.8903)/0.8903 = 0.02\%$, where $\eta_{\text{exp, water}}$ is the viscosity of water measured in this study. The viscosity of solution is given by

$$\eta = \eta_0 \frac{\rho\tau}{d_0\tau_0} \quad (1)$$

where η_0 is the viscosity of water, ρ and ρ_0 are the densities of the solution and water, respectively. τ and τ_0 are the flow times of the solution and water, respectively.

Predictive Equations for Density and Viscosity of the Multicomponent Nonelectrolyte Solution

In the following section, the variables with the superscript o together with the subscript i were used to denote the quantities of component i in the binary solution ($i + \text{H}_2\text{O}$) having the same water activity as that of a multicomponent solution. Those without the superscript o denote the corresponding quantities in the multicomponent solution.

The linear isopiestic relation^{4-6,9} can be expressed as:

$$\sum_i \frac{m_i}{m_i^o} = 1 \quad (2)$$

where m_i and m_i^o are the molalities of the i th solute in multicomponent aqueous solution $1 + 2 + \dots + n + \text{H}_2\text{O}$ and its binary subsystems $i + \text{H}_2\text{O}$ ($i = 1, 2, \dots, n$) of equal water activity.

According to the semi-ideal solution theory, the density of a multicomponent nonelectrolyte solution is related to those of its constituent binary solutions of equal water activity by¹

$$\rho = \sum_i Y_i / \sum_i (Y_i / \rho_i^o) \quad (3)$$

with $Y_i = m_i / (m_i^o + m_i M_i)$, where m , ρ , and M denote molality, density, and molar mass, respectively.

The kinematic viscosity of a multicomponent nonelectrolyte solution is related to those of its constituent binary solutions of equal water activity by⁸

$$\ln \nu = \sum_i \frac{x_i}{x_i^o} \ln \nu_i^o \quad (4)$$

where ν and x are kinematic viscosity and mole fraction, respectively. For the multicomponent electrolyte solutions, it has been shown⁸ that the density term

$$\ln \rho - \sum_i \frac{x_i}{x_i^o} \ln \rho_i^o$$

can be added to the right-hand side of eq 4 so that it can be rewritten as

$$\ln \eta = \sum_i \frac{x_i}{x_i^o} \ln \eta_i^o \quad (5)$$

where η is viscosity. Note that the density of the multicomponent solution (ρ) can be determined from those of its binary subsystems (ρ_i^o) from eq 3.

Comparisons with the Experimental Data

Equations 3 to 5 were tested by comparing with the measured densities and viscosities. The procedure is briefly described as follows:

(1) Represent the measured densities and viscosities of all the binary solutions by the following polynomials:

$$\rho_{i(\text{calc})}^o = 0.99701 + \sum_l A_l (m_i^o)^{l/2} \quad (6)$$

$$\eta_{i(\text{calc})}^o = 0.8903 + \sum_l B_l (m_i^o)^{l/2} \quad (7)$$

where $\rho_{i(\text{calc})}^o$, $\eta_{i(\text{calc})}^o$, and m_i^o represent the density, viscosity, and molality, respectively, of the binary aqueous solution $i + \text{H}_2\text{O}$. The optimum fit was obtained by variation of l until the values of

$$\delta_{\rho,i}^o = \sum_{i=1}^N \left(\frac{|\rho_{i(\text{exp})}^o - \rho_{i(\text{calc})}^o|}{\rho_{i(\text{calc})}^o} \right) / N$$

and

$$\delta_{\eta,i}^o = \sum_{i=1}^N \left(\frac{|\eta_{i(\text{exp})}^o - \eta_{i(\text{calc})}^o|}{\eta_{i(\text{calc})}^o} \right) / N$$

are less than a few parts in 10^4 . The values of A_l , B_l , $\delta_{\rho,i}^o$, and $\delta_{\eta,i}^o$ thus obtained for the three binary solutions are shown in Table 1.

