Densities and Viscosities of Ternary Systems of Water + Glucose + Sodium Chloride at Several Temperatures

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The density and dynamic viscosity of aqueous solutions of sodium chloride, glucose, and glucose + sodium chloride were measured at temperatures from (20 to 40) °C. The concentration range studied for both sodium chloride and glucose was (0 to 4) mol·kg^{-1}. The experimental values of the ternary system were correlated as a function of the salt concentration. In addition, neural networks were used to simulate changes in density and viscosity of the systems studied with temperature and concentration in the ranges mentioned.

Introduction

The application of osmotic treatments to foods such as fruits, vegetables, meat, and fish,[1−5] prior to conventional processing, improves the nutritional and organoleptic properties of these. Another advantage is that the product obtained is stable during storage without having to put it through severe heat treatment, freezing, etc. Both aspects are due to the modification of the chemical composition of the food caused by the controlled elimination of water and the selective incorporation of solutes. The optimization of these material transfer processes requires knowing the physical properties of the aqueous solutions of the osmotic agents used, sugars and inorganic salts, among others. Hence, for the precise design of these processes, one should be able to calculate these properties at any temperature and concentration within the working range.

The densities and viscosities of concentrated aqueous solutions of sugars + inorganic salts have not been studied much to date.[6−8] One of the objectives of this work was to measure density and dynamic viscosity of the ternary system water + glucose + sodium chloride in the temperature range (20 to 40) °C and concentration range (0 to 4) mol·kg^{-1}. Another objective was to have a neural network available to simulate changes in density and viscosity of the ternary system mentioned with temperature and concentration. This tool has been used in the past decade to solve different problems, among them, prediction of boiling temperatures of alkanes,[9] simulation of viscosity variations in aqueous solutions of sucrose,[10] prediction of phase equilibria in biphasic aqueous systems,[11] or design of a combined mixing rule to predict the vapor−liquid equilibria using state equations.[12]

Experimental Section

Aqueous solutions of glucose, sodium chloride, and glucose + sodium chloride were prepared by mass with distilled water, obtained from the MILLI-Q 185 PLUS system with a resistivity of 18.2 MΩ·cm. Analytical grade reagents with 99.5% minimum purity, supplied by Sigma (glucose) and Merck (sodium chloride), were used. All solutions were prepared from water and reagents by mass using a Scaltec SBA31 analytical balance, with readability of ±0.1 mg. The physical properties were measured at temperatures ranging from (20 to 40) °C at 10 °C intervals.

An Anton Paar DMA 4500 densimeter and a Schott-Geräte AVS 350 automatic Ubbelohde viscosimeter were employed to measure density and kinematic viscosity, respectively. The detailed experimental procedure has been described elsewhere.[8] Each measurement was the average of 3 determinations for density and 10 for viscosity, with a maximum deviation of less than 0.01% and 0.4%, respectively. Dynamic viscosity was calculated by multiplying the kinematic viscosity by the corresponding density.

The densimeter and the viscosimeter were calibrated with distilled water. The measured density and kinematic viscosity of water at the working temperatures are included in Table 1 and are compared with values published by Marsh.[13]

Results and Discussion

Density and viscosity of aqueous solutions of glucose and sodium chloride at (20, 30, and 40) °C are presented in Table 1. Some of these values are compared with others found in the literature.[14−17] The experimental results show that both solutions behave normally given that, for each temperature studied, the values of both properties increase as the concentration in both solutions increases, the effect being greater in the case of glucose, especially for viscosity. Moreover, as expected, for all concentrations a reduction is observed in the properties of the solutions investigated with rising temperature, in the case of density this decline being practically constant for both systems in the concentration range studied. However, the decrease in viscosity is not the same for both systems; it is almost constant in the case of sodium chloride and notably accentuated for glucose, as the solutions become more concentrated.

