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Densities and Derived Thermodynamic Properties of 2-Amino-2-methyl-1-propanol + Water Mixtures at Temperatures from (313 to 363) K and Pressures up to 24 MPa

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PρT properties in the compressed liquid phase were determined for 2-amino-2-methyl-1-propanol (AMP) and AMP + water (at $x_1 = 0.0480$, 0.0736, 0.1188, and 0.1668) at temperatures from (313 to 363) K and pressures up to 24 MPa. A vibrating tube densimeter (VTD) was used to measure the densities. The classical calibration method of using two reference fluids (water and nitrogen) was used for the calibration of the VTD. The uncertainty of the measured densities was estimated to be $\pm\ 0.2\ \mathrm{kg \cdot m^{-3}}$. The liquid densities of aqueous AMP solutions reported in this work were correlated using a six-parameter equation. Isothermal compressibilities and isobaric thermal expansivity are calculated using the six-parameter equation within uncertainties estimated to be $\pm\ 3 \cdot 10^{-6}\ \mathrm{MPa^{-1}}$ and $\pm\ 4 \cdot 10^{-7}\ \mathrm{K^{-1}}$, respectively. Also, the excess molar volumes were calculated for the mixtures using densities of AMP calculated with the obtained correlation and densities of water calculated with a reference equation of state. The uncertainty of the excess molar volumes was estimated to be $\pm\ 6 \cdot 10^{-6}\ \mathrm{m^3 \cdot kmol^{-1}}$.

Introduction

The capture of CO_2 is essential to reduce the rate of release of greenhouse gases into the atmosphere.[1] Aqueous alkanolamine solutions are usually used in gas treating processes to remove acid gases such as CO_2 and H_2S from gas streams in natural gas plants, oil refineries, and ammonia plants.[1–3] Sterically hindered alkanolamines have been suggested recently as commercially attractive solvents for acid gas treatment over usual amines such as MEA, DEA, DIPA, and MDEA, and as rate promoters in amine blends.[2,4] The stoichiometry of the reaction allows loadings of CO_2 up to 1 mol of CO_2 per mole of AMP.[4] As a hindered form of monoethanolamine (MEA), AMP [$OH(CH_2)C(CH_3)_2NH_2$] has an excellent absorption capacity, an excellent absorption rate, superior stripping qualities, excellent selectivity, higher degradation resistance, and a lower corrosion rate compared to those of conventional amines.[4,5]

The physical properties of these solutions, such as density, are necessary for the best design of acid gas treatment equipment and for measuring and for interpreting other physicochemical properties such as liquid diffusivities, free-gas solubility, and the reaction kinetics of CO_2 with aqueous amine solutions.[2] Density values of aqueous AMP solutions are available in the literature at atmospheric pressure.[2,4–14] However, there are no measurements of density at high pressure for AMP and AMP (1) + water mixtures (2) reported in the literature. The objective of this work was to measure the effect of pressure on the density of binary aqueous solutions of AMP. Measurements were made over the range of AMP mass fraction of (0.20 to 0.50) at temperatures from (313.15 to 363.15) K and pressures up to 24 MPa. Experimental results were correlated with an empirical equation of six parameters. Since density data at high pressure for AMP and AMP + water mixtures were not found in the literature, the obtained correlations were extrapolated to atmospheric pressure and compared with the values in the literature to check the reliability of the correlations. Some thermophysical properties such as excess molar volumes, isothermal compressibilities, and isobaric thermal expansivities are calculated for the AMP (1) + water (2) system.

Experimental Section

Materials. AMP [$C_4H_{11}NO$, $M/\mathrm{kg \cdot kmol^{-1}} = 89.14$, Chemical Abstract Services registry number (CASRN), 124-68-5] was obtained from Imc. Chemical Group with a mass fraction purity of $w_1 = 0.95$ and a maximum content of water of $w_2 = 0.05$. HPLC water was obtained from Fisher with a stated mass fraction purity better than $w_2 = 0.9995$. Both materials were used without further purification except for careful degassing under vacuum and vigorous stirring. Chromatographic grade nitrogen was from Air Products Infra with a stated volume fraction purity of 0.99995 and was used as received.

Apparatus and Procedure. The apparatus used in this work has been described previously,[15–17] and it was based on that described by Galicia-Luna et al.[18] Its main part was a vibrating tube densimeter (VTD, Anton Parr DMA 60/512P). A variable-volume sapphire tube cell (Armines) was used for feeding the vibrating tube densimeter. The temperature of the VTD was controlled using a recirculation liquid bath (Polyscience) with a thermal stability of ± 0.01 K. The temperature of the sapphire cell was regulated with an air bath with a thermal stability of ± 0.05 K. The density determination was based on measuring the period of oscillation of the vibrating U-shaped tube (Hastelloy C-276/1 $\mathrm{cm^3}$) filled with the liquid sample.

The temperature was measured with platinum probes (Specitec), connected to a digital indicator (Automatic Systems F250), which were calibrated against a 25 Ω reference probe (model 162 CE from Rosemount with a certified uncertainty of ± 0.005 K traceable to the ITS90 scale) connected to a digital indicator

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Table 1. Experimental Densities, ρ, Calculated Isothermal Compressibilities, K_T, and Calculated Isobaric Thermal Expansivities, α_p, of AMP

