Densities and Viscosities of Aqueous Ternary Mixtures of 2-(Methylamino)ethanol and 2-(Ethylamino)ethanol with Diethanolamine, Triethanolamine, *N*-Methyldiethanolamine, or 2-Amino-1-methyl-1-propanol from 298.15 to 323.15 K

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Densities and kinematic viscosities of aqueous ternary solutions of 2-(methylamino)ethanol and 2-(ethylamino)-ethanol with diethanolamine, triethanolamine, *N*-methyldiethanolamine, or 2-amino-1-methyl-1-propanol were measured at temperatures from (298.15 to 323.15) K. The total amine concentration was held constant at 50 mass %, and the (MAE or EAE)/(DEA, TEA, MDEA, or AMP) mass % ratio was varied from 0/50 to 50/0, in 10 mass % steps. The experimental values were correlated with temperature and mole fraction.

Introduction

Some industrial processes, such as natural and refinery gas purification, involve the removal of acid impurities (e.g., hydrogen sulfide (H_2S) and carbon dioxide (CO_2)). They are absorbed in chemical solvents, which are generally alkanolamines in an aqueous solution.

The aqueous solutions of blended amines have received increasing attention in the past few years. They have been demonstrated to be highly efficient in the absorption of acid gases because by utilizing the advantages of each amine and varying the relative concentrations of the amines, an optimum absorption system can be designed for a specific application. Furthermore, the addition of a small amount of sterically hindered amines to the aqueous solution of blended alkanolamines can enhance the capacity and rate of absorption of CO_2 with good stripping characteristics and degradation resistance of the formulated solvent.[1,2]

On the other hand, knowledge of the physical properties of process solutions is necessary for the operation of process equipment. Solution density and viscosity are also important in the mass transfer rate modeling of absorbers and regenerators because these properties affect the liquid−film coefficient for mass transfer.[3,4]

In this work, the density and the kinematic viscosity of ternary aqueous mixtures of either of two amines (2-(methylamino)-ethanol (MAE) and 2-(ethylamino)ethanol (EAE)) with one of diethanolamine (DEA), triethanolamine (TEA), *N*-methyldiethanolamine (MDEA), or 2-amino-1-methyl-1-propanol (AMP) were measured over the range 298.15 to 323.15 K. The total amine concentration was held constants at 50 mass %, and the (MAE or EAE)/(DEA, TEA, MDEA, or AMP) mass % ratio was varied from 0/50 to 50/0, in 10 mass % steps.

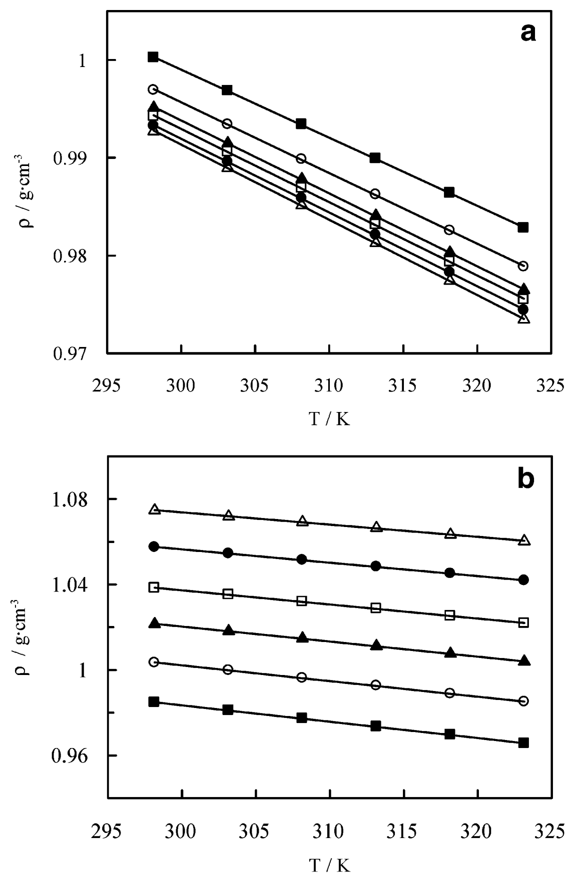

Figure 1. Density dependence with the temperature for aqueous ternary mixtures of (a) MAE (1) + AMP (2) and (b) EAE (1) + TEA (2): △, 0/50; ●, 10/40; □, 20/30; ▲, 30/20; ○, 40/10; ■, 50/0; −, calculated from eq 2.

Experimental Section

Aqueous ternary mixtures were prepared with double-distilled water. The solutes were Merck reagents of nominal purity > 98 % for MAE, EAE, AMP, MDEA, and DEA and > 99 % for

