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Volumetric Properties and Viscosities for Aqueous Diisopropanolamine Solutions from 25 °C to 70 °C

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This paper reports the density and viscosity of aqueous diisopropanolamine (DIPA) solutions at five temperatures in the range 25 °C to 70 °C over the whole concentration range. The results are compared with data published in the literature. The derived excess molar volumes, partial molar volumes, the partial molar volumes at infinite dilution, and viscosity deviations were correlated as a function of composition.

Introduction

Alkanolamine solutions are widely used for the removal of acid gases from natural and synthesis gas streams. Monoethanolamine (MEA), diethanolamine (DEA), diisopropanolamine (DIPA), and methyldiethanolamine (MDEA) are examples of widely used and industrially important alkanolamines. As secondary amines, DEA and DIPA are the most commonly used amines because of their thermal stability and favorable reaction kinetics with CO_2.[1] DIPA is sterically more crowded than DEA. The kinetic data published for aqueous DIPA solutions were reviewed by Versteeg et al.[2] DIPA is also used with an aqueous solution of sulfolane (a physical solvent) in the Sulfinol process (ADIP), a widely used mixed solvent process licensed by Shell. DIPA solutions are reported to have low regeneration steam requirements and to be noncorrosive. DIPA is also used for the selective absorption of H_2S from Claus plant tail gas. It is claimed that it can remove substantial amounts of COS without detrimental effects to the solution.

Even though DIPA is an important alkanolamine, to our knowledge, there are no published data of a comprehensive study of the densities and viscosities of aqueous DIIPA solutions. Wang et al.[3] presented values of the density of pure DIPA at five temperatures (45 °C to 85 °C). Ko et al.[4] published a few values of the viscosity of pure DIPA (50 °C to 80 °C) and the densities and viscosities of aqueous DIPA solutions in six concentrations at 30 °C, 35 ° C, and 40 °C. Snijder et al.[5] measured the density and viscosity of aqueous DIPA at four concentrations for the temperature range (25 °C to 75 °C). Measurements from the literature are compared to the values obtained in this work and are listed in Table 1.

Measurements of the densities and viscosities of the aqueous DIPA solutions were performed at various temperatures, (25, 40, 45.5, 50, 60, and 70) °C, in order to cover the wide range of temperatures found in industrial applications. The excess volumes, the partial molar volumes, the partial molar volumes at infinite dilution, and the deviations of the viscosity were derived.

Table 1. Review of the Literature Data for the Density and Viscosity of DIPA

	ρ/g·cm^{-3}		η/mPa·s	
T/K	this work	lit.	this work	lit.
315.15 (45)		0.988 50[a]		
315.55 (45.5)	0.988 22		186.61	
323.15 (50)	0.984 90		125.73	125.20[b]
328.15 (55)				82.02[b]
328.55 (55.4)		0.981 40[a]		
333.15 (60)	0.977 30		57.98	55.91[b]
338.15 (65)				39.39[b]
338.55 (65.5)		0.973 90[a]		
343.15 (70)	0.969 58		29.55	28.08[b]
348.15 (75)				20.75[b]
348.05 (74.9)		0.966 10[a]		
353.15 (80)				15.57[b]
358.45 (85.3)		0.956 60		

[a] Wang et al.[3] [b] Ko et al.[4]

Experimental Section

DIPA (>98% pure) was purchased from Fluka and was used without further purification. The melting point was determined to be around 45.4 °C by decreasing slowly the temperature in the density meter vibrating tube. The solutions were prepared by mass on an analytical balance (model Ap 205 D, Ohaus, Florham Park, NJ) with ±0.01 mg accuracy. The possible error in the mole fraction is estimated to be around ±0.0001. Densities of the binary mixtures were measured with an Anton Paar DMA-4500 density meter. Calibration was done using air and water at ambient temperature. The densities of water were measured in the temperature range 15−80 °C and were compared to values measured by Bettin et al.[6] and provided by Anton Paar in the instruction manual. The calibration was accepted if the measurements were within $\pm 5 \times 10^{-5}$ g·cm^{-3} of the published values. Accuracies of our densities are about $\pm 5 \times 10^{-5}$ g·cm^{-3} when compared to the densities of pure MDEA published in the literature[7] in the temperature range 25 °C to 80 °C. The densities of water were measured using deionized water.[8] Density measurements were reproducible to $\pm 2 \times 10^{-5}$ g·cm^{-3}.