$\frac{p}{\text{MPa}}$	$\frac{\rho}{\text{kg}\cdot\text{m}^{-3}}$	$\frac{K_T\cdot 10^3}{\text{MPa}^{-1}}$	$\frac{\alpha_p\cdot 10^3}{\text{K}^{-1}}$	$\frac{V^E\cdot 10^3}{\text{m}^3\cdot\text{kmol}^{-1}}$	$\frac{p}{\text{MPa}}$	$\frac{\rho}{\text{kg}\cdot\text{m}^{-3}}$	$\frac{K_T\cdot 10^3}{\text{MPa}^{-1}}$	$\frac{\alpha_p\cdot 10^3}{\text{K}^{-1}}$	$\frac{V^E\cdot 10^3}{\text{m}^3\cdot\text{kmol}^{-1}}$	$\frac{p}{\text{MPa}}$	$\frac{\rho}{\text{kg}\cdot\text{m}^{-3}}$
	T/K = 313.06				T/K = 322.98				T/K = 332.91		
1.000	931.4	0.592	0.911	0.500	922.7	0.633	0.928	0.500	914.0	0.672	0.944
2.000	931.9	0.588	0.907	1.000	922.8	0.630	0.926	1.000	914.4	0.670	0.942
3.000	932.4	0.583	0.903	2.000	923.4	0.626	0.922	2.000	915.0	0.664	0.938
4.000	932.9	0.579	0.900	3.000	924.0	0.621	0.919	3.000	915.6	0.659	0.934
5.000	933.5	0.574	0.896	4.000	924.5	0.616	0.915	4.000	916.1	0.654	0.930
6.000	933.9	0.570	0.892	5.000	925.1	0.611	0.911	5.000	916.7	0.649	0.926
7.000	934.5	0.566	0.889	6.000	925.7	0.607	0.907	6.000	917.3	0.644	0.922
8.000	935.0	0.561	0.885	7.000	926.2	0.602	0.904	7.000	918.0	0.639	0.919
9.007	935.5	0.557	0.881	8.000	926.8	0.597	0.900	8.000	918.5	0.634	0.915
10.003	936.0	0.553	0.878	9.007	927.4	0.593	0.896	9.009	919.1	0.630	0.911
11.000	936.6	0.549	0.874	10.002	927.8	0.588	0.893	10.003	919.7	0.625	0.907
12.000	937.0	0.545	0.871	11.000	928.4	0.584	0.889	11.002	920.2	0.620	0.904
13.000	937.6	0.541	0.867	12.000	928.9	0.580	0.885	12.001	920.8	0.616	0.900
14.000	938.1	0.537	0.864	13.000	929.5	0.575	0.882	13.000	921.3	0.611	0.896
15.002	938.6	0.533	0.861	14.000	930.1	0.571	0.878	14.000	921.9	0.606	0.893
16.000	939.1	0.529	0.857	15.003	930.6	0.567	0.875	15.002	922.4	0.602	0.889
17.001	939.7	0.525	0.854	16.006	931.1	0.563	0.871	16.001	923.0	0.597	0.886
18.002	940.2	0.521	0.850	17.001	931.6	0.559	0.868	17.001	923.5	0.593	0.882
19.000	940.6	0.518	0.847	18.002	932.1	0.555	0.864	18.002	924.1	0.589	0.879
20.029	941.1	0.514	0.844	19.000	932.6	0.551	0.861	19.000	924.6	0.584	0.875
21.004	941.7	0.510	0.841	20.030	933.2	0.546	0.858	20.030	925.2	0.580	0.872
22.004	942.1	0.506	0.837	21.005	933.7	0.543	0.854	21.002	925.6	0.576	0.868
24.004	943.1	0.499	0.831	22.004	934.1	0.539	0.851	22.004	926.2	0.572	0.865
				24.004	935.2	0.531	0.845	23.000	926.7	0.568	0.861
								24.004	927.3	0.564	0.858
	T/K = 342.84				T/K = 352.79				T/K = 362.65		
0.500	905.4	0.713	0.960	0.500	896.8	0.754	0.976	0.504	888.0	0.797	0.991
1.000	905.7	0.710	0.958	1.000	897.2	0.751	0.973	1.002	888.4	0.793	0.989
2.000	906.4	0.704	0.954	2.000	897.9	0.745	0.969	2.000	889.0	0.787	0.985
3.000	907.0	0.699	0.950	3.000	898.5	0.740	0.965	3.000	889.7	0.781	0.981
4.000	907.6	0.693	0.946	4.001	899.2	0.734	0.961	4.000	890.5	0.775	0.976
5.000	908.3	0.688	0.942	5.000	899.9	0.728	0.957	5.000	891.2	0.769	0.972
6.000	908.9	0.683	0.938	6.000	900.5	0.723	0.953	6.000	891.8	0.763	0.968
7.000	909.5	0.678	0.934	7.001	901.2	0.717	0.949	7.000	892.5	0.757	0.964
8.001	910.1	0.672	0.930	8.000	901.8	0.711	0.945	8.001	893.2	0.751	0.960
9.009	910.7	0.667	0.926	9.009	902.4	0.706	0.941	9.010	893.9	0.745	0.956
10.003	911.3	0.662	0.922	10.003	903.1	0.701	0.937	10.003	894.6	0.740	0.952
11.001	911.9	0.657	0.918	11.001	903.7	0.695	0.933	11.001	895.2	0.734	0.948
12.000	912.5	0.652	0.915	12.000	904.3	0.690	0.929	12.000	895.8	0.728	0.944
13.000	913.1	0.647	0.911	13.001	904.9	0.685	0.925	13.001	896.5	0.723	0.940
14.000	913.6	0.643	0.907	14.000	905.5	0.680	0.922	14.000	897.1	0.717	0.936
15.003	914.3	0.638	0.903	15.002	906.1	0.675	0.918	15.003	897.8	0.712	0.932
16.001	914.8	0.633	0.900	16.001	906.7	0.670	0.914	16.001	898.4	0.707	0.928
17.001	915.3	0.628	0.896	17.001	907.4	0.665	0.910	17.000	899.1	0.701	0.924
18.002	915.9	0.624	0.893	18.002	907.9	0.660	0.907	18.002	899.7	0.696	0.921
19.000	916.5	0.619	0.889	18.997	908.5	0.655	0.903	19.000	900.3	0.691	0.917
20.030	917.1	0.615	0.885	20.030	909.1	0.650	0.899	20.030	901.0	0.686	0.913
21.005	917.6	0.610	0.882	21.001	909.7	0.645	0.896	21.004	901.6	0.681	0.910
22.004	918.1	0.606	0.879	22.004	910.3	0.641	0.892	22.004	902.2	0.676	0.906
23.000	918.7	0.601	0.875	23.000	910.9	0.636	0.889	23.000	902.8	0.671	0.902
24.004	919.2	0.597	0.872	24.004	911.4	0.631	0.885	24.003	903.3	0.666	0.899

(Automatic Systems F300S). On the basis of the calibration, the estimated uncertainty in temperature measurements was ± 0.03 K. The pressure was measured with a 25 MPa pressure transducer (SEDEME type TF01 250) connected to a 61/2 digital multimeter (HP-34401A), which was calibrated at temperatures from (313 to 363) K against a dead weight balance (Desgranges & Hout model 5304, with an uncertainty of ± 0.005 % full scale). The estimated uncertainty was ± 0.008 MPa for pressure measurements. The reproducibility of the pressure measurements was checked by comparing pressure calibrations made at different times and by different experimentalists. The reproducibility in pressure measurements was found to be better than 0.01 %.