Table 1. Parameters for the Binary Solutions^a

	B + H ₂ O	C + H ₂ O	D + H ₂ O	B + H ₂ O	C + H ₂ O	D + H ₂ O	
A ₁	-0.097242	-0.28870	-0.0096122	B ₁	-0.92061	0.95121	-22.4119
A ₂	0.63748	0.78404	0.18426	B ₂	5.70456	-2.31718	85.0622
A ₃	-1.25146	-0.64518	-0.080652	B ₃	-10.86891	2.59855	-101.7436
A ₄	1.17740	0.23845	0.013658	B ₄	9.74962	1.09636	19.0742
A ₅	-0.41166	-0.032785	-4.16422 \times 10 ⁻⁴	B ₅	-3.11262	-2.83636	51.1636
				B ₆		1.45532	-38.1034
				B ₇		-0.22664	8.22012
δ_{ρ}^o	2.0 \times 10 ⁻⁶	2.2 \times 10 ⁻⁵	1.3 \times 10 ⁻⁶	δ_{η}^o	2.8 \times 10 ⁻⁶	1.8 \times 10 ⁻⁴	1.0 \times 10 ⁻⁵

^a B = mannitol, C = sorbitol, D = sucrose.

(2) Determine the compositions (m_i^o) of the binary solutions having the same water activity as that of the multicomponent solution of given molalities m_i ($i = 1, 2, \dots, n$) using the osmotic coefficients of mannitol + H₂O, sucrose + H₂O, and sorbitol + H₂O^{16,17} and eq 2.

(3) Insert the values of $\rho_{i(\text{calc})}^o$, $\nu_{i(\text{calc})}^o$ ($= \eta_{i(\text{calc})}^o / \rho_{i(\text{calc})}^o$), and $\eta_{i(\text{calc})}^o$ from eqs 6 or 7 into eqs 3 to 5 to yield the predictions for the multicomponent solutions of given m_i ($i = 1, 2, \dots, n$), which are then compared with the corresponding experimental data.

Table 2. Densities and Viscosities of the Binary Systems at 298.15 K

mannitol + H ₂ O			sorbitol + H ₂ O			sucrose + H ₂ O		
<i>m</i>	ρ	η	<i>m</i>	ρ	η	<i>m</i>	ρ	η
mol·kg ⁻¹	g·cm ⁻³	mPa·s	mol·kg ⁻¹	g·cm ⁻³	mPa·s	mol·kg ⁻¹	g·cm ⁻³	mPa·s
0.1999	1.00902	0.9818	0.5085	1.01167	1.2580	0.4998	1.05715	1.3786
0.4002	1.02081	1.0852	0.9996	1.05299	1.6121	1.0169	1.10566	2.1820
0.5998	1.03184	1.1905	1.9508	1.09873	2.3286	1.4918	1.14243	3.3798
0.8006	1.04259	1.3113	2.9980	1.13174	3.4350	1.9855	1.17515	5.3700
0.9995	1.05172	1.4422	4.0003	1.16061	5.2208	2.5091	1.20532	8.5359
			4.9970	1.18696	7.8960	2.9018	1.22558	12.2306
			5.9945	1.20521	11.2820	3.5582	1.25601	21.5852

In this paper, the average relative differences between the predicted and measured densities (δ_ρ), kinematic viscosities (δ_ν), and viscosities (δ_η) over the entire experimental composition range of the multicomponent solution are defined by

$$\delta_\rho = \sum_{i=1}^N |\delta_{\rho,i}|/N \quad (8)$$

$$\delta_\nu = \sum_{i=1}^N |\delta_{\nu,i}|/N \quad (9)$$

$$\delta_\eta = \sum_{i=1}^N |\delta_{\eta,i}|/N \quad (10)$$

with $\delta_{\rho,i} = (\rho_{i(\text{exp})} - \rho_{i(\text{calc})})/\rho_{i(\text{calc})}$, $\delta_{\nu,i} = (\nu_{i(\text{exp})} - \nu_{i(\text{calc})})/\nu_{i(\text{calc})}$, and $\delta_{\eta,i} = (\eta_{i(\text{exp})} - \eta_{i(\text{calc})})/\eta_{i(\text{calc})}$, where *N* is the number of experimental data.