In the viscosity measurements, the temperature was controlled by means of a digital controller (±0.004 °C) in a well-stirred water bath to better than ±0.01 °C, as measured by a Cole-Parmer resistance thermometer (model H-01158-65, Anjou, Québec, Canada). Viscosities were

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Table 2. Densities of Water (1) + DIPA (2) Mixtures at Various Temperatures

x_2	ρ/g·cm^{-3} at the following temperatures					
	25 °C	40 °C	45.5 °C	50 °C	60 °C	70 °C
0.0000	0.997 04	0.992 21	0.990 21	0.988 04	0.983 12	0.977 77
0.0200	1.005 22	0.999 64	0.997 52	0.995 02	0.989 76	0.983 93
0.0498	1.015 93	1.008 66	1.006 43	1.003 09	0.996 93	0.990 37
0.0701	1.021 72	1.013 20	1.010 34	1.006 95	1.000 34	0.993 22
0.1001	1.027 13	1.017 40	1.014 00	1.010 46	1.003 16	0.995 55
0.1999	1.030 90	1.019 77	1.015 54	1.012 04	1.004 03	0.995 78
0.3006	1.027 13	1.016 15	1.011 90	1.008 24	1.000 17	0.991 86
0.3963	1.022 42	1.011 45	1.007 24	1.003 75	0.995 77	0.987 44
0.5012	1.017 79	1.006 84	1.002 82	0.999 39	0.991 52	0.983 33
0.5957	1.014 09	1.003 20	0.999 15	0.995 71	0.987 88	0.979 75
0.7034	1.010 66	0.999 62	0.995 55	0.992 23	0.984 45	0.976 35
0.8029	1.008 07	0.997 10	0.993 04	0.989 58	0.981 79	0.973 95
0.9016	1.006 28	0.995 03	0.990 99	0.987 51	0.979 72	0.971 72
1.0000			0.988 22	0.984 90	0.977 30	0.969 58

determined with six different viscometers to cover, with precision, the range of temperature from 25 °C to 70 °C. A series of Cannon-Ubbelohde viscometers (0, 0B, 0C, 1, 1B, 2C− Cole Parmer) were used. The efflux time was measured with a hand-held digital stopwatch capable of measuring time to within ±0.01 s. Experiments were repeated a minimum of four times at each temperature for all compositions. The equation for kinematic viscosity, according to Poiseuille's law, is

$$\nu = k_1 t - k_2/t \tag{1}$$

where t is the efflux time and k_1 and k_2 are the viscometer constants. The second term representing the correction due to the kinetic energy was found to be negligible.[9] The value of the absolute viscosity (η) was obtained by multiplying the measured kinematic viscosity (ν) by the measured density. Calibration constants for the two viscometers were checked using high-purity ethylene glycol (EG), diethylene glycol (DEG), and water. A review of published values of the kinematic and dynamic viscosities of EG and DEG, with new experimental data, was published by Lee and Teja.[10] Values of the viscosity of water were taken from ref 11. From the overall average percent deviation of the means of the average efflux time and the accuracy of the density measurement, we estimate the uncertainty of the absolute viscosity to be ±0.3%.

Results and Discussion

Experimentally measured densities of the aqueous DIPA solutions at (25, 40, 45.5, 50, 60, and 70) °C throughout the whole concentration range are listed in Table 2. Our values are in qualitative agreement with the values published by Wang et al.[3]

The values of the measured densities of DIPA/water solutions are shown in Figure 1. The curves show an increase in the density as DIPA is added to water. The maximum values of the density occur at around 20 mol %.

The density values of the binary mixtures were used to calculate the excess molar volume, V_m^E, as

$$V_m^E = V_m - V_1^\circ x_1 - V_2^\circ x_2 \tag{2}$$

where V_m is the molar volume of the mixture and V_1° and V_2° are those of pure water and pure DIPA, respectively; x_1 and x_2 are the mole fractions of the pure components. Figure 2 displays the dependence of V_m^E on the composition at various temperatures. In all cases the V_m^E is negative, as is common for other completely miscible (water + polar organic) solvents with a minimum at around 35 mol % of DIPA. These V_m^E values became less negative with increasing temperature, as is also common. Figures 1 and 2 show a sharp change in the density and V_m^E in the water-rich region. Negative values of V_m^E mean that there is a volume contraction and can thus be explained by the large difference in the molar specific volumes. Pal and Singh[12] concluded that the contraction in the volume is due to the ability of the −OH group to form hydrogen bonds with water molecules. The second interpretation given was that such marked change in V_m^E might also be due to the accommodation of the nonaqueous molecules occupying in the structured water lattice a void space. It is known that the number of cross-associated H-bonds decreases with increasing temperature, which leads to a positive contribution to V_m^E. As a consequence, V_m^E values became more negative with a decrease in temperature.