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

	water				ethanol			
	ρ/g·cm^{-3}		η/mPa·s		ρ/g·cm^{-3}		η/mPa·s	
T/K	this work	lit (ref)	this work	lit (ref)	this work	lit (ref)	this work	lit (ref)
298.15	0.997057	0.99704[a]	0.8899	0.8900[a]	0.785260	0.78525[e] 0.78549[f]	1.0912	1.090[e] 1.084[f]
303.15	0.995637	0.99565[a] 0.99560[c]	0.7956	0.7970[c]	0.780756	0.78080[e] 0.78079[g]	0.9575	0.950[e]
308.15	0.994036	0.99403[a]	0.7220		0.776452	0.77650[e]	0.8758	0.870[e]
313.15	0.992185	0.99221[a] 0.99220[c]	0.6550	0.6560[d] 0.6530[c]	0.772339	0.77220[e]	0.7915	0.790[e]
318.15	0.990220	0.99021[b]	0.5950	0.5950[a]	0.767850	0.76760[e]	0.7218	0.720[e]
323.15	0.987978	0.98804[a] 0.98803[b]	0.5460	0.5470[a]	0.763486	0.76320[e]	0.6323	0.630[e]

[a] Henni et al.[6] [b] Bernal-García et al.[7] [c] Comesaña et al.[8] [d] Bernal-García et al.[9] [e] Gómez and Solimo.[10] [f] Peng and Tu.[11] [g] Pan et al.[12]

Table 2. Density of Aqueous Ternary Mixtures of 2-(Methylamino)ethanol and DEA, TEA, AMP, or MDEA

	ρ/g·cm^{-3}					
mass %/mass %	T = 298.15 K	T = 303.15 K	T = 308.15 K	T = 313.15 K	T = 318.15 K	T = 323.15 K
	2-(Methylamino)ethanol/Diethanolamine					
0/50	1.058259	1.055607	1.052879	1.050068	1.047178	1.044200
10/40	1.044520	1.041638	1.038773	1.035627	1.032500	1.029690
20/30	1.032037	1.029069	1.026028	1.022717	1.019538	1.016453
30/20	1.020413	1.017208	1.014035	1.010695	1.007293	1.004012
40/10	1.009206	1.005890	1.002513	0.999075	0.995572	0.992203
50/0	1.000225	0.996840	0.993406	0.989916	0.986394	0.982806
	2-(Methylamino)ethanol/Triethanolamine					
0/50	1.074721	1.071838	1.069172	1.066505	1.063347	1.060200
10/40	1.058612	1.055723	1.052748	1.049689	1.046538	1.043303
20/30	1.042724	1.039688	1.036565	1.033359	1.030073	1.026706
30/20	1.027019	1.023927	1.020742	1.017459	1.014226	1.010756
40/10	1.013273	1.010037	1.006734	1.003360	0.999910	0.996453
	2-(Methylamino)ethanol/2-Amino-2-methyl-1-propanol					
0/50	0.992713	0.988942	0.985138	0.981292	0.977398	0.973460
10/40	0.993268	0.989589	0.985865	0.982098	0.978275	0.974403
20/30	0.994258	0.990607	0.986906	0.983160	0.979360	0.975507
30/20	0.995113	0.991484	0.987808	0.984079	0.980300	0.976465
40/10	0.996919	0.993408	0.989845	0.986227	0.982551	0.978846
	2-(Methylamino)ethanol/*N*-Methyldiethanolamine					
0/50	1.042463	1.039311	1.036077	1.032745	1.029233	1.025854
10/40	1.032756	1.029548	1.026259	1.022893	1.019444	1.015915
20/30	1.023518	1.020219	1.016851	1.013405	1.009888	1.006279
30/20	1.014218	1.010947	1.007632	1.004191	1.000710	0.997190
40/10	1.006604	1.003120	0.999863	0.996505	0.992930	0.989364

Table 3. Density of Aqueous Ternary Mixtures of 2-(Ethylamino)ethanol and DEA, TEA, AMP, or MDEA

	ρ/g·cm^{-3}					
mass %/mass %	T = 298.15 K	T = 303.15 K	T = 308.15 K	T = 313.15 K	T = 318.15 K	T = 323.15 K
	2-(Ethylamino)ethanol/Diethanolamine					
0/50	1.058259	1.055607	1.052879	1.050068	1.047178	1.044200
10/40	1.043678	1.040795	1.037856	1.034844	1.031771	1.028583
20/30	1.028699	1.025575	1.022383	1.019120	1.015786	1.012385
30/20	1.015096	1.011756	1.008359	1.004899	1.001375	0.997766
40/10	1.000513	0.997278	0.993492	0.989530	0.986242	0.982179
50/0	0.984792	0.981056	0.977274	0.973445	0.969563	0.965630
	2-(Ethylamino)ethanol/Triethanolamine					
0/50	1.074721	1.071838	1.069172	1.066505	1.063347	1.060200
10/40	1.057417	1.054469	1.051437	1.048318	1.045111	1.041823
20/30	1.038339	1.035273	1.031985	1.028684	1.025282	1.021868
30/20	1.021473	1.018153	1.014681	1.011175	1.007534	1.003964
40/10	1.003376	0.999847	0.996246	0.992611	0.988816	0.985096
	2-(Ethylamino)ethanol/2-Amino-2-methyl-1-propanol					
0/50	0.992713	0.988942	0.985138	0.981292	0.977398	0.973460
10/40	0.991265	0.987457	0.983624	0.979755	0.975960	0.972017
20/30	0.989904	0.985933	0.982120	0.978353	0.974544	0.970602
30/20	0.987342	0.984616	0.980877	0.976895	0.973115	0.969178
40/10	0.986751	0.982893	0.979208	0.975322	0.971387	0.967598
	2-(Ethylamino)ethanol/*N*-Methyldiethanolamine					
0/50	1.042463	1.039311	1.036077	1.032745	1.029233	1.025854
10/40	1.030807	1.027527	1.024175	1.020727	1.017211	1.013614
20/30	1.019284	1.015954	1.012448	1.008893	1.005405	1.001655
30/20	1.008191	1.004459	1.000749	0.997602	0.993704	0.989746
40/10	0.996384	0.993077	0.988920	0.985204	0.981632	0.977504

MEA and TEA. All solutions were prepared by mass using a KERN 770 analytical balance with a precision of ± 0.0001 g. The uncertainty of the samples preparation in mole fraction was ± 0.0004.