Table 3. Comparisons of the Predicted and Measured Densities, Kinematic Viscosities, and Viscosities of the Quaternary System Mannitol (B) + Sorbitol (C) + Sucrose (D) + H₂O (A) at 298.15 K

m_B°	m_C°	m_D°	m_B	m_C	m_D	$\rho(\text{g}\cdot\text{cm}^{-3})$		$(\nu \times 10^6)/(\text{m}^2 \cdot \text{s}^{-1})$		$\eta(\text{mPa}\cdot\text{s})$	
mol·kg ⁻¹	mol·kg ⁻¹	mol·kg ⁻¹	mol·kg ⁻¹	mol·kg ⁻¹	mol·kg ⁻¹	exp	cal	exp	eq 4	exp	eq 5
1.0902	1.0893	1.0095	0.6857	0.2856	0.1099	1.06110	1.06098	1.5180	1.5159	1.6106	1.6084
1.0086	1.0076	0.9391	0.3269	0.2167	0.4327	1.07396	1.07351	1.6171	1.6162	1.7369	1.7352
0.9089	0.9082	0.8520	0.5848	0.1821	0.1330	1.05489	1.05421	1.4092	1.4076	1.4865	1.4841
0.8515	0.8508	0.8013	0.2826	0.1588	0.3858	1.06485	1.06425	1.4877	1.4866	1.5842	1.5824
0.8104	0.8097	0.7648	0.1865	0.3728	0.2367	1.05391	1.05339	1.4394	1.4382	1.5170	1.5153
0.7860	0.7853	0.7430	0.4281	0.1316	0.2138	1.05276	1.05214	1.3659	1.3656	1.4380	1.4369
0.7026	0.7018	0.6681	0.3660	0.1381	0.1886	1.04652	1.04609	1.3145	1.3116	1.3756	1.3722
0.6537	0.6528	0.6237	0.1986	0.1512	0.2898	1.04898	1.04860	1.3334	1.3325	1.3987	1.3975
0.6082	0.6072	0.5822	0.2558	0.2356	0.1114	1.03481	1.03425	1.2578	1.2566	1.3016	1.2998
0.5565	0.5555	0.5346	0.2269	0.2167	0.1081	1.03095	1.03045	1.2297	1.2277	1.2678	1.2653
0.5136	0.5125	0.4949	0.1848	0.1821	0.1410	1.03026	1.02986	1.2135	1.2122	1.2502	1.2485
0.4687	0.4676	0.4530	0.1519	0.1889	0.1232	1.02528	1.02489	1.1850	1.1876	1.2150	1.2175

Table 4. Comparisons of the Predicted and Measured Densities, Kinematic Viscosities, and Viscosities of the Ternary System Mannitol (B) + Sorbitol (C) + H₂O (A) at 298.15 K