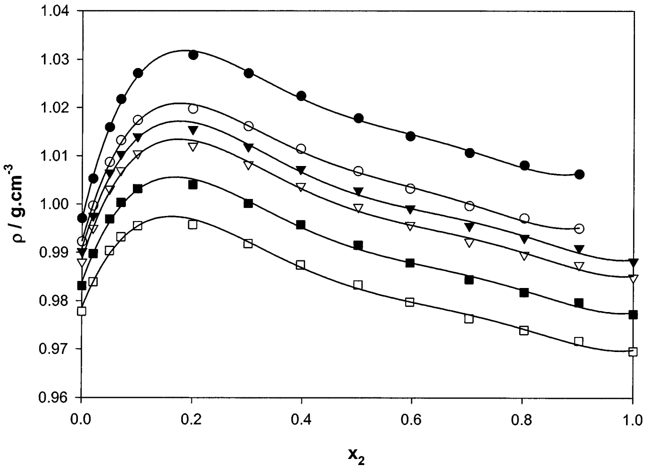

Figure 1. Densities of water (1) + DIPA (2) system at various temperatures: ●, 25 °C; ○, 40 °C; ▼, 45.5 °C; ▽, 50 °C; ■, 60 °C; □, 70 °C.

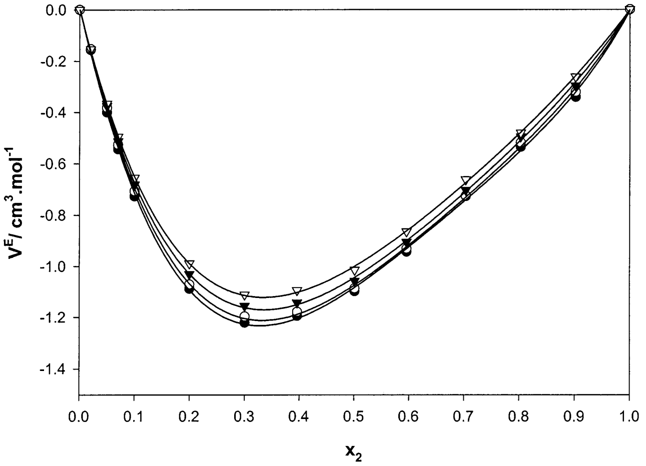

Figure 2. Excess molar volumes of the water (1) + DIPA (2) system at various temperatures: ●, 45.5 °C; ○, 50 °C; ▼, 60 °C; ▽, 70 °C.

The values of the density of various alkanolamines are shown in Figure 3 for comparison. As shown, DIPA has its density increase and then decrease with the addition of alkanolamine (similar to DGA, MDEA, MEA, and EDEA). The values of the densities of aqueous alkanolamines are the largest for TEA followed by DEA, DGA, MDEA, EDEA, MEA, DIPA, and AMP.

In Figure 4, a comparison of the excess volumes of several alkanolamines shows that the addition of DIPA to water brings the largest decrease in the excess volume, very closely followed by MDEA, then AMP, DGA, triethanola-

Table 3. Redlich−Kister Equation Fitting Coefficients of the Excess Volumes (V_m^E/cm^3·mol^{-1}) for Water (1) + DIPA (2) Mixtures at Various Temperatures

T/°C	a_0	a_1	a_2	a_3	a_4	a_5	a_6	σ/cm^3·mol^{-1}
45.5	−4.3814	−2.6216	−1.4648	−1.8983	−1.4681	3.0503		0.007
50	−4.3275	−2.4971	−1.4864	−2.1991	−1.0152	3.2039		0.006
60	−4.2104	−2.4152	−1.2459	−1.8825	−1.0445	2.4663		0.005
70	−4.0463	−2.5176	−0.5807	−0.3928	−4.0199	0.1433	3.5762	0.005

Table 4. Coefficients of the Polynomial ρ/g·cm^{-3} = $\sum_0^n a_k x_2^k$ and the Standard Deviation for the Aqueous DIPA Solutions at Various Temperatures

T/°C	a_0	a_1	a_2	a_3	a_4	a_5	a_6	σ/g·cm^{-3}
25	0.996 89	0.492 29	−2.401 61	4.921 82	−4.699 15	1.705 13		0.0006
40	0.991 98	0.450 13	−2.570 56	6.766 87	−9.629 88	7.087 05	−2.106 70	0.0003
45.5	0.990 14	0.433 75	−2.543 13	6.750 51	−9.532 81	6.864 95	−1.975 25	0.0003
50	0.987 99	0.405 56	−2.352 04	6.146 15	−8.553 59	6.081 32	−1.730 51	0.0002
60	0.983 21	0.370 75	−2.219 39	5.913 86	−8.353 00	6.001 47	−1.719 64	0.0002
70	0.977 94	0.335 05	−2.054 16	5.515 08	−7.814 75	5.619 76	−1.609 40	0.0003

