JOURNAL OF CHEMICAL & ENGINEERING DATA

Article

pubs.acs.org/jced

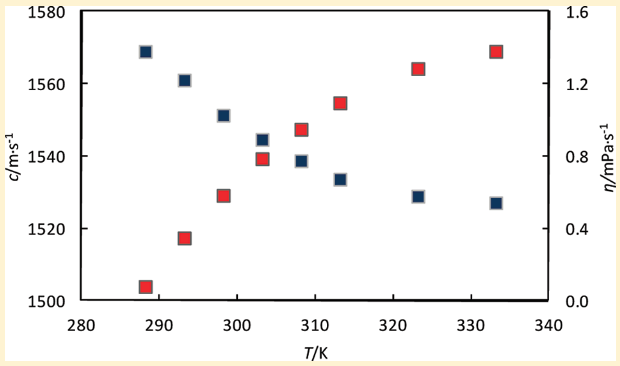
Density, Speed of Sound, Refractive Index, and Viscosity of 1-Amino-2-Propanol {or Bis(2-hydroxypropyl)amine} + Triethanolamine + Water from T = (288.15 to 333.15) K

Diego Gómez-Díaz,*[†] M. Dolores La Rubia,[‡] Ana B. López,[‡] José M. Navaza,[†] Rafael Pacheco,[‡] and Sebastián Sánchez[‡]

[†]Department of Chemical Engineering, ETSE, University of Santiago de Compostela, Rúa Lope Gómez de Marzoa s/n, E-15706, Santiago de Compostela, Spain

[‡]Department of Chemical, Environmental and Materials Engineering, EPS, University of Jaén, Paraje Las Lagunillas s/n, E-23071, Jaén, Spain

ABSTRACT: The density, speed of sound, refractive index, and viscosity of ternary systems formed by 1-amino-2-propanol (MIPA) {or bis(2-hydroxypropyl)amine (DIPA)} + triethanolamine (TEA) + water were determined at several temperatures from T = (288.15 to 333.15) K. The ternary systems analyzed in present work use different total amine concentrations of 5, 10, and 20 % (in volume), and the ratio between amine concentrations, in the nonaqueous fraction, was varied in the entire composition range. The excess volume was determined using the density experimental data for each mixture taking into account the DIPA melting point.



■ INTRODUCTION

The removal of acid gas impurities such as CO_2 and H_2S from natural, refinery, and synthesis gas streams is an important operation in gas processing. The main objective of these processes is to minimize the environmental pollution and, specifically, the greenhouse effect.

The amines that have proved to be of commercial interest for acid gas removal by chemical absorption are monoethanolamine (MEA), diethanolamine (DEA), and *N*-methyldiethanolamine (MDEA). Other amines, such as bis(2-hydroxypropyl)amine (DIPA), 1-amino-2-propanol (MIPA), or 3-amino-1-propanol (AP), have also been used, and some papers about this kind of processes have been published[1−3] in the past few years. The use of mixed amine solvents in gas-treating processes is of increasing interest nowadays.[4−6] Blends of primary and tertiary amines (such as mixtures of MEA + MDEA or piperazine (PZ) + TEA) or secondary and tertiary amines (such as mixtures of DEA and MDEA) combine the high carbon dioxide loading of the tertiary amine with the higher reaction rate of the primary or secondary amine, and for these reasons, they have been suggested for industrial gas-treating processes.[7−9]

The characterization of new mixtures for gas−liquid absorption processes is an important step that allows the analysis and evaluation of mass transfer and carbon dioxide capture capacity[10,11] on the basis of these physical properties. For this reason, in this work, several physical properties (density, speed of sound, refractive index, and viscosity) of tertiary systems using blends of two amines: MIPA (or DIPA) with TEA, were measured over the temperature range employed in this work, (288.15 to 333.15) K. Previous studies have analyzed binary systems involving components used in this work.[12−14] The present study includes the analysis of the influence of composition and temperature upon the previously commented physical properties.

■ EXPERIMENTAL SECTION

Materials. Table 1 shows the sample descriptions used in present work. The reagents were used without further purification.

Table 1. Sample Description Table

chemical name	source	initial mole fraction purity
MIPA[a]	Merck	≥ 0.98
DIPA[b]	Sigma-Aldrich	≥ 0.98
TEA[c]	Panreac	0.98

[a]1-Amino-2-propanol. [b]Bis(2-hydroxypropyl)amine. [c]Triethanolamine.

Samples were prepared individually from pure components before the measurement of different physicochemical properties. The uncertainty of the samples preparation in mole fraction was ± 0.0008. Double-distilled water was used to prepare the amine aqueous solutions.

Received: October 19, 2011
Accepted: February 17, 2012
Published: February 29, 2012

Table 2. Comparison between Density ρ, Speed of Sound c, Viscosity η, and Refractive Index n_D Experimental and Literature Data for Pure Components[a]

	ρ/g·cm^{-3}		c/m·s^{-1}		η/mPa·s		n_D	
T/K	exp	lit.	exp	lit.	exp	lit.	exp	lit.
				TEA				
298.15	1.1210	1.1215[15]	1611.5	1610.5[16]	605.95	607.0[14]	1.4832	1.4835[15]
		1.1208[16]						
				MIPA				
298.15	0.9563	0.95651[13]	1544.1	1544.1[17]	24.234	26.685[18]	1.4461	1.44609[18]
		0.95640[17]						
				DIPA				
323.15	0.9841	0.98490[16]	1414.2		125.65	125.73[16]	1.4512	

[a]Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainties U_c (level of confidence =0.95, k = 2) are $U_c(\rho) = 2\cdot10^{-4}$ g·cm^{-3}, $U_c(c)$ = 1.2 m·s^{-1}, $U_c(\eta)$ = 0.0026 mPa·s, and $U_c(n_D) = 1.3\cdot10^{-4}$.