Table 2 includes the density and viscosity of the aqueous solutions of glucose + sodium chloride at (20, 30, and 40) °C. For all solutions investigated, a decrease in the values of both properties is observed when temperature is increased. For a given temperature, both properties are

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Table 1. Densities and Viscosities of the Binary Solutions of Glucose and Sodium Chloride

		water + c sodium chloride				water + c glucose			
		ρ/(kg·m^{-3})		η/(mPa·s)		ρ/(kg·m^{-3})		η/(mPa·s)	
c/(mol·kg^{-1})	t/°C	exptl	lit	exptl	lit	exptl	lit	exptl	lit
0.000	20	998.2	998.2[a]	1.002	1.002[a]	998.2		1.002	
	30	995.6	995.7[a]	0.797	0.7975[a]	995.6		0.797	
	40	992.2	992.2[a]	0.653	0.6530[a]	992.2		0.653	
0.500	20	1018.6	1018.5[b]	1.041	1.047[b]	1030.7	1030.5[b]	1.256	1.260[b]
			1018.5[c]		1.034[d]		1030.6[e]		
	30	1015.7	1015.5[c]	0.835	0.834[d]	1027.7	1027.7[e]	0.988	
	40	1011.9	1011.8[c]	0.688	0.682[d]	1024.0	1024.0[e]	0.801	
1.000	20	1037.8	1037.8[b]	1.087	1.092[b]	1059.7	1059.3[b]	1.587	1.583[b]
			1037.8[c]		1.079[d]		1059.5[e]		
	30	1034.4	1034.5[c]	0.873	0.873[d]	1056.4	1056.2[e]	1.231	
	40	1030.4	1030.4[c]	0.722	0.716[d]	1052.4	1052.3[e]	0.985	
1.500	20	1056.3	1056.4[b]	1.138	1.144[b]	1085.4	1085.2[b]	1.993	2.004[b]
					1.130[d]		1085.4[e]		
	30	1052.6		0.918	0.917[d]	1081.8	1081.8[e]	1.523	
	40	1048.4		0.760	0.753[d]	1077.6	1077.7[e]	1.205	
2.000	20	1074.1	1074.1[b]	1.196	1.203[b]	1108.8	1108.5[b]	2.512	2.518[b]
			1074.2[c]		1.187[d]		1108.7[e]		
	30	1070.1	1070.2[c]	0.966	0.964[d]	1105.0	1104.8[e]	1.890	
	40	1065.7	1065.8[c]	0.802	0.793[d]	1100.6	1100.5[e]	1.475	
2.500	20	1091.4	1091.3[b]	1.264	1.272[b]	1129.8	1129.5[b]	3.159	3.167[b]
					1.251[d]		1129.7[e]		
	30	1087.2		1.021	1.015[d]	1125.7	1125.7[e]	2.341	
	40	1082.5		0.848	0.836[d]	1121.2	1121.1[e]	1.804	
3.000	20	1107.8	1107.9[b]	1.333	1.346[a]	1148.8	1148.5[b]	3.947	3.966[b]
			1108.0[c]		1.321[d]		1148.8[e]		
	30	1103.4	1103.5[c]	1.077	1.072[d]	1144.6	1144.6[e]	2.873	
	40	1098.6	1098.7[c]	0.895	0.836[d]	1139.9	1139.9[e]	2.182	
3.500	20	1123.9	1123.8[b]	1.411	1.420[b]	1166.3	1165.9[b]	4.960	5.018[b]
					1.398[d]		1166.2[e]		
	30	1119.2		1.140	1.133[d]	1161.9	1161.8[e]	3.553	
	40	1114.3		0.945	0.934[d]	1157.1	1157.0[e]	2.660	
4.000	20	1139.2	1139.4[b]	1.499	1.502[b]	1182.2	1181.7[b]	6.131	6.240[b]
			1139.4[c]		1.483[d]		1182.2[e]		
	30	1134.4	1134.6[c]	1.208	1.199[d]	1177.7	1177.6[e]	4.309	
	40	1129.3	1129.6[c]	1.000	0.989[d]	1172.7	1172.7[e]	3.175	

[a] Reference 13. [b] Reference 14. [c] Reference 15 [d] Reference 16 [e] Reference 17.

enhanced when the concentration of the solutions in the concentration range are being considered augments. When density and viscosity in different ternary systems, having a specific sodium chloride content, are compared with values of binary systems, having the same glucose content as that in the ternary, the effect of the salt is practically the same for the different glucose concentrations. Similarly, when comparing density and viscosity of the different ternary systems having the same glucose content with respect to corresponding values of the binary systems with the same sodium chloride concentration as the ternary, the effect of the sugar is practically the same for the different sodium chloride concentrations. Nonetheless, the effect produced by glucose is greater, especially in the case of viscosity; therefore, of the different ternary systems having a specific total molality, the one with the greatest density and viscosity is that exhibiting the highest glucose concentration.