m_B°	m_C°	m_B	m_C	$\rho(\text{g}\cdot\text{cm}^{-3})$		$(\nu \times 10^6)/(\text{m}^2 \cdot \text{s}^{-1})$		$\eta(\text{mPa}\cdot\text{s})$	
mol·kg ⁻¹	mol·kg ⁻¹	mol·kg ⁻¹	mol·kg ⁻¹	exp	cal	exp	eq 4	exp	eq 5
0.1420	0.1418	0.0809	0.0605	0.98964	0.98945	0.9862	0.9858	0.9760	0.9752
0.2542	0.2539	0.1012	0.1528	0.99452	0.99434	1.0667	1.0659	1.0609	1.0601
0.3013	0.3007	0.1528	0.1482	1.00215	1.00177	1.0776	1.0762	1.0800	1.0785
0.4022	0.4012	0.2028	0.1989	1.01076	1.01045	1.1264	1.1275	1.1385	1.1368
0.5206	0.5196	0.2582	0.2619	1.02050	1.02001	1.1853	1.1841	1.2096	1.2080
0.6172	0.6162	0.3061	0.3106	1.02821	1.02750	1.2309	1.2330	1.2656	1.2678
0.6263	0.6253	0.1254	0.5001	1.02558	1.02523	1.2841	1.2815	1.3169	1.3154
0.6267	0.6257	0.2511	0.3750	1.02686	1.02727	1.2515	1.2519	1.2849	1.2872
0.6270	0.6260	0.3766	0.2500	1.02980	1.02929	1.2212	1.2231	1.2576	1.2597
0.6273	0.6263	0.5020	0.1251	1.03162	1.03131	1.1968	1.1949	1.2346	1.2327
0.7191	0.7183	0.3570	0.3617	1.03550	1.03494	1.2912	1.2878	1.3370	1.3336
0.8254	0.8247	0.6593	0.1660	1.04362	1.04315	1.3038	1.3017	1.3607	1.3586
0.8264	0.8257	0.4944	0.3317	1.04351	1.04257	1.3345	1.3326	1.3926	1.3900
0.8272	0.8266	0.3302	0.4967	1.04295	1.04187	1.3655	1.3638	1.4242	1.4221
0.8283	0.8276	0.1652	0.6625	1.04100	1.04132	1.3995	1.3960	1.4569	1.4551
0.8582	0.8576	0.4219	0.4360	1.04493	1.04418	1.3697	1.3676	1.4312	1.4285
0.9436	0.9429	0.6398	0.3036	1.04802	1.04932	1.3916	1.3880	1.4585	1.4567
0.9581	0.9574	0.4263	0.5314	1.05094	1.05018	1.4345	1.4328	1.5076	1.5051
0.9859	0.9852	0.8528	0.1330	1.05156	1.05130	1.3847	1.3838	1.4561	1.4549
0.9923	0.9916	0.7060	0.2861	1.05105	1.05172	1.4105	1.4112	1.4825	1.4842
1.0040	1.0040	0.5018	0.5022	1.05362	1.05258	1.4521	1.4513	1.5300	1.5278
1.0260	1.0250	0.9008	0.1252	1.05208	1.05277	1.4072	1.4052	1.4805	1.4796
1.0640	1.0640	0.8588	0.2055	1.05491	1.05422	1.4358	1.4382	1.5146	1.5167
1.0650	1.0640	0.2133	0.8513	1.05682	1.05613	1.5330	1.5356	1.6201	1.6226

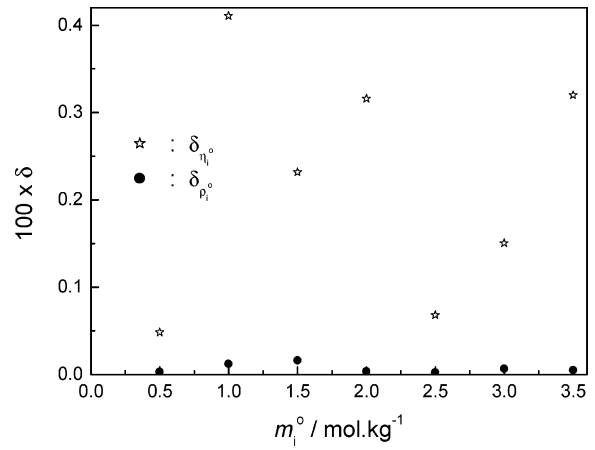


Figure 1. Variation of the δ value with the molality for the binary system sucrose + H₂O at 298.15 K.

Results and Discussion

Table 2 shows the measured densities and viscosities of the binary solutions mannitol + H₂O, sorbitol + H₂O, and sucrose + H₂O at 298.15 K. Figure 1 shows the variations of the values of $\delta_{\rho,i}^\circ (= |\rho_{i(\text{exp})}^\circ - \rho_{i(\text{calc})}^\circ|/\rho_{i(\text{calc})}^\circ)$ and $\delta_{\eta,i}^\circ (= |\eta_{i(\text{exp})}^\circ - \eta_{i(\text{calc})}^\circ|/\eta_{i(\text{calc})}^\circ)$ with the molality in the binary solution sucrose + H₂O at 298.15 K, where $\rho_{i(\text{exp})}^\circ$ and $\eta_{i(\text{exp})}^\circ$ are the densities and viscosities reported in the literature,¹⁸ and $\rho_{i(\text{calc})}^\circ$ and $\eta_{i(\text{calc})}^\circ$ are those calculated from eqs 6 and 7 together with the parameters shown in Table 1. It is seen that the agreements are good. Table