Table 3. Density ρ of MIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K at $p = 10^5$ Pa[a]

		T/K							
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
			Amine Total Concentration = 5 % vol						
0.0126	0.0000	0.9993	0.9983	0.9970	0.9956	0.9939	0.9920	0.9877	0.9826
0.0094	0.0018	1.0011	1.0001	0.9989	0.9974	0.9957	0.9938	0.9896	0.9845
0.0064	0.0035	1.0031	1.0021	1.0008	0.9993	0.9976	0.9958	0.9915	0.9854
0.0033	0.0048	1.0050	1.0040	1.0028	1.0013	0.9996	0.9977	0.9933	0.9876
0.0016	0.0055	1.0059	1.0049	1.0036	1.0021	1.0004	0.9985	0.9943	0.9877
0.0000	0.0064	1.0068	1.0058	1.0046	1.0031	1.0014	0.9995	0.9950	0.9886
			Amine Total Concentration = 10 % vol						
0.0260	0.0000	1.0001	0.9990	0.9976	0.9959	0.9941	0.9921	0.9875	0.9822
0.0196	0.0034	1.0039	1.0027	1.0013	0.9997	0.9979	0.9959	0.9912	0.9859
0.0132	0.0067	1.0081	1.0069	1.0055	1.0039	1.0021	1.0001	0.9947	0.9888
0.0066	0.0101	1.0109	1.0098	1.0084	1.0068	1.0050	1.0030	0.9986	0.9925
0.0033	0.0116	1.0126	1.0115	1.0101	1.0085	1.0067	1.0047	1.0004	0.9943
0.0000	0.0134	1.0148	1.0136	1.0122	1.0106	1.0089	1.0069	1.0023	0.9962
			Amine Total Concentration = 20 % vol						
0.0565	0.0000	1.0030	1.0014	0.9996	0.9975	0.9954	0.9930	0.9878	0.9821
0.0429	0.0073	1.0099	1.0083	1.0065	1.0046	1.0024	1.0001	0.9950	0.9894
0.0285	0.0150	1.0167	1.0152	1.0135	1.0116	1.0095	1.0072	1.0022	0.9967
0.0145	0.0218	1.0240	1.0226	1.0209	1.0190	1.0170	1.0147	1.0096	1.0038
0.0078	0.0256	1.0274	1.0259	1.0242	1.0224	1.0203	1.0181	1.0134	1.0080
0.0000	0.0294	1.0309	1.0294	1.0278	1.0260	1.0240	1.0218	1.0173	1.0112

[a]x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(\rho) = 2\cdot10^{-4}$ g·cm^{-3}.

Methods. *Density and Speed of Sound.* The density (ρ) of pure components and the mixtures of different compounds were measured with an Anton Paar DSA 5000 vibrating tube densimeter and sound analyzer which was calibrated with ultra-pure water and dry air. The glass vibrating-tube was carefully rinsed with filtered ethanol, acetone, and dry air before being loaded with the samples. The uncertainty in the density and speed of sound measurements was $\pm$ $5\cdot10^{-5}$ g·cm^{-3} and $\pm$ 0.8 m·s^{-1}, respectively.

Viscosity. The kinematic viscosity (ν) was determined from the transit time of the liquid meniscus through a Ubbelohde capillary viscosimeter supplied by Schott, capillary number I, (0.63 $\pm$ 0.01) mm internal diameter, and K = 0.01013 mm^2·s^{-1} and capillary number 0c, (0.46 $\pm$ 0.01) mm internal diameter, and K = 0.003164 mm^2·s^{-1}, using eq 1.

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

where t is the efflux time; K is the characteristic constant of the capillary viscometer; and θ is a correction value to correct end effects. Both parameters were obtained from the capillaries supplier (Schott). An electronic stopwatch with an accuracy of $\pm$ 0.01 s was used to measure efflux times. In the measurements, a Schott-Geräte AVS 350 viscometer was used. Each measurement was repeated at least 5 times, and the uncertainty of this measurement is $\pm$ 0.0024 mm^2·s^{-1}. The dynamic viscosity (η) was obtained from the product of the kinematic viscosity (ν) and the corresponding density (ρ) of the mixture, in terms of eq 2 for each mixture composition and with a uncertainty of $\pm$ 0.0026 mPa·s.

$$\eta = \nu\cdot\rho \tag{2}$$

Refractive Index. The refractive index was determined using an Atago RX-5000 refractometer. Before measurements, the refractometer was calibrated using distilled water in accordance with the instrument instructions. The mixtures were directly

Table 4. Speed of Sound c of MIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K at $p = 10^5$ Pa[a]