The behavior described above is similar to that presented by binary and ternary systems containing fructose,[8] in the same concentration and temperature ranges, although some differences exist. For a particular temperature and concentration, aqueous solutions of fructose are slightly denser that those of glucose, the biggest relative differences produced at 20 °C. On the contrary, aqueous solutions of glucose are somewhat more viscous than fructose solutions, the greatest relative differences observed at 40 °C. For aqueous solutions of sugar + sodium chloride, the behavior is similar, given that for a specific temperature and concentration, solutions containing fructose are slightly denser (maximum relative difference at 20 °C) and less viscous than those containing glucose (maximum relative difference at 40 °C).

The densities and viscosities of the ternary system were expressed as a function of the salt concentration using polynomial-type equations.[8] The coefficients obtained for both correlation equations (A_2, A_3, and A_4 of the equation for density and A, B, D and E of the equation for viscosity) are listed in Table 3. The relative deviation between experimental and calculated values never surpassed 0.05% for density and 0.25% for viscosity. Despite the good results obtained in the correlation of the data, there is the inconvenience of having to interpolate when predicting the values of both properties in cases where the glucose concentrations, and/or temperature, do not correspond with those appearing in Table 3.

To avoid this inconvenience, a potent mathematical tool, as is the case of neural networks, was tested to calculate densities and viscosities taking into account simultaneously the concentrations of both solutes. Hence, Neural Network Toolbox from Matlab was used to implement the neural networks and compare the results obtained with both strategies. Two feedforward neural networks with a classical back-propagation algorithm of supervised training[18] were used. The network applied for the densities contained three input neurons (corresponding to glucose and sodium chloride concentrations, and temperature), two neurons in the hidden layer and one output neuron. Initially, using a similar network for the viscosities was thought but the results obtained were not satisfactory. Given that dynamic viscosity is a function of density, the network used for the viscosities includes an extra input neuron (the three from

Table 2. Densities and Viscosities of the Ternary Solutions of Glucose + Sodium Chloride