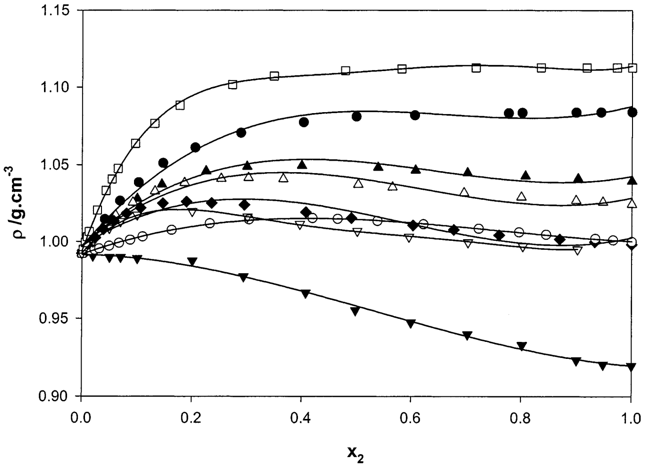

Figure 3. Densities of various aqueous alkanolamine systems at 40 °C: □, TEA;[16] ●, DEA;[16] ▲, DGA;[17] △, MDEA;[7] ◆, EDEA;[7] ○, MEA;[16] ▼, AMP; ▽, DIPA.

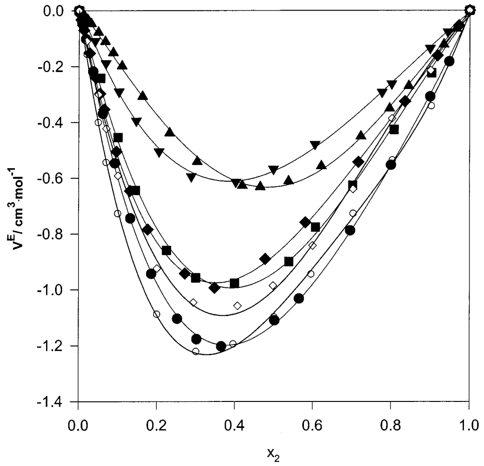

Figure 4. Excess molar volumes of various aqueous alkanolamine systems at 40 °C: ●, MDEA;[7] ◇, AMP;[18] ■, DGA;[17] ◆, TEA;[16] ▲, MEA;[16] ▼, DEA;[16] ○, DIPA.

Table 5. Partial Molar Volumes of DIPA at Infinite Dilution in Water (V_2^∞)

T/°C	V_2^∞/cm^3·mol^{-1}
45.5	126.0
50	126.9
60	127.9
70	129.5

mine (TEA), diethanolamine (DEA), and monoethanolamine (MEA).

A Redlich−Kister[13] relation was used to correlate the excess volume data:

$$V_m^E/\text{cm}^3\cdot\text{mol}^{-1} = x_1 x_2 \sum_{i=0}^{n} a_i (x_1 - x_2)^i \qquad (3)$$

The coefficients and the standard deviation (σ) are presented in Table 3. It is well-known that the Redlich−Kister relation does not correlate well unsymmetrical curves of excess volumes (and viscosity deviations). The introduction of a number of a skewing factor did not reduce the number of coefficients used. We thus present the correlation of the densities of the solutions at each temperature with the following polynomial:

$$\rho/\text{g}\cdot\text{cm}^{-3} = \sum_{k=0}^{n} a_k {x_2}^k \qquad (4)$$

The coefficients and the standard deviation (σ) are presented in Table 4. Hepler[14] and Neal and Goring[15] recognized the usefulness of thermal expansion data for revealing correlations between molecular structure of solutes and their effects on water structure. They suggested using the sign of the second derivative of the partial molar volume at infinite dilution of the solute with respect to the temperature $(\partial^2 V_2^\circ/\partial T^2)_P$ to classify solutes as “structure makers” or “structure breakers”. A positive sign corresponds to a structure-making solute while a negative sign corresponds to a structure-breaking solute.

The partial molar volumes of DIPA at infinite dilution (V_2^∞) in water were obtained using the method proposed by Maham et al.[16] The apparent molar volumes of DIPA in water ($V_{\phi,2}$) were first calculated as

$$V_{\phi,2} = V_2^\circ + (V_m^E/x_2) \qquad (5)$$

where V_1° and V_2° are the molar volumes and x_1 and x_2 are the mole fractions of pure water and DIPA, respectively. An analytical extrapolation of $V_{\phi,1}$ to x_2 =1 leads to V_1^∞, and a similar extrapolation of $V_{\phi,2}$ to x_2 = 0 led to V_2^∞. Partial molar volumes at infinite dilution are listed in Table 5. V_2^∞ values varied linearly with temperature. According to the criterion described above, the solute (DIPA) would be considered as having no net effect on the structure of water. This is consistent with the conclusion of Maham et al.[7,16] and others[17,18] concerning other alkanolamines (MEA, DEA, TEA, MDEA, EDEA, DGA, and AMP). All the values of the molar volumes at infinite dilution (V_2^∞) were smaller than the corresponding molar values of pure DIPA (V_2°).