		T/K							
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
		Amine Total Concentration = 5 % vol							
0.0126	0.0000	1506.4	1519.7	1531.3	1541.9	1550.6	1557.5	1566.6	1571.3
0.0094	0.0018	1504.0	1517.4	1529.1	1539.3	1547.4	1554.8	1564.2	1569.0
0.0064	0.0035	1501.3	1515.1	1527.1	1537.3	1546.1	1553.5	1562.0	1567.3
0.0033	0.0048	1498.7	1511.3	1523.6	1532.8	1541.9	1549.5	1559.9	1565.8
0.0016	0.0055	1494.8	1509.4	1521.4	1532.3	1541.6	1549.3	1559.0	1564.9
0.0000	0.0064	1491.4	1506.2	1518.9	1529.4	1538.8	1546.7	1558.2	1564.3
		Amine Total Concentration = 10 % vol							
0.0260	0.0000	1549.8	1560.1	1568.5	1574.8	1580.4	1584.7	1590.2	1590.8
0.0196	0.0034	1542.0	1553.0	1562.0	1568.9	1575.1	1579.8	1585.8	1587.2
0.0132	0.0067	1535.3	1546.3	1556.4	1564.4	1571.0	1576.6	1581.6	1583.8
0.0066	0.0101	1524.3	1536.3	1546.5	1555.1	1562.5	1568.8	1577.2	1580.3
0.0033	0.0116	1522.2	1534.6	1545.2	1553.7	1561.7	1567.8	1575.2	1578.7
0.0000	0.0134	1517.8	1531.0	1541.8	1550.7	1558.5	1565.0	1573.2	1577.1
		Amine Total Concentration = 20 % vol							
0.0565	0.0000	1635.1	1637.9	1640.0	1641.9	1642.3	1642.4	1636.4	1628.5
0.0429	0.0073	1620.6	1624.9	1628.2	1630.5	1631.2	1631.6	1628.4	1622.2
0.0285	0.0150	1602.2	1608.2	1613.1	1616.8	1619.2	1620.9	1620.4	1616.0
0.0145	0.0218	1586.8	1594.0	1600.1	1604.3	1607.9	1610.3	1611.8	1609.2
0.0078	0.0256	1580.8	1588.5	1595.0	1600.3	1604.2	1607.2	1608.3	1606.7
0.0000	0.0294	1570.1	1579.0	1586.0	1594.3	1597.0	1600.6	1604.6	1603.5

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(c)$ = 1.2 m·s^{-1}.

Table 5. Viscosity η of MIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K at $p = 10^5$ Pa[a]

		T/K							
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
		Amine Total Concentration = 5 % vol							
0.0126	0.0000	1.382	1.228	1.030	0.894	0.781	0.682	0.573	0.543
0.0094	0.0018	1.379	1.221	1.026	0.892	0.774	0.672	0.578	0.542
0.0064	0.0035	1.356	1.198	1.018	0.898	0.776	0.674	0.573	0.543
0.0033	0.0048	1.346	1.181	1.012	0.898	0.776	0.690	0.564	0.541
0.0016	0.0055	1.304	1.175	1.018	0.891	0.767	0.681	0.560	0.538
0.0000	0.0064	1.304	1.141	0.998	0.872	0.765	0.664	0.555	0.536
		Amine Total Concentration = 10 % vol							
0.0260	0.0000	1.731	1.488	1.273	1.122	0.990	0.868	0.720	0.636
0.0196	0.0034	1.691	1.450	1.249	1.100	0.960	0.834	0.705	0.624
0.0132	0.0067	1.660	1.405	1.241	1.082	0.950	0.831	0.705	0.623
0.0066	0.0101	1.628	1.371	1.234	1.076	0.945	0.833	0.693	0.618
0.0033	0.0116	1.593	1.340	1.199	1.052	0.919	0.806	0.680	0.627
0.0000	0.0134	1.570	1.330	1.161	1.039	0.914	0.801	0.688	0.612
		Amine Total Concentration = 20 % vol							
0.0565	0.0000	2.741	2.334	1.985	1.721	1.493	1.299	1.049	0.860
0.0429	0.0073	2.650	2.196	1.908	1.661	1.441	1.263	1.027	0.840
0.0285	0.0150	2.579	2.137	1.877	1.638	1.421	1.247	1.032	0.851
0.0145	0.0218	2.512	2.100	1.840	1.590	1.395	1.234	1.014	0.835
0.0078	0.0256	2.443	2.090	1.813	1.582	1.387	1.230	0.996	0.826
0.0000	0.0294	2.400	2.070	1.789	1.559	1.369	1.204	0.988	0.820

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(\eta)$ = 0.0026 mPa·s.

injected from the stock solution stored at working temperature to avoid evaporation. The refractive index measurements were done after the liquid mixtures attained the constant temperature of the refractometer (this equipment includes an internal thermometer). This procedure was repeated at least three times, and the uncertainty of the measurement was $\pm$ 1.3·10^{-4}. The average of these readings was taken for the refractive index values. This property has not been measured at (323.15 and 333.15) K due to the importance of the evaporation process.

■ RESULTS AND DISCUSSION

A comparison between the experimental results for density, speed of sound, viscosity, and refractive index obtained in present work and literature data for pure components has been included in Table 2, to

Table 6. Refractive Index n_D of MIPA (1) + TEA (2) + Water (3) from T = (288.15 to 313.15) K at $p = 10^5$ Pa[a]

		T/K					
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15
		Amine Total Concentration = 5 % vol					
0.0126	0.0000	1.3399	1.3395	1.3390	1.3384	1.3377	1.3370
0.0094	0.0018	1.3403	1.3399	1.3393	1.3388	1.3380	1.3374
0.0064	0.0035	1.3405	1.3400	1.3395	1.3390	1.3384	1.3376
0.0033	0.0048	1.3405	1.3401	1.3396	1.3390	1.3383	1.3376
0.0016	0.0055	1.3406	1.3403	1.3397	1.3392	1.3385	1.3378
0.0000	0.0064	1.3406	1.3401	1.3396	1.3390	1.3383	1.3379
		Amine Total Concentration = 10 % vol					
0.0260	0.0000	1.3468	1.3463	1.3460	1.3456	1.3449	1.3441
0.0196	0.0034	1.3473	1.3467	1.3463	1.3458	1.3452	1.3444
0.0132	0.0067	1.3478	1.3473	1.3467	1.3462	1.3454	1.3448
0.0066	0.0101	1.3479	1.3474	1.3469	1.3462	1.3455	1.3449
0.0033	0.0116	1.3478	1.3473	1.3468	1.3463	1.3455	1.3448
0.0000	0.0134	1.3479	1.3475	1.3469	1.3463	1.3456	1.3449
		Amine Total Concentration = 20 % vol					
0.0565	0.0000	1.3604	1.3598	1.3590	1.3582	1.3574	1.3564
0.0429	0.0073	1.3616	1.3608	1.3598	1.3591	1.3584	1.3574
0.0285	0.0150	1.3622	1.3614	1.3605	1.3595	1.3588	1.3580
0.0145	0.0218	1.3626	1.3617	1.3610	1.3603	1.3595	1.3586
0.0078	0.0256	1.3628	1.3622	1.3615	1.3608	1.3600	1.3592
0.0000	0.0294	1.3630	1.3624	1.3618	1.3611	1.3603	1.3594

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(n_D) = 1.3 \cdot 10^{-4}$.