c	t	ρ	η	ρ	η	ρ	η	ρ	η
mol· kg^{-1}	°C	kg·m^{-3}	mPa·s	kg·m^{-3}	mPa·s	kg·m^{-3}	mPa·s	kg·m^{-3}	mPa·s
				Water + c Sodium Chloride					
		+ 0.5 molal Glucose		+ 1.0 molal Glucose		+ 1.5 molal Glucose		+ 2.0 molal Glucose	
0.500	20	1049.2	1.309	1076.6	1.653	1101.2	2.083	1123.3	2.630
	30	1045.9	1.035	1073.0	1.287	1097.3	1.598	1119.2	1.985
	40	1041.9	0.843	1068.8	1.044	1092.8	1.267	1114.4	1.554
1.000	20	1066.9	1.368	1093.0	1.727	1116.2	2.177	1137.3	2.751
	30	1063.3	1.085	1089.1	1.349	1112.2	1.674	1133.0	2.080
	40	1059.0	0.886	1084.7	1.087	1107.4	1.329	1128.2	1.630
1.500	20	1084.0	1.433	1108.7	1.810	1131.4	2.287	1150.9	2.887
	30	1080.0	1.139	1104.6	1.417	1127.1	1.760	1146.5	2.184
	40	1075.6	0.932	1099.9	1.143	1122.3	1.400	1141.6	1.712
2.000	20	1100.2	1.506	1123.9	1.903	1144.8	2.405	1163.9	3.031
	30	1096.0	1.199	1119.5	1.489	1140.3	1.852	1159.3	2.293
	40	1091.4	0.980	1114.8	1.203	1135.4	1.473	1154.3	1.799
2.500	20	1116.2	1.589	1138.4	2.006	1158.4	2.538	1176.6	3.194
	30	1111.8	1.264	1133.9	1.570	1153.8	1.952	1171.8	2.414
	40	1107.0	1.036	1128.9	1.266	1148.8	1.553	1166.7	1.891
3.000	20	1131.4	1.681	1152.7	2.120	1171.1	2.676	1189.0	3.378
	30	1126.8	1.336	1148.0	1.658	1166.3	2.055	1184.1	2.548
	40	1121.9	1.093	1142.9	1.336	1161.2	1.632	1178.9	1.993
3.500	20	1146.2	1.780	1166.4	2.248	1184.4	2.848	1200.9	3.572
	30	1141.4	1.414	1161.5	1.754	1179.4	2.177	1195.8	2.688
	40	1136.4	1.155	1156.4	1.413	1174.2	1.727	1190.6	2.098
4.000	20	1160.6	1.891	1179.7	2.385	1196.8	3.029	1212.4	3.788
	30	1155.7	1.498	1174.7	1.854	1191.7	2.315	1207.3	2.842
	40	1150.5	1.221	1169.4	1.494	1186.4	1.825	1201.9	2.214
		+2.5 molal Glucose		+3.0 molal Glucose		+3.5 molal Glucose		+4.0 molal Glucose	
0.500	20	1143.3	3.314	1161.6	4.140	1178.1	5.159	1193.3	6.421
	30	1139.1	2.462	1157.2	3.021	1173.6	3.693	1188.7	4.526
	40	1134.3	1.905	1152.4	2.296	1168.7	2.769	1183.6	3.336
1.000	20	1156.4	3.466	1173.8	4.328	1189.7	5.401	1204.1	6.727
	30	1152.0	2.575	1169.3	3.159	1185.0	3.868	1199.4	4.730
	40	1147.2	1.989	1164.3	2.405	1180.0	2.898	1194.1	3.500
1.500	20	1169.0	3.622	1185.7	4.538	1200.7	5.664	1214.6	7.055
	30	1164.4	2.693	1181.0	3.312	1195.9	4.052	1209.8	4.956
	40	1159.4	2.083	1175.9	2.521	1190.8	3.035	1204.6	3.657
2.000	20	1181.2	3.809	1197.1	4.773	1211.6	5.953	1224.7	7.414
	30	1176.5	2.829	1192.3	3.479	1206.7	4.255	1219.7	5.203
	40	1171.4	2.187	1187.2	2.648	1201.5	3.183	1214.5	3.832
2.500	20	1193.1	4.011	1208.2	5.023	1221.9	6.274	1234.6	7.807
	30	1188.2	2.975	1203.2	3.656	1216.9	4.475	1229.5	5.466
	40	1183.1	2.300	1198.0	2.779	1211.6	3.342	1224.2	4.026
3.000	20	1204.6	4.234	1219.0	5.303	1232.2	6.624	1244.2	8.237
	30	1199.6	3.135	1214.0	3.850	1227.1	4.709	1239.1	5.744
	40	1194.4	2.418	1208.7	2.923	1221.8	3.510	1233.7	4.218
3.500	20	1215.8	4.481	1229.6	5.616	1242.1	6.994	1253.7	8.719
	30	1210.7	3.308	1224.5	4.065	1236.9	4.959	1248.5	6.071
	40	1205.4	2.541	1219.1	3.077	1231.5	3.688	1243.0	4.437
4.000	20	1226.8	4.757	1239.9	5.956	1251.8	7.418	1262.9	9.235
	30	1221.6	3.496	1234.7	4.297	1246.5	5.236	1257.6	6.404
	40	1216.2	2.680	1229.2	3.240	1241.1	3.888	1252.1	4.669

Table 3. Parameters of the Equations[8] for the Sodium Chloride Concentration Dependence of the Density and Viscosity of the Aqueous Solutions of Glucose + Sodium Chloride