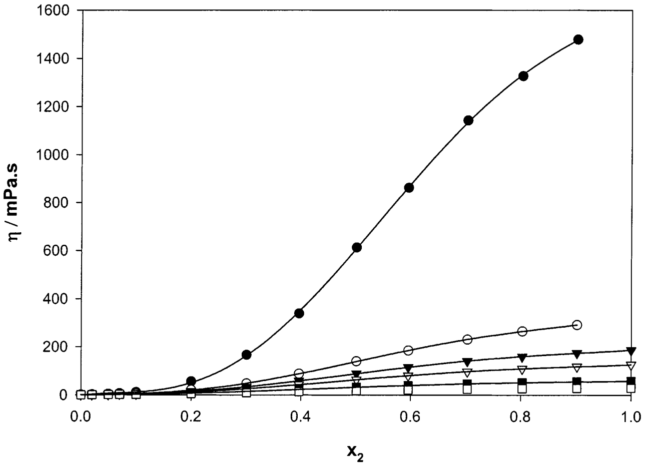

Figure 5. Viscosities of the water (1) + DIPA (2) system at various temperatures: ●, 25 °C; ○, 30 °C; ▼, 45.5 °C; ▽, 50 °C; ■, 60 °C; □, 70 °C.

Table 6. Experimental Viscosities for Water (1) + DIPA (2) Mixtures at Various Temperatures

	η/mPa·s					
x_2	25 °C	40 °C	45.5 °C	50 °C	60 °C	70 °C
0.0000	0.890	0.653	0.595	0.547	0.466	0.405
0.0200	1.645	1.112	0.992	0.907	0.733	0.621
0.0498	3.723	2.218	1.914	1.684	1.355	1.061
0.0701	6.06	3.335	2.776	2.408	1.816	1.412
0.1001	11.55	5.56	4.60	3.78	2.719	2.042
0.1999	55.69	20.63	15.21	12.06	7.50	5.05
0.3006	166.1	46.9	32.42	24.56	14.15	8.70
0.3963	338.7	87.7	58.7	42.8	22.89	13.34
0.5012	613	139.1	88.1	63.37	32.12	17.88
0.5957	861	184.6	114.5	79.93	39.31	21.19
0.7034	1142	229.9	140.0	96.22	46.32	24.42
0.8029	1326	264.6	159.5	108.7	51.38	26.64
0.9016	1478	290.7	174.2	118.0	55.03	28.29
1.0000			186.6	125.7	57.99	29.55

The change in the excess volume can be explained by the DIPA molecule fitting (partially) into the open, or empty, space in liquid water. This picture does not invoke either the structure-making or the -breaking properties and is consistent with the observation that $(\partial^2 \bar{V}_2^{\infty}/\partial T^2)_P$ values are approximately equal to zero.

Our values were on average 4% higher than those published by Ko et al. We have noticed that the viscosity values of TEA published by Maham et al.[19] were on average 3% higher than the values reported by Ko et al. Experimentally measured viscosities of the binary solutions of aqueous DIPA solutions at (25, 40, 45.5, 50, 60, and 70) °C are listed in Table 6 and shown in Figure 5. The figure shows a sharp increase in the viscosity of the mixture after the addition of DIPA (30 mol %), especially at high temperatures. The largest viscosity values were those of pure DIPA at all temperatures. The viscosities of aqueous solutions of DIPA were larger than those of TEA, DEA, AMP, MDEA, DGA, and MEA. The influence of the presence of the ethanol group and the methyl group (on the nitrogen atom) on the viscosity was discussed by Maham et al.[19] DIPA is similar to DEA with two extra methyl groups on the ethanol branches. This addition increases the viscosity so much that DIPA becomes solid in its pure form at ambient temperature. This effect is opposite to that of a methyl group being added to the nitrogen atom. The viscosity stays high after the addition of water, implying the presence of very strong hydrogen bonds.

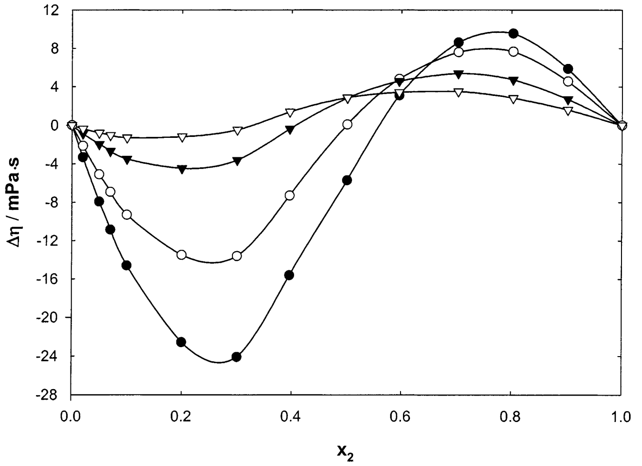

Figure 6. Viscosity deviations for the water (1) + DIPA (2) system at various temperatures: ●, 40 °C; ○, 50 °C; ▼, 60 °C; ▽, 70 °C.