Table 7. Density ρ of DIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K at $p = 10^5$ Pa[a]

		T/K							
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
		Amine Total Concentration = 5 % vol							
0.0071	0.0000	1.0026	1.0016	1.0003	0.9989	0.9972	0.9953	0.9906	0.9823
0.0057	0.0019	1.0035	1.0025	1.0013	0.9998	0.9981	0.9962	0.9918	0.9840
0.0038	0.0033	1.0046	1.0036	1.0023	1.0009	0.9992	0.9973	0.9930	0.9857
0.0018	0.0049	1.0056	1.0046	1.0034	1.0019	1.0002	0.9983	0.9942	0.9866
0.0009	0.0056	1.0060	1.0051	1.0038	1.0023	1.0006	0.9987	0.9945	0.9874
0.0000	0.0064	1.0068	1.0058	1.0046	1.0031	1.0014	0.9995	0.9950	0.9886
		Amine Total Concentration = 10 % vol							
0.0148	0.0000	1.0048	1.0037	1.0024	1.0008	0.9990	0.9971	0.9930	0.9876
0.0112	0.0034	1.0075	1.0064	1.005	1.0035	1.0017	0.9997	0.9954	0.9903
0.0075	0.0066	1.0098	1.0087	1.0073	1.0057	1.0039	1.0021	0.9978	0.9926
0.0040	0.0100	1.0124	1.0113	1.0099	1.0083	1.0065	1.0045	1.0001	0.9941
0.0019	0.0117	1.0135	1.0124	1.0110	1.0094	1.0077	1.0057	1.0011	0.9953
0.0000	0.0134	1.0148	1.0136	1.0122	1.0106	1.0089	1.0069	1.0023	0.9962
		Amine Total Concentration = 20 % vol							
0.0329	0.0000	1.0125	1.011	1.0093	1.0074	1.0053	1.0032	0.9984	0.9928
0.0246	0.0075	1.0172	1.0157	1.014	1.0122	1.0101	1.0078	1.0031	0.9975
0.0165	0.0147	1.0217	1.0202	1.0186	1.0167	1.0147	1.0124	1.0078	1.0022
0.0084	0.0221	1.0264	1.0251	1.0233	1.0215	1.0194	1.0172	1.0126	1.0069
0.0042	0.0256	1.0291	1.0276	1.0260	1.0241	1.0221	1.0199	1.0149	1.0095
0.0000	0.0294	1.0309	1.0294	1.0278	1.0261	1.0240	1.0218	1.0173	1.0112

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(\rho) = 2 \cdot 10^{-4}$ g·cm^{-3}.

confirm the purity of components and the suitability of the experimental procedures to the physical properties determination.

The present work analyzes the influence of mixture composition and temperature upon density, viscosity, speed of sound, and refractive index of ternary systems formed by MIPA (1) (or DIPA) + TEA (2) + water (3), at temperatures from (288.15 to 333.15) K. Experimental mixtures maintain volume ratios between amines and water of 5, 10, and 20 %, and the amine composition in the nonaqueous fraction was varied in the entire composition range. Tables 3 to 10 show the value of these properties determined for all of the compositions and temperatures employed in the present work.

The influence of mixture composition on density and speed of sound for these systems is shown in Figure 1. With regard to the influence of mixture composition on the value of density for

Table 8. Speed of Sound c of DIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K at $p = 10^5$ Pa[a]

x_1	x_2	T/K 288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
Amine Total Concentration = 5 % vol									
0.0071	0.0000	1504.7	1518.4	1529.9	1539.8	1548.3	1555.2	1565.4	1570.2
0.0057	0.0019	1503.8	1517.7	1529.6	1539.3	1548.0	1555.4	1564.1	1569.2
0.0038	0.0033	1501.7	1515.6	1527.9	1538.4	1546.6	1553.8	1563.0	1568.6
0.0018	0.0049	1495.7	1509.9	1522.3	1533.1	1542.0	1549.7	1559.9	1565.7
0.0009	0.0056	1492.8	1507.2	1519.7	1530.7	1539.7	1547.3	1560.1	1565.9
0.0000	0.0064	1491.4	1506.2	1518.9	1529.4	1538.8	1546.7	1558.2	1564.3
Amine Total Concentration = 10 % vol									
0.0148	0.0000	1540.1	1551.4	1560.6	1567.8	1574.2	1579.1	1587.3	1588.2
0.0112	0.0034	1537.6	1548.6	1558.1	1566.1	1572.6	1577.7	1583.4	1585.3
0.0075	0.0066	1530.2	1542.2	1552.2	1560.6	1567.6	1573.2	1580.5	1583.1
0.0040	0.0100	1525.4	1537.5	1547.9	1556.3	1564.1	1569.9	1576.8	1580.0
0.0019	0.0117	1521.3	1533.6	1544.3	1553.0	1560.6	1567.1	1574.9	1578.6
0.0000	0.0134	1517.8	1531.0	1541.8	1550.7	1558.5	1565.0	1573.2	1577.1
Amine Total Concentration = 20 % vol									
0.0329	0.0000	1623.6	1627.6	1630.1	1631.6	1632.2	1631.8	1629.9	1623.1
0.0246	0.0075	1610.0	1616.3	1620.1	1622.5	1624.2	1624.7	1623.1	1617.4
0.0165	0.0147	1597.8	1604.1	1609.1	1612.8	1615.5	1617.3	1617.0	1613.1
0.0084	0.0221	1584.8	1592.5	1598.5	1603.1	1606.8	1609.3	1611.4	1609.1
0.0042	0.0256	1579.4	1587.6	1594.1	1599.3	1603.3	1606.3	1607.2	1605.7
0.0000	0.0294	1570.1	1579.0	1586.0	1592.3	1597.0	1600.6	1604.6	1603.5

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(c)$ = 1.2 m·s^{-1}.