Table 5. Comparisons of the Predicted and Measured Densities, Kinematic Viscosities, and Viscosities of the Ternary System Mannitol (B) + Sucrose (C) + H₂O (A) at 298.15 K

m_B^o mol·kg ⁻¹	m_C^o mol·kg ⁻¹	m_B mol·kg ⁻¹	m_C mol·kg ⁻¹	ρ (g·cm ⁻³)		$(\nu \times 10^6)$ (m ² ·s ⁻¹)		η (mPa·s)	
				exp	cal	exp	eq 4	exp	eq 5
0.1513	0.1495	0.1008	0.04990	1.00912	1.00952	0.9252	0.9247	0.9336	0.9327
0.1902	0.1874	0.1285	0.06080	1.01251	1.01226	0.9571	0.9560	0.9691	0.9682
0.3780	0.3677	0.1208	0.2502	1.03525	1.03501	1.1217	1.1207	1.1612	1.1605
0.4755	0.4594	0.1588	0.3060	1.04337	1.04342	1.2038	1.2025	1.2560	1.2549
0.4832	0.4665	0.3186	0.1589	1.03483	1.03465	1.1519	1.1541	1.1920	1.1944
0.5187	0.4996	0.2589	0.2502	1.04204	1.04236	1.2090	1.2061	1.2598	1.2570
0.6216	0.5944	0.3016	0.3060	1.05017	1.04982	1.2842	1.2847	1.3486	1.3494
0.6295	0.6016	0.4218	0.1985	1.04446	1.04425	1.2430	1.2452	1.2985	1.3010
0.6326	0.6045	0.5104	0.1167	1.04006	1.04056	1.2176	1.2146	1.2664	1.2634
0.6378	0.6092	0.3895	0.2372	1.04704	1.04658	1.2622	1.2654	1.3216	1.3252
0.6433	0.6143	0.2643	0.3619	1.05434	1.05406	1.3188	1.3204	1.3905	1.3924
0.6490	0.6195	0.1344	0.4912	1.06197	1.06176	1.3782	1.3800	1.4636	1.4657
0.7696	0.7283	0.3186	0.4268	1.06348	1.06302	1.4222	1.4231	1.5125	1.5136
0.8330	0.7849	0.6731	0.1506	1.05192	1.05167	1.3410	1.3390	1.4106	1.4086
0.8426	0.7934	0.5157	0.3078	1.06040	1.06005	1.4119	1.4135	1.4972	1.4992
0.8528	0.8025	0.3513	0.4719	1.06933	1.06862	1.4935	1.4959	1.5970	1.6000
0.8638	0.8122	0.1797	0.6432	1.07873	1.07858	1.5857	1.5870	1.7105	1.7124
1.0810	1.0020	0.8748	0.1912	1.06356	1.06226	1.5083	1.5069	1.6042	1.6030
1.0970	1.0150	0.6731	0.3926	1.07383	1.07306	1.6129	1.6169	1.7320	1.7369
1.1130	1.0290	0.4601	0.6037	1.08480	1.08421	1.7364	1.7405	1.8837	1.8887
1.1330	1.0460	0.2371	0.8271	1.09669	1.09605	1.8834	1.8842	2.0655	2.0672

Table 6. Comparisons of the Predicted and Measured Densities, Kinematic Viscosities, and Viscosities of the Ternary System Sorbitol (B) + Sucrose (C) + H₂O (A) at 298.15 K