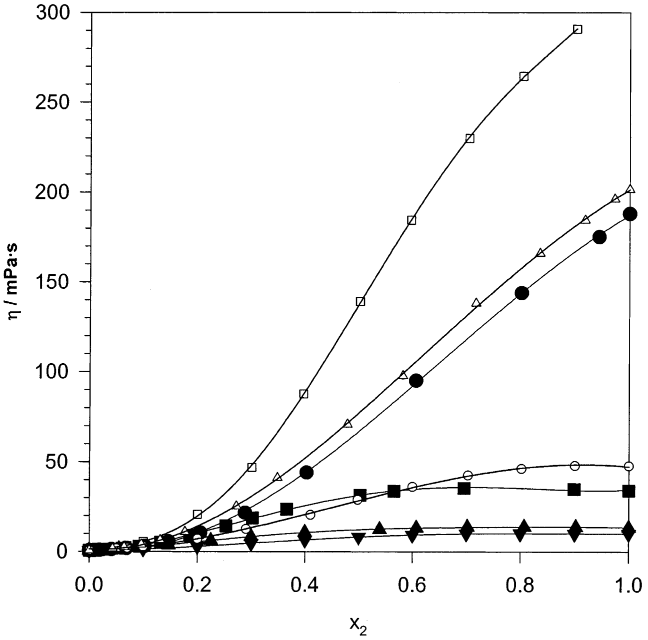

Figure 7. Comparison of the viscosities of various aqueous alkanolamines solutions at 40 °C: ●, DEA;[20] ○, AMP;[18] ■, MDEA;[20] ▲, DGA;[17] ▼, MEA;[24] □, DIPA; △, TEA.[19]

Experimental viscosity values of the binary mixtures were used to calculate the viscosity deviation, defined by

$$\Delta\eta = \eta - \eta_1 x_1 - \eta_2 x_2 \qquad (6)$$

where η is the viscosity of the mixture and η_1 and η_2 are those of pure water and pure DIPA, respectively; x_1 and x_2 are the mole fractions of the pure components. The viscosity deviation represents deviations from a rectilinear dependence of viscosity on mole fraction. Figure 6 displays the dependence of $\Delta\eta$ on the composition and temperature. Values of $\Delta\eta$ were negative up to 60 mol % with a minimum at 30 mol %; then they became positive throughout the whole concentration range with a maximum around 80 mol % for all temperatures. Figure 7 displays the different viscosity curves of aqueous solutions of two primary alkanolamines (MEA and DGA), a secondary alkanolamine (DEA), a tertiary alkanolamine (MDEA), a secondary hindered amine (DIPA), and a primary hindered amine (AMP).

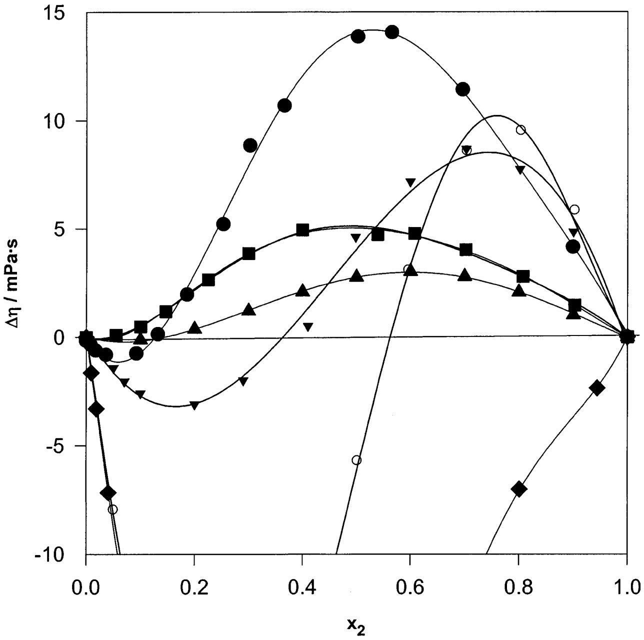

Figure 8. Comparison of the viscosity deviations of various aqueous alkanolamine solutions at 40 °C: ●, MDEA;[20] ■, DGA;[17] ▲, MEA;[24] ▼, AMP;[18] ◆, DEA;[20] ○, DIPA.

Table 7. Redlich−Kister Equation Fitting Coefficients of the Viscosity Deviations ($\Delta\eta$/mPa·s) for Water (1) + DIPA (2) Mixtures at Various Temperatures

T/°C	a_0	a_1	a_2	a_3	a_4	σ/mPa·s
45.5	−23.126	−204.228	−76.805	93.918	57.493	0.51
50	−1.4540	−131.435	−74.607	52.742	57.480	0.40
60	10.632	−54.692	−38.470	16.946	24.510	0.16
70	11.071	−23.144	−22.619	4.26	13.289	0.11

Table 8. Coefficients of the Polynomial ln η/mPa·s = ln $\eta_0 + \sum_1^n a_k x_2^k$ and the Standard Deviation for the Water (1) + DIPA (2) Mixtures at Various Temperatures[a]

T/°C	a_1	a_2	a_3	a_4	a_5	a_6	σ/mPa·s
25	32.623	−85.556	167.338	−211.657	145.483	−40.785	0.009
40	28.281	−83.930	187.112	−262.246	195.841	−59.008	0.012
45.5	27.058	−82.400	182.951	−249.312	178.612	−51.162	0.014
50	26.025	−81.334	185.715	−259.319	189.559	−55.211	0.016
60	24.340	−81.911	196.485	−281.112	208.164	−61.139	0.019
70	22.437	−77.352	186.073	−265.054	195.327	−57.144	0.015

[a] η_0 is the viscosity of pure water.