Table 4. Kinematic Viscosity of Aqueous Ternary Mixtures of 2-(Methylamino)ethanol and DEA, TEA, AMP, or MDEA

	ν/mm^2·s^{-1}					
mass %/mass %	T = 298.15 K	T = 303.15 K	T = 308.15 K	T = 313.15 K	T = 318.15 K	T = 323.15 K
2-(Methylamino)ethanol/Diethanolamine						
0/50	9.5728	7.7416	6.3597	5.3135	4.5366	3.9129
10/40	9.3022	7.5174	6.1751	5.1591	4.3999	3.7493
20/30	9.0319	7.2887	5.9819	5.0069	4.2434	3.6317
30/20	8.7457	7.0614	5.7867	4.8558	4.1055	3.5105
40/10	8.4610	6.8362	5.6211	4.7041	3.9838	3.3835
2-(Methylamino)ethanol/Triethanolamine						
0/50	6.4977	5.4776	4.5673	3.8746	3.3566	2.9119
10/40	6.8851	5.7466	4.8108	4.0730	3.4794	3.0195
20/30	7.1915	5.9603	4.9919	4.1953	3.5749	3.0992
30/20	7.4924	6.1828	5.1516	4.3140	3.6688	3.1526
40/10	7.8670	6.4327	5.2909	4.4242	3.7628	3.1946
50/0	8.1909	6.6142	5.4077	4.5440	3.8338	3.2360
2-(Methylamino)ethanol/2-Amino-2-methyl-1-propanol						
0/50	11.0092	8.5399	6.8043	5.4428	4.4903	3.7998
10/40	10.4098	8.1594	6.5288	5. 3022	4.3722	3.6548
20/30	9.9351	7.7788	6.2934	5.0753	4.2437	3.5752
30/20	9.4715	7.3768	6.0235	4.8967	4.0593	3.4409
40/10	8.7901	7.1030	5.7031	4.6446	3.9142	3.3240
2-(Methylamino)ethanol/*N*-Methyldiethanolamine						
0/50	9.3827	7.6064	6.1970	5.1733	4.4222	3.7893
10/40	9.1276	7.4066	6.0371	5.0486	4.3029	3.6758
20/30	8.8864	7.2078	5.8790	4.9243	4.1837	3.5624
30/20	8.6525	7.0084	5.7241	4.7977	4.0661	3.4491
40/10	8.4202	6.8109	5.5635	4.6721	3.9498	3.3454

Table 5. Kinematic Viscosity of Aqueous Ternary Mixtures of 2-(Ethylamino)ethanol and DEA, TEA, AMP, or MDEA

	ν/mm^2·s^{-1}					
mass %/mass %	T = 298.15 K	T = 303.15 K	T = 308.15 K	T = 313.15 K	T = 318.15 K	T = 323.15 K
2-(Ethylamino)ethanol/Diethanolamine						
0/50	9.5728	7.7416	6.3597	5.3135	4.5366	3.9129
10/40	9.4538	7.6292	6.2422	5.1979	4.4245	3.7974
20/30	9.3342	7.5187	6.1269	5.0840	4.3087	3.6849
30/20	9.2152	7.4030	6.0148	4.9725	4.1950	3.5700
40/10	9.0958	7.2905	5.8969	4.8552	4.0832	3.4578
50/0	8.9763	7.1788	5.7780	4.7394	3.9686	3.3436
2-(Ethylamino)ethanol/Triethanolamine						
0/50	6.4977	5.4776	4.5673	3.8746	3.3566	2.9119
10/40	6.9889	5.7878	4.8090	4.0485	3.4787	2.9956
20/30	7.4902	6.1345	5.0504	4.2217	3.6006	3.0813
30/20	7.9899	6.4747	5.2925	4.3950	3.7234	3.1687
40/10	8.4844	6.8393	5.5349	4.5676	3.8471	3.2543
2-(Ethylamino)ethanol/2-Amino-2-methyl-1-propanol						
0/50	11.0091	8.5399	6.8043	5.4428	4.4903	3.7998
10/40	10.6566	8.2763	6.6539	5.3066	4.4350	3.7109
20/30	10.2359	7.9853	6.3994	5.2122	4.2728	3.6122
30/20	9.9325	7.7745	6.1890	5.0427	4.1878	3.5465
40/10	9.5725	7.5940	6.0645	4.9252	4.0906	3.4744
2-(Ethylamino)ethanol/*N*-Methyldiethanolamine						
0/50	9.3827	7.6064	6.1970	5.1733	4.4222	3.7893
10/40	9.3083	7.5151	6.1147	5.0849	4.3313	3.6983
20/30	9.2292	7.4294	6.0279	4.9963	4.2387	3.6125
30/20	9.1439	7.3471	5.9427	4.9125	4.1488	3.5228
40/10	9.0599	7.2556	5.8622	4.8247	4.0584	3.4335

The density, ρ, was measured at 5 K intervals, at temperatures between (298.15 and 323.15) K, using an Anton Paar DSA 5000 densimeter with a precision of $\pm 1 \cdot 10^{-6}$ g·cm^{-3}. The apparatus allows varying the temperature in the range used in the present study. The uncertainty in the density measurement was $\pm 5 \cdot 10^{-5}$ g·cm^{-3}.