Table 9. Viscosity η of DIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K at $p = 10^5$ Pa[a]

x_1	x_2	T/K 288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
Amine Total Concentration = 5 % vol									
0.0071	0.0000	1.478	1.261	1.097	0.958	0.834	0.738	0.597	0.560
0.0057	0.0019	1.438	1.245	1.072	0.931	0.813	0.708	0.579	0.542
0.0038	0.0033	1.427	1.235	1.075	0.930	0.805	0.712	0.574	0.533
0.0018	0.0049	1.368	1.185	1.026	0.892	0.769	0.673	0.565	0.529
0.0009	0.0056	1.340	1.153	1.007	0.873	0.756	0.654	0.560	0.526
0.0000	0.0064	1.304	1.141	0.998	0.872	0.765	0.664	0.555	0.520
Amine Total Concentration = 10 % vol									
0.0148	0.0000	1.834	1.610	1.370	1.211	1.046	0.914	0.775	0.667
0.0112	0.0034	1.772	1.525	1.319	1.146	1.011	0.889	0.752	0.661
0.0075	0.0066	1.749	1.509	1.310	1.133	1.009	0.889	0.729	0.650
0.0040	0.0100	1.730	1.465	1.282	1.126	0.997	0.859	0.724	0.644
0.0019	0.0117	1.652	1.444	1.267	1.116	0.972	0.848	0.712	0.627
0.0000	0.0134	1.570	1.330	1.161	1.039	0.914	0.801	0.688	0.612
Amine Total Concentration = 20 % vol									
0.0329	0.0000	3.378	2.803	2.363	2.080	1.803	1.540	1.200	0.985
0.0246	0.0075	3.191	2.664	2.248	1.915	1.642	1.429	1.140	0.970
0.0165	0.0147	2.940	2.460	2.051	1.762	1.560	1.324	1.100	0.927
0.0084	0.0221	2.729	2.315	1.977	1.706	1.507	1.308	1.050	0.892
0.0042	0.0256	2.600	2.210	1.910	1.660	1.454	1.260	1.030	0.848
0.0000	0.0294	2.400	2.070	1.789	1.570	1.369	1.204	0.988	0.820

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(\eta)$ = 0.0026 mPa·s.

both systems, an increase in TEA composition in the liquid mixture produces an increase in density value, with a higher slope for the MIPA + TEA + water system. The high influence of TEA upon the density value is in agreement with previous studies.[16] The same behavior has been observed for all temperatures studied for these systems. The experimental results obtained for speed of sound show that the behavior for each analyzed system has been similar. The speed of sound data decreases when mixture is enriched in TEA.[16]

The influence of mixture composition on the viscosity and refractive index for these systems is shown in Figure 2. In relation to the influence of mixture composition on the value of

Table 10. Refractive Index n_D of DIPA (1) + TEA (2) + Water (3) from T = (288.15 to 313.15) K at p = 10^5 Pa[a]

		T/K					
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15
		Amine Total Concentration = 5 % vol					
0.0071	0.0000	1.3405	1.3401	1.3396	1.3390	1.3383	1.3377
0.0057	0.0019	1.3410	1.3406	1.3401	1.3395	1.3388	1.3382
0.0038	0.0033	1.3409	1.3405	1.3400	1.3394	1.3388	1.3381
0.0018	0.0049	1.3408	1.3403	1.3398	1.3392	1.3385	1.3380
0.0009	0.0056	1.3407	1.3402	1.3396	1.3389	1.3383	1.3378
0.0000	0.0064	1.3406	1.3401	1.3396	1.3390	1.3383	1.3379
		Amine Total Concentration = 10 % vol					
0.0148	0.0000	1.3470	1.3465	1.3460	1.3454	1.3446	1.3439
0.0112	0.0034	1.3477	1.3472	1.3467	1.3461	1.3454	1.3446
0.0075	0.0066	1.3477	1.3472	1.3467	1.3460	1.3454	1.3446
0.0040	0.0100	1.3481	1.3475	1.3469	1.3463	1.3456	1.3447
0.0019	0.0117	1.3478	1.3473	1.3467	1.3461	1.3454	1.3446
0.0000	0.0134	1.3479	1.3475	1.3469	1.3463	1.3456	1.3449
		Amine Total Concentration = 20 % vol					
0.0329	0.0000	1.3626	1.3619	1.3613	1.3606	1.3598	1.3589
0.0246	0.0075	1.3630	1.3622	1.3617	1.3609	1.3600	1.3592
0.0165	0.0147	1.3630	1.3623	1.3616	1.3610	1.3601	1.3592
0.0084	0.0221	1.3631	1.3625	1.3618	1.3612	1.3604	1.3596
0.0042	0.0256	1.3631	1.3625	1.3618	1.3611	1.3604	1.3596
0.0000	0.0294	1.3630	1.3624	1.3618	1.3611	1.3603	1.3594

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively. Standard uncertainties u are $u(T)$ = 0.01 K, $u(p)$ = 20 Pa, $u(x)$ = 0.0008, and the combined expanded uncertainty U_c (level of confidence = 0.95, k = 2) is $U_c(n_D)$ = $1.3\cdot10^{-4}$.