Figure 8 shows that MDEA, DIPA, AMP, and MEA had negative viscosity deviations in the water-rich region at all temperatures which then became positive. The DEA viscosity deviations calculated by Teng et al.[20] were negative for all compositions at all temperatures except at 70 °C and 80 °C, where they became positive in the DEA-rich region. In summary, all alkanolamines show a change in the sign of the viscosity deviations with a minimum in the water-rich region and a maximum in the amine-rich region. This remark applies to all classes of alkanolamines (primary, secondary, tertiary, and hindered alkanolamines). In previous studies,[21] we have suggested the possible formation of complexes in ethanolamine solutions. Recently, Burke et al.[22] and Hawrylak et al.[23] measured the sound velocity in several aqueous alkanolamine solutions (TEA, MDEA, DMEA, and DEEA). They attributed the presence of a common intersection point in the adiabatic compressibility isotherms to the formation of clathrate-like structures in the water-rich region.

The calculated values of $\Delta\eta$ were correlated with a Redlich−Kister[13] relation:

$$\Delta\eta/\mathrm{mPa\cdot s} = x_1 x_2 \sum_{i=0}^{n} a_i (x_1 - x_2)^i \tag{7}$$

where x_1 is the mole fraction of water and x_2 is the mole fraction of DIPA. The coefficients and the standard deviation (σ) are presented in Table 7. We also present the correlation of the viscosities of the solutions at each temperature with the following polynomial:

$$\ln \eta/\mathrm{mPa\cdot s} = \ln \eta_0 + \sum_{k=1}^{6} a_k {x_2}^k \tag{8}$$

where η is the viscosity of the binary solution, η_0 is the viscosity of pure water, and x_2 is the mole fraction of DIPA. The values of the polynomial coefficients a_k are listed in Table 8.

Conclusions

This paper reports experimental data for the densities and viscosities of the aqueous DIPA solutions over a range of temperature from 25 °C to 70 °C. The calculated V_m^E values for the aqueous DIPA solutions were all negative at all temperatures and compositions. The criterion proposed by Hepler[14] suggests that the addition of DIPA to water had no effect on its structure, a conclusion similar to that of Maham et al.[7,16] for MEA, DEA, TEA, MEA, and EDEA and Henni et al.[18,23] for AMP and DGA. The viscosity deviations $\Delta\eta$ for DIPA + water were negative in the water-rich region and then became positive in the amine-rich region at all temperatures. This conclusion is valid for all alkanolamines studied thus far (MEA, DEA, TEA, MEA, DGA, and EDEA).

Aqueous AMP, DGA, MDEA, and MEA solutions exhibited S-shaped viscosity curves. Aqueous DEA and DIPA viscosities did not have an S-shaped curve but still exhibited a change in the sign of the viscosity deviations from negative to positive in the amine-rich region. The formation of clathrate proposed by Burke et al.[22] and Hawrylak et al.[23] seems to be in contradiction with the neutral structure effect of alkanolamines resulting from applying Hepler's criterion.

Literature Cited

(1) Davis, R. A.; Menendez, R. E.; Sandall, O. C. Physical, Thermodynamic and Transport Properties for carbon Dioxide and Nitrous Oxide in Solutions of Diethanolamine or Diisopropanoalmine in Polyethylene Glycol. *J. Chem. Eng. Data* **1993**, *38*, 119−124.

(2) Versteeg, G. F.; van Dijck, L. A. J.; van Swaaij, W. P. M. On the Kinetics between CO_2 and Alkanolamines both in Aqueous and Nonaqueous Solutions. An Overview. *Chem. Eng. Commun.* **1996**, *144*, 113−158.

(3) Wang, Y. W.; Xu, S.; Otto, F. D.; Mather, A. E. Solubility of N_2O in Alkanolamines and In Mixed Solvents. *Chem. Eng. J.* **1992**, *48*, 31−40.

(4) Ko, J.-J.; Tsai, T.-C.; Lin, C.-Y.; Wang, H.-M.; Li, M.-H. Diffusivity of Nitrous Oxidein Aqueous Alkanolamine Solutions. *J. Chem. Eng. Data* **2001**, *46*, 160−165.