The kinematic viscosity, υ, was determined from the transit time of the liquid meniscus through a capillary supplied by Schott (cap no. I, (0.58 $\pm$ 0.01) mm i.d., K = 0.009918 mm^2·s^{-2}) measured with a an uncertainty of $\pm$ 0.0005 mm^2·s^{-1} using

$$\nu = K(t - \theta) \tag{1}$$

where t is the efflux time, K is the characteristic constant of the capillary viscometer, and θ is a correction value to correct the final effects.

The glass capillary was connected to a Schott-Geräte AVS 350 automatic Ubbelohde viscometer. An electronic stopwatch

Table 6. Density Parameters A_0 and A_1 (in eq 2) for Aqueous Ternary Mixtures of 2-(Methylamino)ethanol + (DEA, TEA, AMP, or MDEA) and 2-(Ethylamino)ethanol + (DEA, TEA, AMP, or MDEA)[a]

mass %/mass %	A_0/g·cm^{-3}	$A_1 \cdot 10^4$/g·cm^{-3}·K^{-1}	$\sigma_{st} \cdot 10^2$	A_0/g·cm^{-3}	$A_1 \cdot 10^4$/g·cm^{-3}·K^{-1}	$\sigma_{st} \cdot 10^2$
	2-(Methylamino)ethanol/Diethanolamine			2-(Ethylamino)ethanol/Diethanolamine		
0/50	1.2260	5.6224	0.012	1.2260	5.6224	0.013
10/40	1.2230	5.9834	0.011	1.2236	6.0319	0.012
20/30	1.2193	6.2757	0.010	1.2234	6.5257	0.011
30/20	1.2166	6.5766	0.008	1.2218	6.9287	0.010
40/10	1.2127	6.8233	0.006	1.2195	7.3394	0.021
50/0	1.2080	6.9670	0.007	1.2134	7.6639	0.008
	2-(Methylamino)ethanol/Triethanolamine			2-(Ethylamino)ethanol/Triethanolamine		
0/50	1.2465	5.7568	0.022	1.2465	5.7568	0.022
10/40	1.2413	6.1234	0.014	1.2435	6.2379	0.014
20/30	1.2339	6.4080	0.013	1.2355	6.6074	0.012
30/20	1.2209	6.4972	0.013	1.2310	7.0233	0.011
40/10	1.2142	6.7346	0.010	1.2218	7.3216	0.010
	2-(Methylamino)ethanol/2-Amino-2-methyl-1-propanol			2-(Ethylamino)ethanol/2-Amino-2-methyl-1-propanol		
0/50	1.2223	7.6996	0.009	1.2223	7.6996	0.009
10/40	1.2183	7.5448	0.007	1.2206	7.6914	0.004
20/30	1.2179	7.4995	0.009	1.2189	7.6825	0.006
30/20	1.2176	7.4583	0.009	1.2172	7.6746	0.010
40/10	1.2126	7.2316	0.008	1.2154	7.6668	0.008
	2-(Methylamino)ethanol/*N*-Methyldiethanolamine			2-(Ethylamino)ethanol/*N*-Methyldiethanolamine		
0/50	1.2413	6.6635	0.013	1.2413	6.6635	0.013
10/40	1.2338	6.7362	0.012	1.2360	6.8778	0.012
20/30	1.2292	6.8934	0.012	1.2296	7.0484	0.013
30/20	1.2176	6.8167	0.011	1.2256	7.2935	0.024
40/10	1.2113	6.8645	0.012	1.2222	7.5686	0.022

[a] $\sigma_{st} = [\sum(\rho_{cal} - \rho_{exp})^2/(N - n)]^{1/2}$ where N is the number of data points and n is the number of parameters.

Table 7. Viscosity Parameters A_2 and A_3 (in eq 3) for Aqueous Ternary Mixtures of 2-(Methylamino)ethanol + (DEA, TEA, AMP, or MDEA) and 2-(Ethylamino)ethanol + (DEA, TEA, AMP, or MDEA)[a]