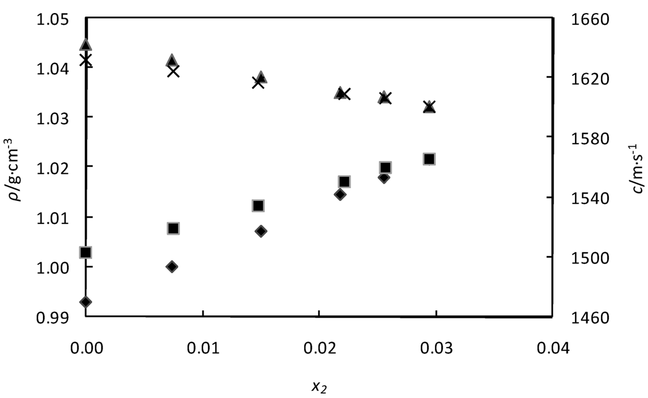


Figure 1. Influence of mixture composition on density and speed of sound. MIPA (1) + TEA (2) + water (3) system: ♦, density; ▲, speed of sound. DIPA (1) + TEA (2) + water (3) system: ■, density; ×, speed of sound. T = 313.15 K.

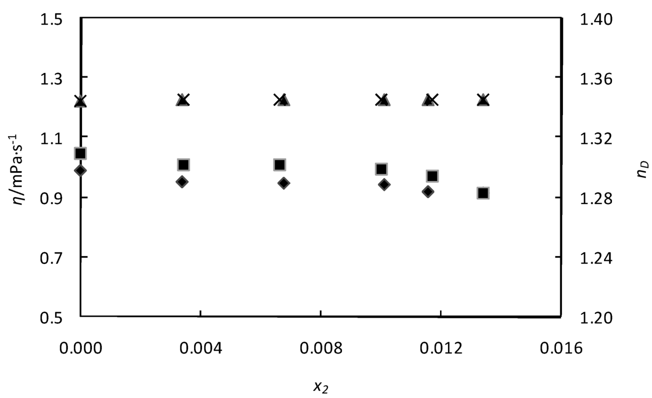


Figure 2. Influence of mixture composition on viscosity and refractive index. MIPA (1) + TEA (2) + water (3) system: ♦, viscosity; ▲, refractive index. DIPA (1) + TEA (2) + water (3) system: ■, viscosity; ×, refractive index. T = 308.15 K.

viscosity for both systems, the viscosity shows a low decrease in its value when TEA composition increases in the mixture.

For refractive index values, the behavior for both systems is very similar, and this property takes similar values observing a noninfluence of TEA composition and the use of MIPA and DIPA. The behavior observed for all of the physical properties is in agreement with previous studies that analyze other ternary systems based on amine blends.[10,11]

Another interesting aspect in this kind of characterization is the influence of temperature upon the behavior of this system and over the different physical properties. Figure 3 shows the influence of temperature in the behavior of speed of sound and viscosity. An increase in temperature produces opposite effects on speed of sound and viscosity. The obtained behavior for speed of sound shows an increase in the value of this property when temperature increases. However, viscosity shows a decrease in the value when the temperature increased.

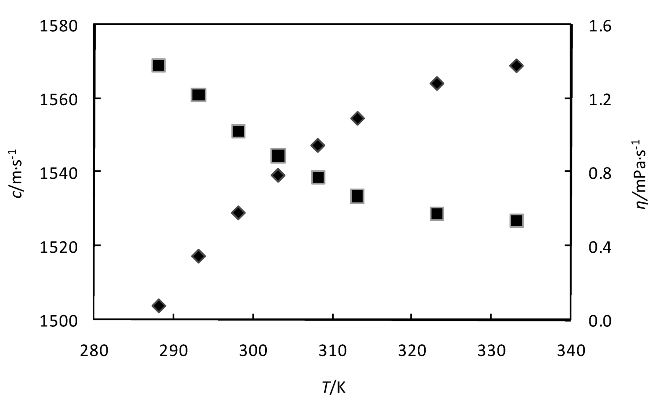


Figure 3. Influence of temperature on speed of sound and viscosity for MIPA (1) + TEA (2) + water (3) systems: ♦, speed sound; ■, viscosity. x_2 = 0.0018. Amine total concentration = 5 % vol.

Figure 4 shows the influence of total amine content and the relation between the blended amines upon the viscosity value for the MIPA + TEA + water system. The effect caused by the amine ratio shows the same behavior previously commented in Figure 2, but a higher influence of TEA composition upon viscosity, that causes a decrease, is observed for the most concentrated system in amines (20 %). Also, an increase in the total amines concentration in the mixture produces a clear increase in the value of viscosity for all of the MIPA/TEA relations.

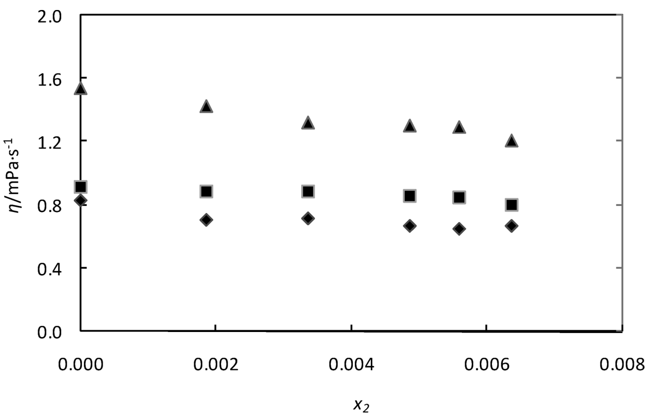


Figure 4. Influence of the total composition of amine on viscosity for MIPA (1) + TEA (2) + water (3). Amine/water volume relation: ♦, 5 %; ■, 10 %; ▲, 20 %. T = 313.15 K.