(5) Snidjer, E. D.; te Riele, M. J. M.; Versteeg, G. F.; van Swaaij, W. P. M. The Diffusion Coefficients of Several Aqueous Alkanolamine Solutions. *Ind. Eng. Chem. Res.* **1993**, *38*, 475−480.

(6) Bettin, H.; Spieweck, F. Die Dichte des Wassers als Funktion der Temperatur nach Einführung der Internationalen Temperaturskala von 1990. *PTB-Mitt.* **1990**, *100*, 195−196.

(7) Maham, Y.; Teng, T. T.; Mather, A. E.; Hepler, L. G. Volumetric Properties of (Water − Diethanolamine) Systems. *Can. J. Chem.* **1995**, *73*, 1514−1519.

(8) American Society of Testing Materials. *Annual Book of ASTM Standards*: Density and Relative Density of Liquids By Digital Density Meter; Standard D 4052-81; 1986, *05.03*, 294−298.

(9) Cannon, M. R.; Manning, R. E.; Bell, J. D. Viscosity Measurement: The Kinetic Energy Correction and a New Viscometer. *Anal. Chem.* **1960**, *32* (3), 355−358.
(10) Lee, R.-J.; Teja, A. S. Viscosities of Poly(ethylene glycols). *J. Chem. Eng. Data* **1990**, *35*, 385−387.
(11) Stokes, R. H.; Mills, R. *Viscosity of Electrolytes and Related Properties*; Pergamon Press: New York, 1965.
(12) Pal, A.; Singh, Y. P. Excess Molar Volumes and Viscosities for Glycol-Water Solutions at theTemperature 308.15 K: Ethylene Glycol Monomethyl, Diethylene Glycol Monomethyl, and Triethylene Glycol Monomethyl Ethers. *J. Chem. Eng. Data* **1996**, *41*, 425−427.
(13) Redlich, O.; Kister, A. T. Algebraic Representation of Thermodynamic Properties and the Classification of Solutions. *Ind. Eng. Chem.* **1948**, *40*, 345−348.
(14) Hepler, L. G. Thermal Expansion and Structure in Water and Aqueous Solutions. *Can J. Chem.* **1969**, *47*, 4613−4617.
(15) Neal, J. L.; Goring, D. A. I. Volume−Temperature Relationship of Hydrophobic and Hydrophilic Nonelectrolyte in Water. *J. Phys. Chem.* **1970**, *74*, 658−664.
(16) Maham, Y.; Teng, T. T.; Hepler, L. G.; Mather, A. E. Densities, Excess Molar Volumes, and Partial Molar Volumes for Binary Mixtures of Water with Monoethanolamine, Diethanolamine, and Triethanolamine from 25 to 80 °C. *J. Solution Chem.* **1994**, *23* (2), 195−205.
(17) Henni, A.; Tontiwachwuthikul, P.; Chakma, A.; Mather, A. E. Volumetric Properties andViscosities for Aqueous Diglycolamine Solutions from 25 °C to 70 °C. *J. Chem. Eng. Data* **2001**, *46*, 56−62.
(18) Henni, A.; Hromek, J. J.; Tontiwachwuthikul, P.; Chakma, A. Volumetric Properties and Viscosities for Aqueous AMP Solutions from 25 ° C to 70 °C. *J. Chem. Eng. Data* **2003**, *48*, 551−556.
(19) Maham, Y.; Liew, C.-N.; Mather, A. E. Viscosities and Excess Properties of Aqueous Solutions of Ethanolamines from 25 to 80 °C. *J. Solution Chem.* **2002**, *31* (9), 743−756.
(20) Teng, T. T.; Maham, Y.; Hepler, L. G.; Mather, A. E. Viscosity of Aqueous Solutions of *N*-Methyldiethanolamine and of Diethanolamine. *J. Chem. Eng. Data* **1994**, *39*, 290−293.
(21) Henni, A.; Maham, Y.; Tontiwachwuthikul, P.; Chakma, A.; Mather, A. E. Densities and Viscosities for Binary Mixtures of Triethylene Glycol Monomethyl Ether and *N*-Methyldiethanolamine from 25 °C to 70 °C and *N*-Methyldiethanolamine + Ethanol at 40 °C. *J. Chem. Eng. Data* **2000**, *45*, 247−253.
(22) Burke, S. E.; Hawrylak, B.; Palepu, R. Thermodynamic Transfer Functions at Infinite Dilution and Clathrate Formation of Ethanolamine in Water. *Thermochim. Acta* **2000**, *345*, 101−107.
(23) Hawrylak, B.; Burke, S. E.; Palepu, R. Partial Molar and Excess Volumes and Adiabatic Compressibilities of Binary Mixtures of Ethanolamines with Water. *J. Solution Chem.* **2000**, *29* (6), 575−594.
(24) Lee, M.-J.; Lin, T.-K. Density and Viscosity for Mononethanolamines + Water, + Ethanol and 2-Propanol. *J. Chem. Eng. Data* 1**995**, *40*, 336−339.

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