mass %/mass %	A_2/mm^2·s^{-1}	$A_3 \cdot 10^{-8}$/K^3	σ_{st}	A_2/mm^2·s^{-1}	$A_3 \cdot 10^{-8}$/K^3	σ_{st}
	2-(Methylamino)ethanol/Diethanolamine			2-(Ethylamino)ethanol/Diethanolamine		
0/50	0.1462	1.1061	0.055	0	1.1061	0.055
10/40	0.1358	1.1187	0.038	0.1333	1.1275	0.049
20/30	0.1295	1.1233	0.037	0.1213	1.1496	0.041
30/20	0.1247	1.1250	0.034	0.1099	1.1727	0.032
40/10	0.1196	1.1273	0.023	0.0994	1.1962	0.028
50/0	0.1108	1.1397	0.026	0.0892	1.2216	0.024
	2-(Methylamino)ethanol/Triethanolamine			2-(Ethylamino)ethanol/Triethanolamine		
0/50	0.1514	0.9974	0.029	0.1514	0.9974	0.029
10/40	0.1456	1.0230	0.017	0.1338	1.0485	0.015
20/30	0.1399	1.0448	0.016	0.1185	1.0987	0.016
30/20	0.1316	1.0721	0.016	0.1068	1.1431	0.018
40/10	0.1188	1.1115	0.013	0.0967	1.1854	0.023
	2-(Methylamino)ethanol/2-Amino-2-methyl-1-propanol			2-(Ethylamino)ethanol/2-Amino-2-methyl-1-propanol		
0/50	0.0706	1.3373	0.058	0.0706	1.3373	0.058
10/40	0.0791	1.2922	0.027	0.0737	1.3171	0.059
20/30	0.0841	1.2626	0.055	0.0787	1.2883	0.048
30/20	0.0845	1.2482	0.065	0.0801	1.2751	0.065
40/10	0.0910	1.2114	0.046	0.0820	1.2605	0.042
	2-(Methylamino)ethanol/*N*-Methyldiethanolamine			2-(Ethylamino)ethanol/*N*-Methyldiethanolamine		
0/50	0.1357	1.1210	0.053	0.1357	1.1210	0.053
10/40	0.1311	1.1233	0.042	0.1251	1.1406	0.048
20/30	0.1258	1.1273	0.034	0.1154	1.1597	0.045
30/20	0.1203	1.1322	0.028	0.1063	1.1795	0.037
40/10	0.1159	1.1349	0.026	0.0977	1.1997	0.029

[a] $\sigma_{st} = [\sum(\nu_{cal} - \nu_{exp})^2/(N - n)]^{1/2}$ where N is the number of data points and n is the number of parameters.

with an accuracy of ± 0.01 s was used for measuring efflux times. The viscometer was immersed in a bath, and the precision of the temperature control in all these measurements was ± 0.05 K. Each measurement was repeated at least five times with a maximum deviation of less than 0.4 %. The dynamic viscosity, η, was calculated by multiplying the kinematic viscosity by the corresponding density ($\eta = \nu\rho$).

The densimeter and the viscometer were calibrated with double-distilled water and absolute ethanol (reagent supplied by Merck with a purity of ≥ 99.5 %), as is recommended by Marsh.[5] The values measured to the temperature of work are included in Table 1 and are compared with values published by other authors.[6−12]

Results and Discussion

Experimental data for the ternary mixtures studied are presented in Tables 2 to 5. In all systems, the density and viscosity decreased with increasing temperature for any given mass percent ratio of amine.

The influence of the temperature on the density was a linear dependence in the range temperature studied, whereas several authors in the literature have found nonlinear dependences over

Table 8. Density Parameters A_{ij} (in eq 4) for Aqueous Ternary Mixtures of 2-(Methylamino)ethanol + (DEA, TEA, AMP, or MDEA) and 2-(Ethylamino)ethanol + (DEA, TEA, AMP, or MDEA)[a]

	T/K					
	298.15	303.15	308.15	313.15	318.15	323.15
	2-(Methylamino)ethanol (1) + Diethanolamine (2) + Water (3)					
A_{12}	−0.1927	−0.1931	−0.1950	−0.1967	−0.2007	−0.2039
A_{13}	0.0903	0.0806	0.0717	0.0635	0.0560	0.0494
A_{23}	0.4743	0.4674	0.4615	0.4560	0.4513	0.4476
$\sigma_{st}\cdot 10^2$	0.053	0.055	0.057	0.065	0.071	0.057
	2-(Methylamino)ethanol (1) + Triethanolamine (2) + Water (3)					
A_{12}	0.1288	0.1166	0.1044	0.0629	0.1019	0.1254
A_{13}	0.0926	0.0831	0.0743	0.0664	0.0590	0.0526
A_{23}	0.6707	0.6572	0.6475	0.6396	0.6282	0.6190
$\sigma_{st}\cdot 10^2$	0.028	0.033	0.028	0.027	0.022	0.019
	2-(Methylamino)ethanol + 2-Amino-2-methyl-1-propanol (2) + Water (3)					
A_{12}	−0.2480	−0.2552	−0.2634	−0.2717	−0.2819	−0.2920
A_{13}	0.0923	0.0826	0.0738	0.0656	0.0582	0.0516
A_{23}	0.0498	0.0361	0.0236	0.0119	0.0010	−0.0083
$\sigma_{st}\cdot 10^2$	0.036	0.037	0.039	0.042	0.045	0.047
	2-(Methylamino)ethanol (1) + *N*-Methyldiethanolamine (2) + Water (3)					
A_{12}	−0.2120	−0.2253	−0.2048	−0.2103	−0.2114	−0.2430
A_{13}	0.0918	0.0822	0.0735	0.0657	0.0576	0.0507
A_{23}	0.3556	0.3431	0.3309	0.3199	0.3092	0.3013
$\sigma_{st}\cdot 10^2$	0.052	0.054	0.049	0.047	0.050	0.051
	2-(Ethylamino)ethanol (1) + Diethanolamine (2) + Water (3)					
A_{12}	0.1441	0.1463	0.1437	0.1351	0.1403	0.1458
A_{13}	0.0155	0.0023	−0.0106	−0.0236	−0.0335	−0.1523
A_{23}	0.4686	0.4616	0.4558	0.4510	0.4460	0.4425
$\sigma_{st}\cdot 10^2$	0.040	0.044	0.040	0.034	0.040	0.034
	2-(Ethylamino)ethanol (1) + Triethanolamine (2) + Water (3)					
A_{12}	0.6366	0.6562	0.6291	0.5980	0.6058	0.6834
A_{13}	0.0137	−0.0001	−0.0126	−0.0241	−0.0351	−0.1533
A_{23}	0.6704	0.6567	0.6470	0.6389	0.6281	0.6193
$\sigma_{st}\cdot 10^2$	0.037	0.036	0.036	0.034	0.035	0.035
	2-(Ethylamino)ethanol (1) + 2-Amino-2-methyl-1-propanol (2) + Water (3)					
A_{12}	0.0261	0.0431	0.0498	0.0592	0.0673	0.0712
A_{13}	0.0127	−0.0004	−0.0128	−0.0245	−0.0355	−0.1536
A_{23}	0.0488	0.0345	0.0216	0.0097	−0.0014	−0.0112
$\sigma_{st}\cdot 10^2$	0.031	0.018	0.022	0.012	0.015	0.015
	2-(Ethylamino)ethanol (1) + *N*-Methyldiethanolamine (2) + Water (3)					
A_{12}	0.1640	0.1552	0.1335	0.0998	0.1128	0.1772
A_{13}	0.0138	0.0002	−0.0124	−0.0241	−0.0352	−0.1532
A_{23}	0.3523	0.3397	0.3284	0.3179	0.3068	0.2978
$\sigma_{st}\cdot 10^2$	0.011	0.026	0.020	0.024	0.025	0.019