m_B^o mol·kg ⁻¹	m_C^o mol·kg ⁻¹	m_B mol·kg ⁻¹	m_C mol·kg ⁻¹	ρ (g·cm ⁻³)		$(\nu \times 10^6)$ (m ² ·s ⁻¹)		η (mPa·s)	
				exp	cal	exp	eq 4	exp	eq 5
0.4089	0.3978	0.2065	0.1969	1.02302	1.02278	1.1928	1.1919	1.2203	1.2189
0.5296	0.5107	0.2591	0.2608	1.03665	1.03617	1.2907	1.2881	1.3380	1.3350
0.6236	0.5971	0.3036	0.3064	1.04590	1.04523	1.3649	1.3620	1.4276	1.4255
0.6325	0.6052	0.5104	0.1168	1.03256	1.03218	1.3384	1.3356	1.3820	1.3806
0.6375	0.6098	0.3895	0.2372	1.04160	1.04111	1.3594	1.3597	1.4160	1.4176
0.6428	0.6146	0.2643	0.3619	1.05096	1.05034	1.3883	1.3858	1.4591	1.4575
0.6483	0.6197	0.1344	0.4912	1.06070	1.06002	1.4125	1.4140	1.4982	1.5003
0.7158	0.6808	0.3560	0.3422	1.05386	1.05306	1.4349	1.4350	1.5122	1.5133
0.8106	0.7656	0.4017	0.3862	1.06180	1.06107	1.5129	1.5139	1.6064	1.6084
0.8329	0.7854	0.6731	0.1507	1.04989	1.04918	1.4683	1.4692	1.5416	1.5434
0.8423	0.7938	0.5157	0.3078	1.05915	1.05845	1.5199	1.5162	1.6098	1.6068
0.8524	0.8027	0.3513	0.4719	1.06886	1.06810	1.5706	1.5680	1.6788	1.6766
0.8632	0.8123	0.1797	0.6432	1.07885	1.07817	1.6288	1.6251	1.7572	1.7536
1.0810	1.0020	0.8748	0.1910	1.06750	1.06689	1.6450	1.6435	1.7560	1.7534
1.0970	1.0160	0.6731	0.3923	1.07763	1.07699	1.7229	1.7264	1.8567	1.8593
1.1130	1.0300	0.4601	0.6040	1.08825	1.08726	1.8204	1.8195	1.9810	1.9782
1.1325	1.0466	0.2371	0.8275	1.09892	1.09801	1.9293	1.9276	2.1202	2.1168
1.3740	1.2510	0.6482	0.6607	1.10120	1.10051	2.0694	2.0698	2.2788	2.2770
1.7370	1.5510	0.8125	0.8258	1.12037	1.11953	2.5154	2.5198	2.8182	2.8219
2.2205	1.9382	1.6842	0.4681	1.12326	1.12285	2.6957	2.6980	3.0280	3.0307
2.2459	1.9583	1.0316	1.0588	1.14364	1.14286	3.3058	3.3096	3.7806	3.7846
2.5494	2.1956	2.1968	0.3037	1.12836	1.12746	2.8658	2.8641	3.2337	3.2312
2.6348	2.2617	1.2288	1.2069	1.15868	1.15756	4.0233	4.0216	4.6617	4.6584
2.6483	2.2721	2.5006	0.1267	1.12569	1.12510	2.7886	2.7910	3.1391	3.1426
2.7803	2.3738	2.2167	0.4812	1.13996	1.13931	3.3006	3.3036	3.7626	3.7666
2.8898	2.4578	0.5267	2.0098	1.18918	1.18835	5.8126	5.8178	6.9122	6.9168
3.3057	2.7732	0.2519	2.5619	1.21206	1.21277	8.0978	8.1002	9.8150	9.8191
3.4401	2.8742	1.5059	1.6160	1.18896	1.18815	6.1462	6.1470	7.3076	7.3114
4.0052	3.2945	1.8125	1.8036	1.20601	1.20522	7.9006	7.8976	9.5282	9.5206

3 compares the predicted and measured densities for the quaternary solution mannitol (B) + sorbitol (C) + sucrose (D) + H₂O (A) at 298.15 K, and the agreement, $\delta_\rho = 4.3 \times 10^{-4}$, is good. Tables 4 to 6 compare the predicted and measured densities for the ternary solutions mannitol (B) + sorbitol (C) + H₂O (A), mannitol (B) + sucrose (C) + H₂O (A), and sorbitol (B) + sucrose (C) + H₂O (A) at 298.15 K. The fifth and sixth columns show that the agreements are quite good, with the δ_ρ values being $(5.0, 3.8, \text{ and } 6.3) \times 10^{-4}$, respectively. The δ_ρ values for the strong electrolyte mixtures in general range from 1.0×10^{-4} to 5.8×10^{-4} .⁹ For example, the average relative difference (δ_ρ) between the predicted and measured densities at 298.15 K^{19–22} are 3.5×10^{-4} for NaCl + KCl + H₂O (I_{\max}