The classic method of calibration[18] using two reference fluids was used for the calibration of the VTD. Water and nitrogen were used as reference fluids in this work. Reference densities values of water and nitrogen were obtained with the equations of state of Wagner and Pruss[19] and Span et al.,[20] respectively. The density of the fluid inside the vibrating tube, ρ_F, was calculated by

$$\rho_F(p,T) = \rho_{H_2O}(p,T) + \frac{1}{A}(p,T)\left[\tau_F^2(p,T) - \tau_{H_2O}^2(p,T)\right] \quad (1)$$

where $1/A$ is defined as follows

$$\frac{1}{A} = \frac{\rho_{H_2O} - \rho_{N_2}}{\tau_{H_2O}^2 - \tau_{N_2}^2} \quad (2)$$

where $\rho_F(p,T)$, $\rho_{H_2O}(p,T)$, and $\rho_{N_2}(p,T)$ are the densities of the liquid sample and reference fluids, respectively. $\tau_F(p,T)$, $\tau_{H_2O}(p,T)$, and $\tau_{N_2}(p,T)$ are the periods of oscillation of the fluid under study, water, and nitrogen, respectively. The calibration was made at the same temperature and pressure that were used for the liquid under study. The uncertainty of the measured

Table 2. Experimental Densities, ρ, Calculated Isothermal Compressibilities, K_T, Calculated Isobaric Thermal Expansivities, α_p, and Calculated Excess Molar Volumes, V^E, of an AMP (1) + Water (2) Mixture at $w_1 = 0.1997$