Table 9. Density and Dynamic Viscosity for Pure DEA, TEA, AMP, MDEA, MAE, EAE, and Water from 298.15 K to 323.15 K

		pure component						
T/K		DEA	TEA	AMP	MDEA	MAE	EAE	water
298.15	ρ/g·cm^{-3}	1.094019	1.120993	0.930516	1.036832	0.937683	0.913386	0.997057
	η/mPa·s	566.3	666.88	132.30	77.19	10.996	12.348	0.8899
303.15	ρ/g·cm^{-3}	1.090788	1.118209	0.926403	1.033056	0.933789	0.909401	0.995637
	η/mPa·s	383.9	460.48	99.48	57.86	8.7976	9.9379	0.7956
308.15	ρ/g·cm^{-3}	1.087508	1.115384	0.922259	1.029261	0.929880	0.905405	0.994036
	η/mPa·s	262.4	326.69	69.98	44.14	7.3105	8.1387	0.7220
313.15	ρ/g·cm^{-3}	1.084199	1.112570	0.918079	1.025447	0.925948	0.901388	0.992185
	η/mPa·s	188.2	236.09	47.8	34.31	6.6098	6.5974	0.6550
318.15	ρ/g·cm^{-3}	1.080862	1.109783	0.913866	1.021622	0.921996	0.897344	0.990220
	η/mPa·s	145.6	162.69	32.17	26.53	4.9956	5.5664	0.5950
323.15	ρ/g·cm^{-3}	1.077491	1.106929	0.909622	1.017781	0.918024	0.893275	0.987978
	η/mPa·s	119.5	99.76	24.21	21.67	4.3481	4.6264	0.5460

large ranges of temperature. For this reason the experimental data, ρ_m, were correlated with the temperature, T, by the following equation:

$$\rho_m = A_0 - A_1 T \quad (2)$$

where A_0 and A_1 are two fitted parameters whose values are listed in Table 6.

However, the influence of the temperature on the kinematic viscosity was a nonlinear dependence. For this reason, several equations have been used to fit our experimental values. The best one is an exponential equation:

$$\upsilon = A_2 \exp\left(\frac{A_3}{T^3}\right) \quad (3)$$

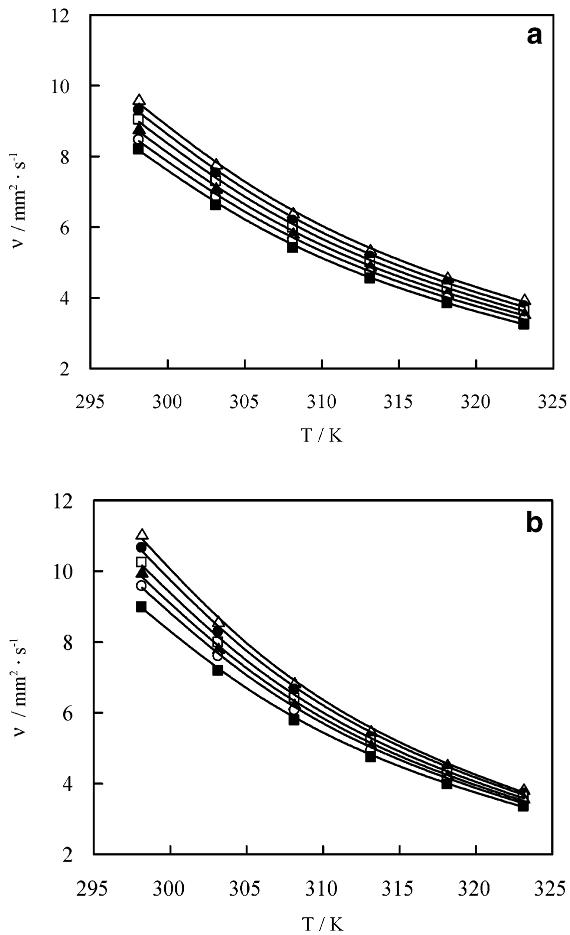

Figure 2. Viscosity dependence with the temperature for aqueous ternary mixtures of (a) MAE (1) + DEA (2) and (b) EAE (1) + AMP (2): △, 0/50; ●, 10/40; □, 20/30; ▲, 30/20; ○, 40/10; ■, 50/0; —, calculated from eq 3.

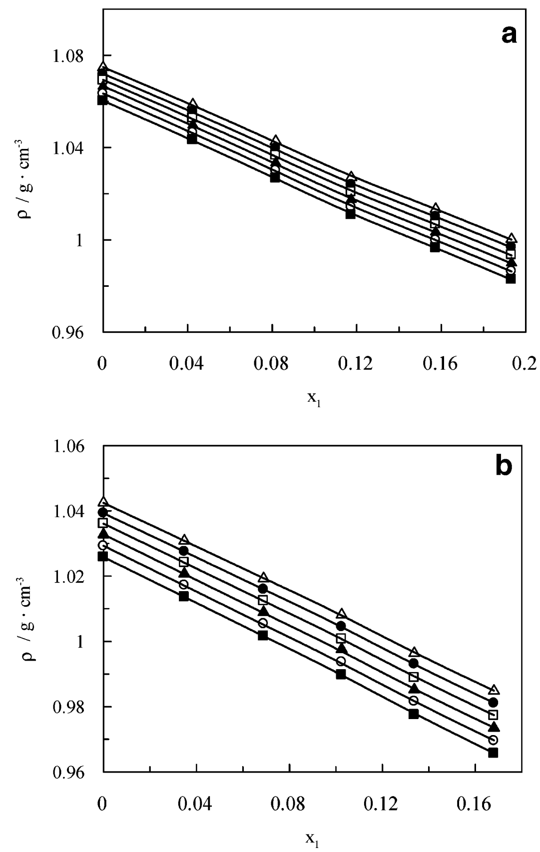

Figure 3. Experimental and calculated densities, ρ, for aqueous ternary mixtures of (a) MAE (1) + TEA (2) and (b) EAE (1) + MDEA (2): △, 298.15 K; ●, 303.15 K; □, 308.15 K; ▲, 313.15 K; ○, 318.15 K; ■, 323.15 K; —, calculated from eq 4.

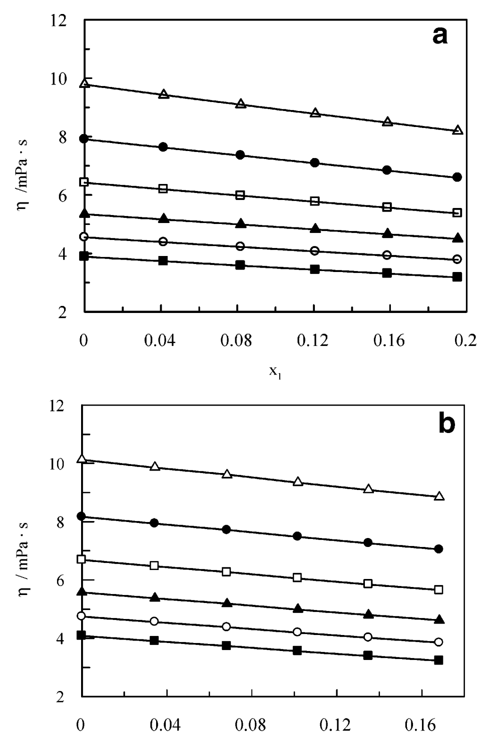

Figure 4. Experimental and calculated dynamic viscosities, η, for aqueous ternary mixtures of (a) MAE (1) + MDEA (2) and (b) EAE (1) + DEA (2): △, 298.15 K; ●, 303.15 K; □, 308.15 K; ▲, 313.15 K; ○, 318.15 K; ■, 323.15 K; —, calculated from eq 5.

where A_2 and A_3 are the fitting parameters whose values are reported in Table 7 for all the studied systems. Equations 2 and 3 fit satisfactorily the experimental data of density and kinematic viscosity (see Figures 1 and 2).

Furthermore, for a given temperature the experimental densities were correlated with the mole fraction by means of eq 4, similar to Nissan's equation[13] for the dynamic viscosity of ternary mixtures:

$$\rho_m = \sum_{i=1}^{3} x_i \rho_i + \sum_{i \neq j} A_{ij} x_i x_j \qquad (4)$$

In this equation, ρ_i is the density of pure i-component at the working temperature, and A_{ij} are the fitting parameters whose values are reported in Table 8. All the ρ_i values used in this work were those determined experimentally (Table 9).