$= 4.4 \text{ mol}\cdot\text{kg}^{-1}$), 1.6×10^{-4} for KCl + KBr + H₂O ($I_{\max} = 5.0 \text{ mol}\cdot\text{kg}^{-1}$), 2.2×10^{-4} for KCl + CaCl₂ + H₂O ($I_{\max} = 3.6 \text{ mol}\cdot\text{kg}^{-1}$), and 3.5×10^{-4} for HCl + KCl + NaCl + H₂O ($I_{\max} = 2.2 \text{ mol}\cdot\text{kg}^{-1}$), in which I_{\max} is the maximum ionic strength.⁹ The above results indicate that eq 3 holds well for both the multicomponent electrolyte solutions and the multicomponent nonelectrolyte solutions.

The results from the last four columns of Table 3 show that the agreements between the predicted and measured kinematic viscosities and viscosities of the quaternary solution mannitol (B) + sucrose (C) + sorbitol (D) + H₂O (A) at 298.15 K are good. The values of δ_ν and δ_η are 1.1×10^{-3} and 1.4×10^{-3} , respectively, suggesting that the effect of the density term

$$\left(\ln \rho - \sum_i \frac{x_i}{x_i^o} \ln \rho_i^o \right)$$

is small. The last four columns of Tables 4 to 6 compare the predicted and measured kinematic viscosities and viscosities of the ternary solutions mannitol (B) + sorbitol (C) + H₂O (A), mannitol (B) + sucrose (C) + H₂O (A), and sorbitol (B) + sucrose (C) + H₂O (A) at 298.15 K. The values of δ_v and δ_η are (1.3, 1.9, and 2.5) $\times 10^{-3}$ and (1.4, 2.1, and 2.6) $\times 10^{-3}$, respectively, suggesting that the addition of the above-mentioned density term has little effect on the predicted results. This may be due to the fact that, for mixtures obeying the linear isopiestic relation, the apparent molar volumes of the components in a mixture of several solutes can be taken as those of the single solutes in a solution of the same water activity as the mixture.^{1,5} Note that, the δ_η values for the strong electrolyte mixtures in general range from 0.6×10^{-4} to 4.8×10^{-4} . For example, the average relative differences (δ_η) between the predicted and measured viscosities at 298.15 K^{19,21,22} are 2.6×10^{-3} for NaCl + KCl + H₂O ($I_{\max} = 4.4 \text{ mol}\cdot\text{kg}^{-1}$), 0.6×10^{-3} for HCl + KCl + H₂O ($I_{\max} = 4.0 \text{ mol}\cdot\text{kg}^{-1}$), 2.2×10^{-3} for KCl + CaCl₂ + H₂O ($I_{\max} = 3.6 \text{ mol}\cdot\text{kg}^{-1}$), and 2.2×10^{-3} for HCl + KCl + NaCl + H₂O ($I_{\max} = 4.0 \text{ mol}\cdot\text{kg}^{-1}$),⁸ indicating that eq 5 holds well for both the multicomponent electrolyte solutions and the multicomponent nonelectrolyte solutions.

Conclusions

The densities and viscosities were measured for the quaternary system mannitol + sorbitol + sucrose + H₂O and its binary and ternary subsystems (mannitol + H₂O, sucrose + H₂O, and sorbitol + H₂O) and (mannitol + sorbitol + H₂O, mannitol + sucrose + H₂O, and sorbitol + sucrose + H₂O) at 298.15 K. The results were used to test the applicability of simple equations for the density, kinematic viscosity, and viscosity of the multicomponent nonelectrolyte solution. The comparison results show that eqs 3 to 5 can yield good predictions for the densities, kinematic viscosities, and viscosities of the ternary and quaternary nonelectrolyte solutions from the data of the binary solutions that do not involve multicomponent parameters, indicating that these equations can make use of the information on the binary solutions, avoid much complexity in calculation of multicomponent viscosities, and provide good predictions for the multicomponent solutions.

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