p/MPa	ρ/kg·m^{-3}	$K_T \cdot 10^3$/MPa^{-1}	$\alpha_p \cdot 10^3$/K^{-1}	$V^E \cdot 10^3$/m^3·kmol^{-1}	p/MPa	ρ/kg·m^{-3}	$K_T \cdot 10^3$/MPa^{-1}	$\alpha_p \cdot 10^3$/K^{-1}	$V^E \cdot 10^3$/m^3·kmol^{-1}	p/MPa	ρ/kg·m^{-3}	$K_T \cdot 10^3$/MPa^{-1}	$\alpha_p \cdot 10^3$/K^{-1}	$V^E \cdot 10^3$/m^3·kmol^{-1}
T/K = 313.13					T/K = 323.10					T/K = 332.99				
0.500	989.5	0.395	0.538	−0.222	0.513	984.2	0.407	0.587	−0.219	0.503	978.2	0.421	0.634	−0.215
1.000	989.8	0.394	0.538	−0.222	1.007	984.4	0.407	0.587	−0.219	1.000	978.5	0.420	0.634	−0.215
2.000	990.1	0.393	0.537	−0.220	2.005	984.8	0.405	0.585	−0.216	2.000	978.7	0.418	0.632	−0.209
3.000	990.5	0.391	0.536	−0.218	3.005	985.1	0.403	0.584	−0.214	3.000	979.2	0.416	0.631	−0.209
4.000	990.9	0.390	0.534	−0.215	4.001	985.5	0.402	0.583	−0.212	4.000	979.6	0.415	0.630	−0.206
5.000	991.2	0.388	0.533	−0.213	5.000	986.0	0.400	0.581	−0.212	5.001	979.9	0.413	0.628	−0.204
6.000	991.6	0.387	0.532	−0.211	6.003	986.3	0.399	0.580	−0.209	6.000	980.4	0.412	0.627	−0.203
7.000	992.0	0.385	0.531	−0.209	7.003	986.8	0.397	0.579	−0.208	7.001	980.8	0.410	0.625	−0.203
8.000	992.4	0.384	0.530	−0.209	8.001	987.1	0.396	0.578	−0.206	8.001	981.2	0.408	0.624	−0.201
9.007	992.8	0.382	0.529	−0.207	9.013	987.5	0.394	0.577	−0.204	9.009	981.5	0.407	0.623	−0.197
10.002	993.2	0.381	0.528	−0.207	10.002	987.9	0.392	0.575	−0.203	10.003	982.0	0.405	0.621	−0.197
11.000	993.6	0.379	0.526	−0.205	11.001	988.3	0.391	0.574	−0.201	11.001	982.3	0.404	0.620	−0.194
12.000	994.0	0.378	0.525	−0.203	12.004	988.7	0.389	0.573	−0.200	12.000	982.8	0.402	0.619	−0.194
13.000	994.4	0.376	0.524	−0.201	13.009	989.0	0.388	0.572	−0.198	13.000	983.2	0.400	0.617	−0.192
14.000	994.7	0.375	0.523	−0.199	13.999	989.4	0.386	0.570	−0.196	14.000	983.6	0.399	0.616	−0.191
15.002	995.1	0.374	0.522	−0.198	15.001	989.8	0.385	0.569	−0.195	14.999	984.0	0.397	0.615	−0.189
16.000	995.5	0.372	0.521	−0.196	16.002	990.2	0.384	0.568	−0.193	16.001	984.3	0.396	0.613	−0.187
17.001	995.9	0.371	0.520	−0.195	17.001	990.6	0.382	0.567	−0.193	17.001	984.8	0.394	0.612	−0.187
18.002	996.3	0.369	0.519	−0.194	18.004	991.0	0.381	0.566	−0.190	18.006	985.2	0.393	0.611	−0.185
19.000	996.7	0.368	0.518	−0.192	19.000	991.4	0.379	0.564	−0.189	19.001	985.5	0.391	0.610	−0.184
20.030	997.1	0.366	0.517	−0.191	20.030	991.7	0.378	0.563	−0.187	20.029	985.9	0.390	0.608	−0.181
21.004	997.4	0.365	0.516	−0.190	21.005	992.1	0.376	0.562	−0.186	21.005	986.3	0.388	0.607	−0.180
22.004	997.8	0.364	0.514	−0.188	22.004	992.5	0.375	0.561	−0.185	22.004	986.7	0.387	0.606	−0.179
23.000	998.2	0.362	0.513	−0.187	22.998	992.9	0.373	0.560	−0.183	23.000	987.0	0.385	0.605	−0.177
24.004	998.5	0.361	0.512	−0.186	24.004	993.3	0.372	0.559	−0.182	24.008	987.4	0.384	0.603	−0.176
T/K = 342.92					T/K = 352.86					T/K = 362.74				
0.509	971.6	0.435	0.681	−0.206	0.500	965.0	0.450	0.726	−0.207	0.532	957.9	0.467	0.770	−0.205
1.001	971.8	0.434	0.680	−0.205	1.000	965.2	0.449	0.725	−0.206	1.001	958.0	0.466	0.770	−0.203
2.000	972.2	0.432	0.678	−0.203	2.000	965.7	0.448	0.724	−0.206	2.000	958.5	0.464	0.768	−0.201
3.000	972.7	0.431	0.677	−0.202	3.000	966.2	0.446	0.722	−0.206	3.000	959.0	0.462	0.766	−0.199
4.000	973.1	0.429	0.675	−0.199	4.000	966.5	0.444	0.720	−0.201	4.000	959.4	0.460	0.764	−0.198
5.000	973.6	0.427	0.674	−0.199	5.000	966.9	0.442	0.719	−0.199	5.000	960.1	0.459	0.763	−0.204
6.000	974.0	0.426	0.672	−0.198	6.000	967.3	0.441	0.717	−0.197	6.000	960.4	0.457	0.761	−0.198
7.001	974.4	0.424	0.671	−0.196	7.000	967.8	0.439	0.716	−0.195	7.000	960.7	0.455	0.759	−0.193
8.000	974.8	0.422	0.670	−0.194	8.000	968.2	0.437	0.714	−0.194	8.001	961.2	0.453	0.758	−0.192
9.009	975.2	0.421	0.668	−0.193	9.009	968.6	0.435	0.713	−0.192	9.009	961.6	0.451	0.756	−0.190
10.002	975.6	0.419	0.667	−0.192	10.002	969.1	0.434	0.711	−0.192	10.004	962.1	0.450	0.754	−0.189
11.001	976.0	0.417	0.665	−0.190	11.001	969.5	0.432	0.709	−0.191	11.001	962.4	0.448	0.753	−0.186
12.000	976.5	0.416	0.664	−0.190	12.000	970.0	0.430	0.708	−0.190					
13.000	976.9	0.414	0.662	−0.188	13.000	970.4	0.429	0.706	−0.188					
14.000	977.3	0.412	0.661	−0.187	14.000	970.8	0.427	0.705	−0.187					
15.002	977.7	0.411	0.660	−0.186	15.003	971.2	0.425	0.703	−0.186					
16.002	978.2	0.409	0.658	−0.185	16.001	971.6	0.424	0.702	−0.184					
17.001	978.6	0.408	0.657	−0.183	17.001	972.1	0.422	0.700	−0.183					
18.002	979.0	0.406	0.655	−0.182	18.002	972.5	0.420	0.699	−0.182					
18.999	979.2	0.405	0.654	−0.178	19.001	972.9	0.419	0.697	−0.180					
20.029	979.8	0.403	0.652	−0.180	20.029	973.3	0.417	0.696	−0.178					
21.004	980.2	0.402	0.651	−0.178	21.004	973.8	0.416	0.694	−0.178					
22.004	980.6	0.400	0.650	−0.177	22.004	974.1	0.414	0.693	−0.176					
23.001	981.0	0.398	0.648	−0.175	23.000	974.5	0.412	0.691	−0.174					
24.005	981.5	0.397	0.647	−0.176	24.004	975.0	0.411	0.690	−0.174					

density was calculated using the law of propagation of errors. In this work, the estimated uncertainty was estimated to be ± 0.2 kg·m^{-3} for liquid densities at a 95 % confidence level. Calibrations of temperature probes, the pressure transducer, and the VTD were performed before and after experimental measurements were performed.

Loading of the Measurement Cell. A detailed procedure of loading the measurement cell has been presented previously.[17,18] The samples with the desired compositions were prepared by successive loadings of a known mass of the pure compounds in the sapphire feeding cell. The amounts of pure compounds (AMP and water) were determined by weighting carried out with an uncertainty of ± 10^{-7} kg using a Sartorius comparator balance (MCA1200), which was periodically calibrated with a standard mass of 1 kg of class E1. First, AMP was fed to the evacuated cell; once the mass of AMP added had been determined, water was fed in liquid state with the help of a syringe pump (Isco 100DM) to the cell, and its mass was determined. Three masses were determined: m_1, mass of the evacuated cell; m_2, mass of the cell plus AMP; m_3, mass of m_2 plus water. Then, the mass of AMP was equal to ($m_2 - m_1$), and the mass of water was obtained with ($m_3 - m_2$). With the masses of the two compounds and the molecular weights, the corresponding molar composition was determined for the synthesized mixture. We reported mole fraction and mass fraction in this work; the first was reported because excess molar volumes were calculated on these bases, and for comparisons of density data, mass fraction was more adequate because in the literature these values are frequently reported. The resulting uncertainty for the mole fraction of the mixtures was lower than ± 10^{-4}. The uncertainty in mass fraction was estimated to be lees than ± $3 \cdot 10^{-4}$.