c	t	eq. for density			eq. for viscosity				c	t	eq. for density			eq. for viscosity			
mol·kg^{-1}	°C	A_2	A_3	A_4	10^3A	10^3B	10^3D	10^3E	mol·kg^{-1}	°C	A_2	A_3	A_4	10^3A	10^3B	10^3D	10^3E
0.500	20	38.85	−2.084	−0.554	7.624	89.47	14.817	0.199	2.500	20	28.16	−1.205	−0.377	63.27	204.2	36.06	0.609
	30	38.30	−2.287	−0.432	8.661	77.76	10.574	0.099		30	28.10	−1.566	−0.249	61.14	142.32	29.16	0.027
	40	37.36	−1.805	−0.532	9.412	66.30	8.655	0.021		40	27.22	−0.911	−0.415	59.91	102.71	24.03	0.315
1.000	20	35.25	−1.347	−0.641	7.569	112.50	19.513	0.163	3.000	20	26.96	−1.744	−0.174	54.86	286.7	40.59	0.803
	30	34.54	−1.230	−0.627	8.100	96.29	13.644	0.036		30	26.60	−1.767	−0.136	45.83	215.7	25.41	0.488
	40	34.13	−1.313	−0.563	44.33	42.32	17.895	0.281		40	26.10	−1.445	−0.221	28.14	178.88	16.076	0.225
1.500	20	34.19	−3.128	−0.025	−3.252	174.82	13.887	0.952	3.500	20	24.60	−0.921	−0.347	−53.64	456.1	36.26	1.241
	30	33.61	−3.013	−0.032	−8.002	155.77	4.220	0.907		30	24.28	−0.878	−0.346	−52.56	346.6	18.941	0.768
	40	32.36	−2.045	−0.274	−5.234	125.65	4.780	0.398		40	24.17	−1.038	−0.275	−37.05	264.9	97.52	0.671
2.000	20	29.88	−0.774	−0.607	28.80	182.60	27.72	0.352	4.000	20	23.11	−0.949	−0.260	37.25	505.2	50.66	1.565
	30	29.24	−0.592	−0.622	22.54	149.65	17.627	0.206		30	23.05	−1.191	−0.174	64.56	321.3	37.44	0.653
	40	28.02	0.454	−0.902	18.618	125.46	11.198	0.157		40	22.49	−0.674	−0.325	32.26	271.3	15.87	0.704

before and one for density); the hidden layer contains three neurons and one output neuron. In both cases, the function applied to calculate the output value of the neurons of the hidden layer was the hyperbolic tangent:

$$f(x) = \tanh(xL) \qquad (1)$$

where x is the input value to a neuron and L a sharpness fitting variable of the function, given a value of 1.5.

To train each network, the experimental values of the corresponding property were used as input patterns for the systems having a glucose concentration of 0, 1, 2, 3, and 4 mol·kg^{-1}, sodium chloride concentration of 0, 1, 2, 3, and 4

Table 4. Densities and Viscosities, Experimental and Calculated, of the Ternary Solutions of Glucose + Sodium Chloride