Finally, the model of Grunberg and Nissan[13,14] for the viscosity of liquid mixtures was used to correlate the viscosity data of the amine mixtures. For a ternary mixture, the equation of Grunberg and Nissan has the following form:

$$\ln \eta_m = x_1 \ln \eta_1 + x_2 \ln \eta_2 + x_3 \ln \eta_3 + x_1 x_2 G_{12} + x_1 x_3 G_{13} + x_2 x_3 G_{23} \qquad (5)$$

where η_m is the dynamic viscosity of the mixture; η_1, η_2, and η_3 are the viscosity of pure liquids (Table 9); and G_{12}, G_{13}, and G_{23} are three fitting parameters, whose values are reported in Table 10. Viscosities of pure DEA, TEA, AMP, and MDEA were obtained from the literature,[14] and viscosities of pure MAE, EAE, and water were obtained experimentally.

Table 10. Viscosity Parameters G_{ij} (in eq 5) for Aqueous Ternary Mixtures of 2-(Methylamino)ethanol + (DEA, TEA, AMP, or MDEA) and 2-(Ethylamino)ethanol + (DEA, TEA, AMP, or MDEA)[a]

	T/K					
	298.15	303.15	308.15	313.15	318.15	323.15
2-(Methylamino)ethanol (1) + Diethanolamine (2) + Water (3)						
G_{12}	0.3982	0.2876	0.5069	0.4704	0.2385	0.5183
G_{13}	10.9774	10.4492	9.9120	9.5369	9.1618	8.6934
G_{23}	11.9133	11.4145	10.9670	10.5726	10.2613	9.8631
σ_{st}	0.003	0.003	0.002	0.002	0.002	0.003
2-(Methylamino)ethanol (1) + Triethanolamine (2) + Water (3)						
G_{12}	−2.1830	−1.3298	1.1846	0.1322	−0.4563	1.6785
G_{13}	10.9839	10.4633	9.9060	9.5256	9.1639	8.6743
G_{23}	14.0552	13.6911	13.1188	12.6840	12.4619	12.3247
σ_{st}	0.005	0.003	0.003	0.005	0.002	0.003
2-(Methylamino)ethanol + 2-Amino-2-methyl-1-propanol (2) + Water (3)						
G_{12}	2.25468	0.88154	1.45262	−0.15265	−0.42231	−0.53111
G_{13}	11.12551	10.61114	10.02901	9.61574	9.23837	8.77927
G_{23}	11.90520	11.08888	10.46970	9.93504	9.58506	9.19497
σ_{st}	0.006	0.006	0.002	0.008	0.007	0.004
2-(Methylamino)ethanol (1) + *N*-Methyldiethanolamine (2) + Water (3)						
G_{12}	−0.02451	0.31067	0.35135	0.39341	0.37641	0.38208
G_{13}	10.99564	10.46383	9.91778	9.54827	9.16744	8.69048
G_{23}	15.89108	15.21133	14.48125	13.91582	13.55440	13.07679
$\sigma_{st}\cdot 10$	0.008	0.007	0.008	0.005	0.006	0.007
2-(Ethylamino)ethanol (1) + Diethanolamine (2) + Water (3)						
G_{12}	0.34662	0.42726	0.58578	0.69975	0.78192	0.92328
G_{13}	13.25744	12.55949	11.83409	11.22999	10.72103	10.21326
G_{23}	11.89471	11.39689	10.95031	10.55871	10.24437	9.87087
σ_{st}	0.001	0.001	0.001	0.001	0.001	0.001
2-(Ethylamino)ethanol (1) + Triethanolamine (2) + Water (3)						
G_{12}	−1.54979	−2.83207	−2.11184	−2.07050	−2.12264	−2.14939
G_{13}	13.27416	12.58264	11.84702	11.24473	10.73480	12.54232
G_{23}	14.12874	13.76787	13.19809	12.74137	10.22566	12.39592
σ_{st}	0.006	0.006	0.005	0.005	0.005	0.005
2-(Ethylamino)ethanol (1) + 2-Amino-2-methyl-1-propanol (2) + Water (3)						
G_{12}	2.35447	1.23711	0.93091	1.45153	0.61501	0.83031
G_{13}	13.30669	12.61467	11.86644	11.25079	10.73321	10.24921
G_{23}	11.90901	11.07395	10.48414	9.88952	9.57371	9.18423
σ_{st}	0.007	0.008	0.006	0.004	0.005	0.005
2-(Ethylamino)ethanol (1) + *N*-Methyldiethanolamine (2) + Water (3)						
G_{12}	0.55001	0.36635	0.53439	0.57153	0.83952	1.21015
G_{13}	13.28368	12.58886	11.86585	11.26623	10.75840	10.25021
G_{23}	15.97862	15.29223	14.56276	13.99379	13.62884	13.14458
$\sigma_{st}\cdot 10$	0.004	0.006	0.004	0.006	0.004	0.005

[a] $\sigma_{st} = [\sum(\ln \eta_{cal} - \ln \eta_{exp})^2/(N - n)]^{1/2}$ where N is the number of data points and n is the number of parameters.

The calculated densities and viscosities from eqs 4 and 5 are in excellent agreement with the experimental data of this study (see Figures 3 and 4). The deviations in all cases are less than 0.5 %.

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