Table 3. Experimental Densities, ρ, Calculated Isothermal Compressibilities, K_T, Calculated Isobaric Thermal Expansivities, α_p, and Calculated Excess Molar Volumes, V^E, of an AMP (1) + Water (2) Mixture at $w_1 = 0.2821$

p MPa	ρ $kg \cdot m^{-3}$	$K_T \cdot 10^3$ MPa^{-1}	$\alpha_p \cdot 10^3$ K^{-1}	$V^E \cdot 10^3$ $m^3 \cdot kmol^{-1}$	p MPa	ρ $kg \cdot m^{-3}$	$K_T \cdot 10^3$ MPa^{-1}	$\alpha_p \cdot 10^3$ K^{-1}	$V^E \cdot 10^3$ $m^3 \cdot kmol^{-1}$	p MPa	ρ $kg \cdot m^{-3}$	$K_T \cdot 10^3$ MPa^{-1}	$\alpha_p \cdot 10^3$ K^{-1}	$V^E \cdot 10^3$ $m^3 \cdot kmol^{-1}$
T/K = 313.13					T/K = 323.08					T/K = 332.01				
0.995	988.9	0.393	0.606	−0.347	1.026	982.8	0.409	0.653	−0.335	1.005	976.1	0.426	0.700	−0.325
2.002	989.2	0.392	0.604	−0.344	2.026	983.2	0.407	0.651	−0.334	2.004	976.5	0.424	0.698	−0.322
2.993	989.6	0.390	0.603	−0.342	2.996	983.5	0.405	0.650	−0.331	2.997	977.0	0.422	0.696	−0.320
4.001	990.0	0.388	0.601	−0.339	4.009	983.9	0.404	0.648	−0.329	4.002	977.4	0.420	0.694	−0.318
4.995	990.4	0.386	0.599	−0.337	5.006	984.3	0.402	0.647	−0.326	5.002	977.8	0.419	0.692	−0.316
6.005	990.8	0.384	0.598	−0.335	6.002	984.7	0.400	0.645	−0.324	5.997	978.2	0.417	0.691	−0.314
6.987	991.1	0.383	0.597	−0.332	6.993	985.1	0.398	0.643	−0.322	6.999	978.6	0.415	0.689	−0.311
7.991	991.5	0.381	0.595	−0.330	7.994	985.5	0.396	0.642	−0.320	7.996	979.0	0.413	0.687	−0.310
8.997	991.9	0.379	0.594	−0.328	9.012	985.9	0.394	0.640	−0.317	8.992	979.4	0.411	0.685	−0.307
9.995	992.3	0.377	0.592	−0.326	9.998	986.3	0.393	0.638	−0.315	9.994	979.8	0.409	0.684	−0.305
10.990	992.6	0.376	0.591	−0.323	11.009	986.6	0.391	0.637	−0.312	11.040	980.2	0.407	0.682	−0.303
11.991	993.0	0.374	0.589	−0.321	11.995	987.0	0.389	0.635	−0.311	11.992	980.6	0.405	0.680	−0.301
12.982	993.4	0.372	0.588	−0.319	12.991	987.4	0.387	0.634	−0.309	12.990	981.0	0.403	0.679	−0.299
13.991	993.8	0.371	0.586	−0.317	14.001	987.8	0.385	0.632	−0.306	13.989	981.4	0.402	0.677	−0.297
14.997	994.2	0.369	0.585	−0.315	14.989	988.2	0.384	0.631	−0.305	14.989	981.8	0.400	0.675	−0.295
15.990	994.5	0.367	0.583	−0.312	15.999	988.5	0.382	0.629	−0.302	15.990	982.2	0.398	0.674	−0.293
16.989	994.9	0.366	0.582	−0.311	16.987	988.9	0.380	0.628	−0.301	17.000	982.5	0.396	0.672	−0.290
17.988	995.3	0.364	0.581	−0.309	17.980	989.3	0.379	0.626	−0.298	17.987	982.9	0.394	0.670	−0.289
18.987	995.6	0.362	0.579	−0.307	18.996	989.7	0.377	0.624	−0.296	18.991	983.3	0.393	0.669	−0.286
19.996	996.0	0.361	0.578	−0.306	19.986	990.1	0.375	0.623	−0.295	19.984	983.7	0.391	0.667	−0.285
20.955	996.4	0.359	0.576	−0.304	20.987	990.4	0.373	0.621	−0.292	20.986	984.1	0.389	0.665	−0.283
T/K = 342.91					T/K = 352.85					T/K = 362.73				
1.020	969.0	0.445	0.745	−0.310	0.997	961.9	0.465	0.790	−0.305	0.999	954.1	0.486	0.834	−0.292
2.011	969.5	0.443	0.743	−0.309	2.011	962.4	0.462	0.788	−0.304	1.999	954.5	0.483	0.831	−0.289
3.009	969.9	0.441	0.741	−0.306	2.994	962.8	0.460	0.786	−0.301	2.998	955.1	0.481	0.829	−0.289
4.010	970.3	0.439	0.739	−0.304	4.000	963.2	0.458	0.784	−0.299	3.996	955.4	0.479	0.827	−0.285
4.994	970.8	0.437	0.737	−0.302	5.006	963.7	0.456	0.781	−0.297	4.996	955.9	0.476	0.825	−0.283
5.994	971.2	0.435	0.735	−0.301	6.000	964.1	0.454	0.779	−0.295	5.993	956.3	0.474	0.823	−0.281
7.035	971.6	0.432	0.733	−0.297	6.999	964.5	0.452	0.777	−0.293	6.993	956.8	0.472	0.821	−0.280
7.995	972.0	0.430	0.732	−0.296	7.996	965.0	0.450	0.776	−0.291	8.006	957.3	0.470	0.818	−0.277
8.990	972.4	0.429	0.730	−0.294	8.992	965.4	0.447	0.774	−0.289	8.992	957.7	0.468	0.816	−0.276
9.998	972.9	0.427	0.728	−0.292	9.994	965.8	0.445	0.772	−0.287	9.994	958.1	0.465	0.814	−0.273
10.992	973.3	0.425	0.726	−0.290	10.987	966.2	0.443	0.770	−0.285	10.992	958.6	0.463	0.812	−0.270
11.994	973.7	0.423	0.724	−0.289	12.010	966.7	0.441	0.768	−0.283	11.992	959.1	0.461	0.810	−0.270
12.992	974.1	0.421	0.722	−0.287	12.992	967.1	0.439	0.766	−0.280	12.991	959.5	0.459	0.808	−0.267
13.990	974.5	0.419	0.721	−0.284	13.990	967.5	0.437	0.764	−0.279	13.992	959.9	0.457	0.806	−0.265
14.992	974.9	0.417	0.719	−0.283	14.990	968.0	0.435	0.762	−0.277	14.988	960.4	0.455	0.804	−0.263
15.993	975.4	0.415	0.717	−0.281	15.988	968.4	0.433	0.760	−0.275	15.987	960.8	0.453	0.802	−0.262
16.987	975.8	0.413	0.715	−0.279	16.991	968.8	0.431	0.758	−0.274	16.990	961.3	0.451	0.800	−0.261
17.985	976.2	0.411	0.714	−0.278	17.991	969.2	0.429	0.756	−0.272	18.019	961.7	0.448	0.798	−0.258
18.987	976.6	0.409	0.712	−0.277	18.988	969.6	0.427	0.754	−0.269	18.985	962.1	0.447	0.796	−0.257
19.984	977.0	0.407	0.710	−0.274	19.987	970.1	0.425	0.752	−0.268	19.985	962.6	0.444	0.794	−0.255
20.986	977.4	0.406	0.708	−0.273	20.985	970.5	0.424	0.751	−0.266					