c	t	ρ/(kg·m^{-3})			η/(mPa·s)		
mol·kg^{-1}	°C	exptl	Net 1	interp	exptl	Net2	interp
Water + 1.2 molal Glucose + c Sodium Chloride							
1.20	25	1106.7	1106.6	1106.5	1.701	1.707	1.727
1.20	30	1104.6	1104.4	1104.4	1.506	1.511	1.509
1.20	35	1102.4	1102.3	1102.1	1.345	1.345	1.362
2.20	25	1135.9	1136.0	1135.7	1.879	1.896	1.912
2.20	30	1133.6	1133.7	1133.5	1.664	1.680	1.671
2.20	35	1131.3	1131.3	1131.1	1.486	1.495	1.529
3.20	25	1163.5	1163.5	1163.2	2.094	2.109	2.139
3.20	30	1161.0	1161.0	1160.8	1.853	1.867	1.865
3.20	35	1158.5	1158.5	1158.2	1.653	1.662	1.732
3.80	25	1179.1	1179.0	1178.9	2.244	2.251	2.298
3.80	30	1176.6	1176.5	1176.4	1.982	1.992	2.000
3.80	35	1174.0	1173.9	1173.8	1.767	1.771	1.880
Water + 1.8 molal Glucose + c Sodium Chloride							
1.20	25	1133.1	1132.7	1132.4	2.226	2.225	2.266
1.20	30	1130.9	1130.4	1130.3	1.951	1.953	1.958
1.20	35	1128.5	1128.2	1127.9	1.727	1.725	1.750
2.20	25	1159.4	1159.6	1159.2	2.453	2.473	2.523
2.20	30	1157.1	1157.1	1156.9	2.151	2.169	2.179
2.20	35	1154.6	1154.7	1154.4	1.902	1.916	1.949
3.20	25	1184.8	1184.7	1184.5	2.732	2.746	2.838
3.20	30	1182.3	1182.2	1182.0	2.393	2.406	2.443
3.20	35	1179.7	1179.6	1179.4	2.115	2.124	2.184
3.80	25	1199.3	1199.1	1198.9	2.926	2.923	3.058
3.80	30	1196.8	1196.5	1193.3	2.558	2.559	2.627
3.80	35	1194.1	1193.9	1193.7	2.258	2.259	2.345
Water + 2.7 molal Glucose + c Sodium Chloride							
1.20	25	1166.3	1166.3	1166.1	3.296	3.292	3.383
1.20	30	1164.0	1163.8	1163.8	2.843	2.843	2.872
1.20	35	1161.6	1161.4	1161.3	2.482	2.484	2.540
2.20	25	1190.1	1190.0	1189.8	3.630	3.642	3.817
2.20	30	1187.6	1187.5	1187.4	3.135	3.144	3.248
2.20	35	1185.1	1184.9	1184.8	2.734	2.744	2.878
3.20	25	1212.5	1212.4	1212.3	4.051	4.034	4.359
3.20	30	1209.9	1209.8	1209.7	3.490	3.478	3.714
3.20	35	1207.3	1207.2	1207.1	3.036	3.030	3.298
3.80	25	1225.3	1225.2	1225.2	4.314	4.294	4.738
3.80	30	1222.7	1222.6	1222.6	3.711	3.696	4.036
3.80	35	1220.0	1220.0	1219.9	3.229	3.216	3.589
Water + 3.2 molal Glucose + c Sodium Chloride							
1.20	25	1182.6	1182.5	1182.5	4.080	4.073	4.180
1.20	30	1180.2	1180.0	180.2	3.492	3.489	3.509
1.20	35	1177.7	1177.5	1177.6	3.027	3.025	3.106
2.20	25	1205.0	1204.9	1204.8	4.499	4.503	4.624
2.20	30	1202.5	1202.3	1202.3	3.849	3.849	3.876
2.20	35	1199.9	1199.7	1199.7	3.330	3.335	3.483
3.20	25	1226.0	1226.0	1225.9	4.997	4.989	5.158
3.20	30	1223.4	1223.4	1223.3	4.258	4.256	4.309
3.20	35	1220.8	1220.8	1220.7	3.677	3.678	3.949
3.80	25	1238.2	1238.1	1238.1	5.341	5.308	5.528
3.80	30	1235.5	1235.5	1235.4	4.549	4.519	4.605
3.80	35	1232.8	1232.9	1232.7	3.923	3.899	4.275

mol·kg^{-1} and at temperatures of 20, 30, and 40 °C, that is, 75 input patterns that correspond to water 1, to the binary system water + sodium chloride 4, to the binary system water + glucose 4, and to the ternary system 16, for the three temperatures. In this process, the mean relative deviations between experimental and calculated values were 0.02% for density and 0.45% for viscosity.

It is essential to be able to use the neural network to predict density and viscosity values that were not included in the set of data applied in the training phase. With the objective of evaluating the prediction capacity of both networks, calculated values were compared with experimental values. First, the values of both properties were used for the remaining 168 cases, found in Tables 1 and 2, obtaining mean relative deviations between experimental and calculated values of 0.02% for density and 0.42% for viscosity. Later, values of density and viscosity were determined experimentally for different concentrations and temperatures, in the ranges studied, which appear in Table 4, along with the calculated values. The mean relative deviations were 0.01% for density and 0.34% for viscosity, with the deviation being less than 1% for all. Similarly,