The excess molar volumes of mixtures (V^E) were calculated from density measures by applying eq 3

$$V^E = \sum_{i=1}^{3} x_i M_i (\rho^{-1} - \rho_i^{-1}) \quad (3)$$

where x_i, M_i, and ρ_i are the mole fractions, molecular weights, and densities of pure components, respectively. DIPA shows a low solubility in water, and for this reason the excess volume corresponding to systems with DIPA has been only calculated for high temperatures. The corresponding excess molar volume uncertainty was ± 0.001 $cm^3 \cdot mol^{-1}$.

The calculated values corresponding to excess molar volumes for the experimental systems analyzed in the present work are

Table 12. Excess Volume V^E of DIPA (1) + TEA (2) + Water (3) from T = (323.15 to 333.15) K[a]

		T/K	
x_1	x_2	323.15	333.15
Amine Total Concentration = 5 % vol			
0.0071	0.0000	−0.0518	−0.0128
0.0057	0.0019	−0.0586	−0.0038
0.0038	0.0033	−0.0679	−0.0229
0.0018	0.0049	−0.0766	−0.0263
0.0009	0.0056	−0.0756	−0.0348
0.0000	0.0064	−0.0778	−0.0503
Amine Total Concentration = 10 % vol			
0.0148	0.0000	−0.1040	−0.0962
0.0112	0.0034	−0.1205	−0.1186
0.0075	0.0066	−0.1375	−0.1337
0.0040	0.0100	−0.1507	−0.1317
0.0019	0.0117	−0.1541	−0.1389
0.0000	0.0134	−0.1610	−0.1402
Amine Total Concentration = 20 % vol			
0.0329	0.0000	−0.2330	−0.2235
0.0246	0.0075	−0.2653	−0.2558
0.0165	0.0147	−0.2989	−0.2895
0.0084	0.0221	−0.3333	−0.3220
0.0042	0.0256	−0.3485	−0.3433
0.0000	0.0294	−0.3641	−0.3447

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively.

Table 11. Excess Volume V^E of MIPA (1) + TEA (2) + Water (3) from T = (288.15 to 333.15) K[a]

		T/K							
x_1	x_2	288.15	293.15	298.15	303.15	308.15	313.15	323.15	333.15
Amine Total Concentration = 5 % vol									
0.0126	0.0000	−0.0485	−0.0505	−0.0527	−0.0547	−0.0566	−0.0584	−0.0632	−0.0640
0.0094	0.0018	−0.0560	−0.0573	−0.0587	−0.0600	−0.0614	−0.0626	−0.0673	−0.0672
0.0064	0.0035	−0.0678	−0.0684	−0.0691	−0.0697	−0.0704	−0.0710	−0.0735	−0.0532
0.0033	0.0048	−0.0801	−0.0797	−0.0797	−0.0796	−0.0796	−0.0795	−0.0786	−0.0652
0.0016	0.0055	−0.0828	−0.0820	−0.0815	−0.0810	−0.0807	−0.0804	−0.0812	−0.0503
0.0000	0.0064	−0.0866	−0.0854	−0.0844	−0.0836	−0.0829	−0.0822	−0.0778	−0.0503
Amine Total Concentration = 10 % vol									
0.0260	0.0000	−0.1133	−0.1165	−0.1197	−0.1228	−0.1259	−0.1289	−0.1333	−0.1355
0.0196	0.0034	−0.1353	−0.1371	−0.1391	−0.1410	−0.1431	−0.1450	−0.1453	−0.1456
0.0132	0.0067	−0.1623	−0.1625	−0.1630	−0.1637	−0.1645	−0.1653	−0.1501	−0.1365
0.0066	0.0101	−0.1609	−0.1600	−0.1594	−0.1589	−0.1587	−0.1586	−0.1592	−0.1401
0.0033	0.0116	−0.1662	−0.1643	−0.1629	−0.1617	−0.1607	−0.1600	−0.1610	−0.1410
0.0000	0.0134	−0.1756	−0.1729	−0.1707	−0.1687	−0.1671	−0.1656	−0.1610	−0.1402
Amine Total Concentration = 20 % vol									
0.0565	0.0000	−0.2905	−0.2927	−0.2954	−0.2983	−0.3014	−0.3044	−0.3090	−0.3141
0.0429	0.0073	−0.3253	−0.3259	−0.3271	−0.3286	−0.3304	−0.3320	−0.3344	−0.3382
0.0285	0.0150	−0.3410	−0.3399	−0.3395	−0.3395	−0.3398	−0.3404	−0.3395	−0.3413
0.0145	0.0218	−0.3643	−0.3606	−0.3578	−0.3555	−0.3537	−0.3522	−0.3447	−0.3363
0.0078	0.0256	−0.3640	−0.3589	−0.3548	−0.3513	−0.3483	−0.3458	−0.3441	−0.3416
0.0000	0.0294	−0.3573	−0.3510	−0.3457	−0.3410	−0.3370	−0.3334	−0.3333	−0.3149

[a] x_1 and x_2 are the mole fractions of MIPA and TEA, respectively.

shown in Tables 11 and 12. These data show, for analyzed systems, negative values of excess molar volume for all of the compositions included in the studied ranges. This behavior is in agreement with previous studies that analyze the binary aqueous mixtures of the components used in present work.[13−15]

CONCLUSIONS

Different physical properties have been determined for the systems MIPA (or DIPA) + TEA + water, and the presence of TEA produces an increase in density and refractive index, but on the other hand, a low influence of TEA in comparison with MIPA (or DIPA) was observed in relation to speed of sound and viscosity. The effect of temperature in these mixtures produces a decrease in the magnitude of all properties except for speed of sound. The excess molar volume shows negative values for all compositions and temperatures.