Procedure. The experimental procedure consists of four steps: (1) sensor calibration, (2) cell loading, (3) setting up of the experimental conditions, and (4) measurements at equilibrium. Measurements were made at a constant temperature, and the pressure measurements start at 1 MPa, which is increased approximately every 1 MPa up to 24 MPa. Four measurements for the same point were taken once the pressure and period signals were kept constant.

Results and Discussion

Experimental Densities. Compressed liquid densities were determined for AMP and AMP (1) + water (2) mixtures (at $x_1 = 0.0480$, 0.0736, 0.1188, and 0.1668) at temperatures from (313 to 363) K and pressures up to 24 MPa. The corresponding mass fractions of the mixtures are as follows: $w_1 = 0.1997$, 0.2821, 0.4002, and 0.4976, respectively. The experimental densities are reported in Tables 1 to 5. Densities as a function of pressure are plotted in Figure 1 at 313.13 K for AMP and four mixtures of AMP (1) + water (2). Densities of AMP are lower than those for the mixtures, and the densities of the mixtures decrease as the AMP content increases in the mixture for the composition range studied in this work.

The experimental densities for AMP and for each mixture were correlated with a six-parameter equation:[21]

$$v/(\mathrm{m^3 \cdot kg^{-1}}) = (d_1 + d_2 p)/(d_3 - d_4 T + d_5 T^{1/2} + d_6 p) \quad (3)$$

where d_i values are fitted to experimental density data.

The values for the parameters of eq 3 were obtained by minimizing the deviations between the model and the experimental densities of the pure fluid using the Marquardt–Levenberg least-squares optimization with the following objective function, S

$$S = \sum_{i=1}^{n} [1 - \rho_i(\mathrm{cal})/\rho_i]^2 \quad (4)$$

The standard deviation (SDV) was used to evaluate the different correlations. The definition of SDV can be found in a previous paper.[21] The parameters, temperature, pressure, and density intervals, data points used for the correlation, and the SDV to evaluate the correlations are reported in Table 6 for AMP and AMP (1) + water (2). In Figure 2, deviations between experimental densities and values calculated with the six-parameter equation are plotted for AMP. The maximum deviations are ± 0.02 %, and similar plots can be generated for

Table 4. Experimental Densities, ρ, Calculated Isothermal Compressibilities, K_T, Calculated Isobaric Thermal Expansivities, α_p, and Calculated Excess Molar Volumes, V^E, of an AMP (1) + Water (2) Mixture at w_1 = 0.4002