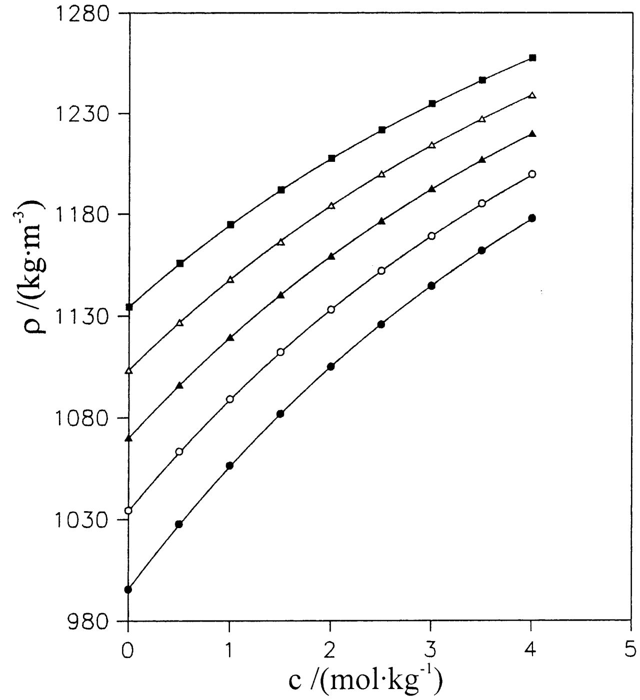

Figure 1. Density of the aqueous solutions of glucose + sodium chloride at 30 °C plotted against the glucose concentration: ●, 0 mol·kg^{-1} sodium chloride; ○, 1.0 mol·kg^{-1} sodium chloride; ▲, 2.0 mol·kg^{-1} sodium chloride; △, 3.0 mol·kg^{-1} sodium chloride; ■, 4.0 mol·kg^{-1} sodium chloride; —, calculated from net 1.

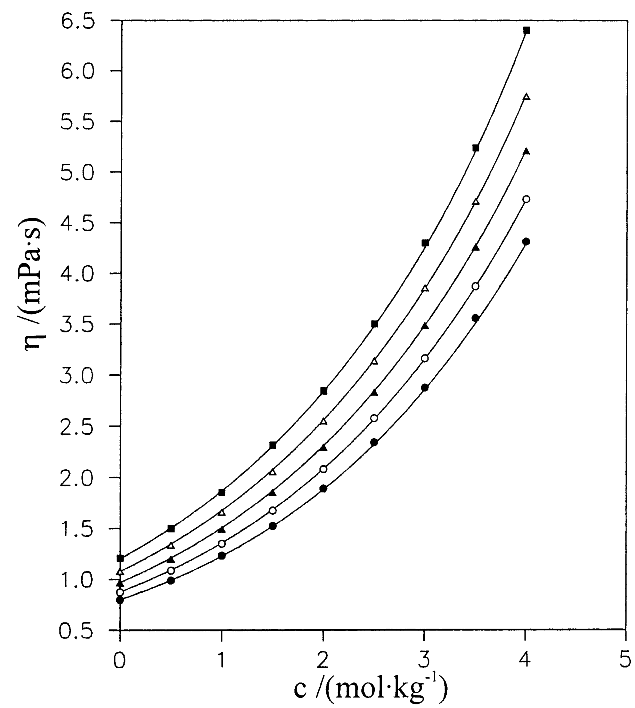

Figure 2. Viscosity of the aqueous solutions of glucose + sodium chloride at 30 °C plotted against the glucose concentration: ●, 0 mol·kg^{-1} sodium chloride; ○, 1.0 mol·kg^{-1} sodium chloride; ▲, 2.0 mol·kg^{-1} sodium chloride; △, 3.0 mol·kg^{-1} sodium chloride; ■, 4.0 mol·kg^{-1} sodium chloride; —, calculated from net 2.

Table 4 shows the values calculated using the coefficients from Table 3 after carrying out the necessary interpolations. In this case, the mean relative deviation of density (0.02%) was similar to that obtained with the neural network but much greater for viscosity (3.50%) with a maximum deviation of 9.83%.

Figures 1 and 2 show the experimental densities and viscosities, respectively, at 30 °C of the ternary system against glucose concentration. Additionally, the lines determined directly from the calculated values are included for each, that is, using neuronal networks. In both cases, the comparison is considered excellent.

These results indicate that neural networks, after being trained with a reduced number of experimental values, are efficient tools used to calculate density and viscosity for any concentration and temperature included within the working range.

Literature Cited

(1) Bolin, H. R.; Huxsoll, C. C.; Jackson, R.; Ng, K. C. Effect of Osmotic Agents and Concentration on Fruit Quality. *J. Food Sci.* **1983**, *48*, 202−205.