AUTHOR INFORMATION

Corresponding Author

*E-mail: diego.gomez@usc.es.

Funding

Financial support for this work was provided by regional government Xunta de Galicia (project number: 10MDS265021PR). A.B.L. and D.G.-D. acknowledge the Consejería de Innovación, Ciencia y Empresa (Andalucía regional government) and Ministerio de Ciencia e Innovación the FPI grant and "Ramón y Cajal" position, respectively.

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Mandal, B. P.; Bandyopadhyayb, S. S. Absorption of Carbon Dioxide into Aqueous Blends of 2-Amino-2-Methyl-1-Propanol and Monoethanolamine. *Chem. Eng. Sci.* **2006**, *65*, 5440−5447.

(2) Navaza, J. M.; Gómez-Díaz, D.; La Rubia, M. D. Removal Process of CO_2 using MDEA Aqueous Solutions in a Bubble Column Reactor. *Chem. Eng. J.* **2009**, *146*, 184−188.

(3) Kadiwala, S.; Rayer, A. V.; Henni, A. Kinetics of Carbon Dioxide (CO_2) with Ethylenediamine, 3-Amino-1-Propanol in Methanol and Ethanol, and with 1-Dimethylamino-2-Propanol and 3-Dimethylamino-1-Propanol in Water using Stopped-Flow Technique. *Chem. Eng. J.* **2012**, *179*, 262−271.

(4) Sun, W. C.; Yong, C. B.; Li, M. H. Kinetics of the Absorption of Carbon Dioxide into Mixed Aqueous Solutions of 2-Amino-2-Methyl-l-Propanol and Piperazine. *Chem. Eng. Sci.* **2005**, *60*, 503−516.

(5) Mandal, B. P.; Bandyopadhyay, S. S. Absorption of Carbon Dioxide into Aqueous Blends of 2-Amino-2-Methyl-1-Propanol and Monoethanolamine. *Chem. Eng. Sci.* **2006**, *61*, 5440−5447.

(6) Chung, P. Y.; Soriano, A. N.; Leron, R. B.; Li, M. H. Equilibrium Solubility of Carbon Dioxide in the Amine Solvent System of (Triethanolamine + Piperazine + Water). *J. Chem. Thermodyn.* **2010**, *42*, 802−807.

(7) Saha, A. K.; Bandyopadhyay, S. S.; Biswas, A. K. Kinetics of Absorption of CO_2 into Aqueous Solutions of 2-Amino-2-Methyl-1-Propanol. *Chem. Eng. Sci.* **1995**, *50*, 3587−3598.

(8) Glasscock, D. A.; Critchfield, J. E.; Rochelle, G. T. CO_2 Absorption/Desorption in Mixtures of Methyldiethanolamine with Monoethanolamine or Diethanolamine. *Chem. Eng. Sci.* **1991**, *46*, 2829−2845.

(9) Mandal, B. P.; Guha, M.; Biswas, A. K.; Bandyopadhyay, S. S. Removal of Carbon Dioxide by Absorption in Mixed Amines: Modelling of Absorption in Aqueous MDEA/MEA and AMP/MEA Solutions. *Chem. Eng. Sci.* **2001**, *56*, 6217−6224.

(10) Murshid, G.; Shariff, A. M.; Keong, L. K.; Bustam, M. A. Physical Properties of Aqueous Solutions of Piperazine and (2-Amino-2-methyl-1-propanol + Piperazine) from (298.15 to 333.15) K. *J. Chem. Eng. Data* **2011**, *56*, 2660−2663.

(11) Rebolledo-Libreros, M. E.; Trejo, A. Density and Viscosity of Aqueous Blends of Three Alkanolamines: N-Methyldiethanolamine, Diethanolamine, and 2-Amino-2-methyl-1-propanol in the Range of (303 to 343) K. *J. Chem. Eng. Data* **2006**, *51*, 702−707.

(12) Tseng, Y. M.; Thompson, A. R. Densities and Refractive Indices of Aqueous Monoethanolamine, Diethanolamine, Triethanolamine. *J. Chem. Eng. Data* **1964**, *9*, 264−267.

(13) Rayer, A. V.; Kadiwala, S.; Narayanaswamy, K.; Henni, A. Volumetric Properties, Viscosities, and Refractive Indices for Aqueous 1-Amino-2-Propanol (Monoisopropanolamine (MIPA)) Solutions from (298.15 to 343.15) K. *J. Chem. Eng. Data* **2010**, *55*, 5562−5568.

(14) Henni, A.; Hromek, J. J.; Tontiwachwuthikul, P.; Chakma, A. Volumetric Properties and Viscosities for Aqueous Diisopropanolamine Solutions from 25 to 70 °C. *J. Chem. Eng. Data* **2003**, *48*, 1062−1067.

(15) Hawrylak, B.; Burke, S. E.; Palepu, R. Partial Molar and Excess Volumes and Adiabatic Compressibilities of Binary Mixtures of Ethanolamines with Water. *J. Sol. Chem.* **2000**, *29*, 575−594.

(16) Álvarez, E.; Cerdeira, F.; Gómez-Díaz, D.; Navaza, J. M. Density, Speed of Sound, Isentropic Compressibility, and Excess Volume of Binary Mixtures of 1-Amino-2-propanol or 3-Amino-1-propanol with 2-Amino-2-methyl-1-propanol, Diethanolamine, or Triethanolamine from (293.15 to 323.15) K. *J. Chem. Eng. Data* **2010**, *55*, 2567−2575.

(17) Mokraoui, S.; Valtz, A.; Coquelet, C.; Richon, D. Volumetric Properties of the Isopropanolamine−Water Mixture at Atmospheric Pressure from 283.15 to 353.15K. *Thermochim. Acta* **2006**, *440*, 122−128.

(18) 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*, 743−756.