p	ρ	$K_T \cdot 10^3$	$\alpha_p \cdot 10^3$	$V^E \cdot 10^3$	p	ρ	$K_T \cdot 10^3$	$\alpha_p \cdot 10^3$	$V^E \cdot 10^3$	p	ρ	$K_T \cdot 10^3$	$\alpha_p \cdot 10^3$	$V^E \cdot 10^3$
MPa	$kg \cdot m^{-3}$	MPa^{-1}	K^{-1}	$m^3 \cdot kmol^{-1}$	MPa	$kg \cdot m^{-3}$	MPa^{-1}	K^{-1}	$m^3 \cdot kmol^{-1}$	MPa	$kg \cdot m^{-3}$	MPa^{-1}	K^{-1}	$m^3 \cdot kmol^{-1}$
		T/K = 313.13					T/K = 323.10					T/K = 333.05		
0.998	985.4	0.407	0.744	−0.507	1.002	978.0	0.427	0.775	−0.478	1.028	970.4	0.448	0.806	−0.450
2.006	985.8	0.405	0.742	−0.503	2.023	978.4	0.425	0.773	−0.475	1.998	970.8	0.446	0.804	−0.447
2.995	986.2	0.403	0.740	−0.502	3.001	978.9	0.423	0.771	−0.472	3.001	971.2	0.444	0.802	−0.444
3.995	986.6	0.401	0.738	−0.498	4.011	979.2	0.421	0.769	−0.468	4.010	971.6	0.441	0.800	−0.441
4.999	986.9	0.399	0.736	−0.495	5.000	979.7	0.419	0.767	−0.466	5.003	972.1	0.439	0.798	−0.439
5.999	987.3	0.397	0.734	−0.493	6.002	980.0	0.417	0.765	−0.462	5.997	972.5	0.437	0.795	−0.437
6.994	987.7	0.396	0.733	−0.489	6.999	980.4	0.415	0.763	−0.460	7.000	972.9	0.435	0.793	−0.434
7.986	988.1	0.394	0.731	−0.486	7.990	980.8	0.413	0.761	−0.457	8.010	973.3	0.433	0.791	−0.430
8.992	988.5	0.392	0.729	−0.484	9.002	981.2	0.411	0.759	−0.453	8.996	973.7	0.431	0.789	−0.426
9.992	988.9	0.390	0.727	−0.481	9.990	981.6	0.409	0.757	−0.451	9.998	974.2	0.429	0.787	−0.426
10.993	989.2	0.388	0.725	−0.478	10.992	982.0	0.407	0.755	−0.449	10.998	974.6	0.427	0.785	−0.422
11.992	989.6	0.386	0.723	−0.475	11.996	982.5	0.405	0.753	−0.447	12.011	975.0	0.425	0.783	−0.419
13.002	990.0	0.385	0.721	−0.472	12.990	982.8	0.403	0.752	−0.444	13.000	975.4	0.423	0.781	−0.417
13.999	990.4	0.383	0.720	−0.470	13.994	983.2	0.401	0.750	−0.440	13.987	975.8	0.421	0.779	−0.415
14.999	990.8	0.381	0.718	−0.467	14.992	983.6	0.399	0.748	−0.438	14.990	976.2	0.419	0.777	−0.411
15.992	991.2	0.379	0.716	−0.466	15.995	984.0	0.398	0.746	−0.436	15.984	976.6	0.417	0.775	−0.410
16.994	991.5	0.377	0.714	−0.463	16.986	984.4	0.396	0.744	−0.434	16.990	977.0	0.415	0.773	−0.405
17.989	991.9	0.376	0.712	−0.460	17.993	984.8	0.394	0.742	−0.430	18.003	977.4	0.413	0.771	−0.404
18.990	992.3	0.374	0.711	−0.459	18.995	985.1	0.392	0.740	−0.428	18.986	977.8	0.411	0.769	−0.402
19.992	992.7	0.372	0.709	−0.456	19.992	985.5	0.390	0.738	−0.426	19.988	978.2	0.409	0.767	−0.399
20.691	993.0	0.371	0.708	−0.454	21.297	986.0	0.388	0.736	−0.422	21.502	978.8	0.406	0.764	−0.396
		T/K = 342.93					T/K = 352.87					T/K = 362.74		
1.004	962.4	0.470	0.836	−0.420	1.007	954.4	0.492	0.866	−0.403	1.014	946.1	0.516	0.896	−0.381
2.006	962.8	0.467	0.834	−0.418	2.012	954.9	0.490	0.864	−0.400	1.992	946.6	0.513	0.893	−0.379
3.009	963.3	0.465	0.832	−0.416	3.000	955.3	0.488	0.861	−0.397	3.010	947.1	0.511	0.891	−0.375
4.013	963.7	0.463	0.829	−0.412	4.011	955.8	0.485	0.859	−0.395	4.009	947.5	0.508	0.888	−0.371
4.998	964.2	0.461	0.827	−0.410	5.007	956.3	0.483	0.857	−0.391	5.001	948.0	0.506	0.886	−0.370
5.995	964.6	0.458	0.825	−0.407	6.009	956.7	0.480	0.854	−0.390	6.003	948.5	0.503	0.884	−0.368
6.996	965.0	0.456	0.823	−0.405	7.008	957.2	0.478	0.852	−0.386	6.999	949.0	0.501	0.881	−0.365
7.995	965.5	0.454	0.821	−0.402	8.014	957.6	0.476	0.850	−0.384	7.990	949.4	0.499	0.879	−0.361
8.994	965.9	0.452	0.819	−0.401	8.988	958.1	0.474	0.848	−0.382	8.995	949.9	0.496	0.876	−0.359
10.004	966.3	0.450	0.816	−0.396	9.986	958.5	0.471	0.846	−0.379	10.039	950.4	0.494	0.874	−0.357
10.993	966.8	0.447	0.814	−0.395	11.001	959.0	0.469	0.843	−0.376	10.986	950.8	0.491	0.872	−0.354
12.000	967.2	0.445	0.812	−0.392	12.004	959.5	0.467	0.841	−0.375	11.991	951.3	0.489	0.869	−0.352
12.990	967.6	0.443	0.810	−0.391	12.991	959.8	0.465	0.839	−0.370	12.999	951.8	0.487	0.867	−0.349
13.993	968.0	0.441	0.808	−0.387	13.986	960.3	0.462	0.837	−0.368	13.999	952.2	0.484	0.865	−0.347
14.985	968.5	0.439	0.806	−0.385	14.991	960.8	0.460	0.834	−0.366	14.990	952.7	0.482	0.863	−0.346
15.999	968.9	0.437	0.804	−0.383	15.997	961.2	0.458	0.832	−0.364	15.993	953.2	0.480	0.860	−0.343
16.987	969.3	0.435	0.802	−0.380	16.988	961.6	0.456	0.830	−0.361	16.984	953.6	0.478	0.858	−0.341
17.994	969.8	0.433	0.800	−0.378	17.995	962.0	0.454	0.828	−0.358	18.005	954.1	0.475	0.856	−0.338
18.984	970.2	0.431	0.798	−0.377	18.987	962.5	0.452	0.826	−0.357	18.993	954.5	0.473	0.854	−0.336
19.987	970.6	0.429	0.796	−0.375	19.995	962.9	0.449	0.824	−0.354	19.978	955.0	0.471	0.851	−0.333
20.996	971.0	0.427	0.794	−0.370	20.986	963.3	0.447	0.822	−0.351	21.014	955.4	0.469	0.849	−0.330

the case of mixtures. Additionally, the correlations obtained for AMP and for each mixture represented the experimental data with relative SDV's lower than 0.01 %.

To check for the reliability of the correlations obtained herein, indeed of the experimental densities, and since there was not reported data at high pressure for the systems studied here, the correlations at w_1 = 0.1997 and 0.4002 were extrapolated to atmospheric pressures. These compositions were chosen due their closeness in composition with the literature data. In Figure 3, two comparisons are shown; one shows the deviations of data from Li and Lie[7] at w_1 = 0.2 with values calculated with the correlation obtained in this work at w_1 = 0.1997, and the other shows the deviations of data from Aguila et al.[9] at w_1 = 0.4 with values calculated with the correlation obtained in this work at w_1 = 0.4002. Our correlation at w_1 = 0.1997 agreed with the data of Li and Lie[7] with 0.02 %, while our correlation at w_1 = 0.4002 agreed with the data of Aguila et al.[9] with 0.05 %. These results showed the good convergency at atmospheric pressure of the correlations obtained in this work.