(2) Bohuon, P.; Collignan, A.; Rios, G. M.; Raoult-Wack, A. L. Process in Ternary Liquids: Experimental Study of Mass Transport Under Natural and Forced Convection. *J. Food Eng.* **1998**, *37*, 451−469.

(3) Collignan, A.; Raoult-Wack, A. L. Dewatering and Salting of Cod by Immersion in Concentrated Sugar/Salt Solutions. *Lebensm.-Wiss. Technol.* **1994**, *27*, 259−264.

(4) Jayaraman, K. S.; Gupta, D. K. D.; Rao, N. B. Effect of Pretreatment with Salt and Sucrose on the Quality and Stability of Deshydrated Cauliflower. *Int. J. Food Sci. Technol.* **1990**, *25*, 47−60.

(5) Sabadini, E.; Carvalho, B. C., Jr.; Sobral, P. J.; Hubinger, M. D. Mass Transfer and Diffusion Coefficient Determination in the Wet and Dry Salting of Meat. *Drying Technol.* **1998**, *16*, 2095−2115.

(6) Herrington, T. M.; Jackson, R. J. Densities of Sucrose Solutions Containing Potassium Chloride. *Int. Sugar J.* **1983**, *85*, 364−369.

(7) Bohuon, P.; Le Maguer, M.; Raoult-Wack, A. L. Densities and Viscosities of Ternary Systems of NaCl−Sucrose-Water from 283.15 to 303.15 K. *J. Chem. Eng. Data* **1997**, *42*, 266−269.

(8) Comesaña, J. F.; Otero, J. J.; Camesella, E.; Correa, A. Densities and Viscosities of Ternary Systems of Water+Fructose+Sodium Chloride from 20 to 40 °C. *J. Chem. Eng. Data* **2001**, *46*, 1153−1155.

(9) Cherqaoui, D.; Villemin, D. Use of a Neural Network to Determine the Boiling Point of Alkanes. *J. Chem. Soc., Faraday Trans.* **1994**, *90*, 97−102.

(10) Bouchard, C.; Grandjean, B. P. A. A Neural Network Correlation for the Variation of Viscosity of Sucrose Aqueous Solutions with Temperature and Concentration. *Lebensm.-Wiss. Technol.* **1995**, *28*, 157−159.

(11) Kan, P.; Lee, C. J. A Neural Network Model for Prediction of Phase Equilibria in Aqueous Two-Phase Extraction. *Ind. Eng. Chem. Res.* **1996**, *35*, 2015−2023.

(12) Alvarez, E.; Riverol, C.; Correa, J. M.; Navaza, J. M. Design of a Combined Mixing Rule for the Prediction of Vapor-Liquid Equilibria Using Neural Networks. *Ind. Eng. Chem. Res.* **1999**, *38*, 1706−1711.

(13) Marsh, K. N. Recommended Reference Materials for the Realization of Physicochemical Properties; Blackwell Scientific Publications: Oxford, U.K., 1987.

(14) Weast, R. C. *Handbook of chemistry and physics*, 57th ed; The Chemical Rubber Company: Cleveland, OH, 1976.

(15) Pitzer, K. S.; Peiper, J. C.; Busey, R. H. Thermodynamic Properties of Aqueous Sodium Chloride Solutions. *J. Phys. Chem. Ref. Data* **1984**, *13*, 1−102.

(16) Afzal, M.; Saleem, M.; Mahmooh, M. T. Temperature and Concentration Dependence of Viscosity of Aqueous Electrolytes from 20 to 50 °C. Chlorides of Na^{+}, K^{+}, Mg^{2+}, Ba^{2+}, Sr^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, and Cr^{3+}. *J. Chem. Eng. Data* **1989**, *34*, 339−346.

(17) Bettin, H.; Emmerich, A.; Spieweck, F.; Toth, H. Density Data for Aqueous Solutions of Glucose, Fructose and Invert Sugar. *Zuckerindustrie* **1998**, *123*, 341−348.

(18) Rumelhart, D. E.; Hinton, G. E.; Williams, R. J. Learning Representations by Back-propagating Error. *Nature* **1986**, *323*, 533−536.

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