Derived Properties. The experimental densities can be used to obtain other important properties, such as excess molar volumes, isothermal compressibilities (K_T), and isobaric thermal expansivities (α_p).

The excess molar volumes are calculated according to the following expression

$$V^E/\mathrm{m^3 \cdot kmol^{-1}} = \frac{x_1 M_1 + x_2 M_2}{\rho^{\mathrm{mix}}} - (x_1 V_1 + x_2 V_2) \qquad (5)$$

where V^E is the excess molar volume, ρ^{mix} is the density of the mixture, V_1 and V_2 are the pure component molar volumes at the measured temperature and pressure of the mixture, M_1 and M_2 are the molecular weights of AMP and water, respectively, and x_1 and x_2 are the mole fractions of AMP and water, respectively. V_1 is calculated using the six-parameter equation, and V_2 is calculated using the EoS proposed by Wagner and Pruss.[19] The uncertainty in V^E was estimated to be ± $6 \cdot 10^{-6}$ $m^3 \cdot kmol^{-1}$ in the whole interval of measurements reported in this work. The excess molar volumes are reported in Tables 2 to 5. V^E exhibits negative deviations from ideality in the investigated temperature and pressure ranges studied here. V^E values are less negative when the temperature increases at a constant pressure, while V^E values are less negative when the pressure increases at a constant temperature.

The effect of pressure on density can be described by the isothermal compressibility that is calculated using the isothermal pressure derivative of density according to the following expression

$$K_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T \tag{6}$$

In this work, the isothermal compressibility of each compound has been determined analytically by differentiating eq 3 along with the parameters reported in Table 6. This results in the following expression for the isothermal compressibility

$$K_T/\text{MPa}^{-1} = d_6/(d_3 - d_4T + d_5T^{1/2} + d_6p) - d_2/(d_1 + d_2p) \tag{7}$$

The isothermal compressibilities for AMP and for each mixture are reported in Tables 1 to 5, and for the purposes of illustration, the isothermal compressibilities of AMP and AMP (1) + water (2) mixtures are plotted in Figure 4 at 313.13 K.

Table 5. Experimental Densities, ρ, Calculated Isothermal Compressibilities, K_T, Calculated Isobaric Thermal Expansivities, α_p, and Calculated Excess Molar Volumes, V^E, of an AMP (1) + Water (2) Mixture at w_1 = 0.4976

p/MPa	ρ/kg·m^{-3}	$K_T \cdot 10^3$/MPa^{-1}	$\alpha_p \cdot 10^3$/K^{-1}	$V^E \cdot 10^3$/m^3·kmol^{-1}	p/MPa	ρ/kg·m^{-3}	$K_T \cdot 10^3$/MPa^{-1}	$\alpha_p \cdot 10^3$/K^{-1}	$V^E \cdot 10^3$/m^3·kmol^{-1}	p/MPa	ρ/kg·m^{-3}	$K_T \cdot 10^3$/MPa^{-1}	$\alpha_p \cdot 10^3$/K^{-1}	$V^E \cdot 10^3$/m^3·kmol^{-1}
		T/K = 313.13					T/K = 323.09					T/K = 333.04		
0.999	978.1	0.429	0.819	−0.506	1.002	970.1	0.452	0.844	−0.454	1.029	961.9	0.476	0.869	−0.406
2.014	978.5	0.426	0.816	−0.503	1.995	970.5	0.449	0.842	−0.451	1.994	962.4	0.473	0.867	−0.405
3.001	978.9	0.424	0.814	−0.500	3.001	971.0	0.447	0.839	−0.448	3.005	962.8	0.471	0.864	−0.401
4.001	979.3	0.422	0.812	−0.496	4.009	971.4	0.445	0.837	−0.445	4.012	963.3	0.468	0.862	−0.399
4.999	979.7	0.420	0.810	−0.493	5.001	971.8	0.443	0.835	−0.442	4.995	963.7	0.466	0.859	−0.396
6.000	980.2	0.418	0.807	−0.490	5.995	972.2	0.440	0.832	−0.439	5.995	964.1	0.464	0.857	−0.393
6.995	980.6	0.416	0.805	−0.488	7.011	972.6	0.438	0.830	−0.436	7.056	964.6	0.461	0.854	−0.391
8.003	980.9	0.414	0.803	−0.483	7.990	973.0	0.436	0.828	−0.432	7.994	965.0	0.459	0.852	−0.386
8.997	981.4	0.412	0.801	−0.481	9.002	973.5	0.434	0.826	−0.430	8.994	965.5	0.457	0.850	−0.385
9.999	981.8	0.410	0.799	−0.478	9.974	973.9	0.432	0.823	−0.427	9.997	965.9	0.454	0.848	−0.383
10.989	982.1	0.408	0.797	−0.475	10.992	974.3	0.429	0.821	−0.424	10.996	966.3	0.452	0.845	−0.379
11.996	982.6	0.405	0.794	−0.473	11.993	974.7	0.427	0.819	−0.422	11.991	966.7	0.450	0.843	−0.376
13.006	983.0	0.403	0.792	−0.470	12.991	975.1	0.425	0.817	−0.419	12.988	967.2	0.447	0.841	−0.373
14.001	983.4	0.401	0.790	−0.467	13.986	975.6	0.423	0.814	−0.416	13.992	967.6	0.445	0.838	−0.371
15.001	983.8	0.399	0.788	−0.464	14.991	976.0	0.421	0.812	−0.414	14.999	968.0	0.443	0.836	−0.369
15.992	984.2	0.398	0.786	−0.463	15.999	976.4	0.419	0.810	−0.410	15.982	968.4	0.441	0.834	−0.366
16.992	984.6	0.396	0.784	−0.460	16.994	976.8	0.417	0.808	−0.408	16.996	968.9	0.439	0.832	−0.363
17.985	985.0	0.394	0.782	−0.457	18.003	977.2	0.415	0.806	−0.405	17.988	969.3	0.436	0.829	−0.360
18.990	985.4	0.392	0.780	−0.455	18.986	977.6	0.413	0.804	−0.404	18.986	969.7	0.434	0.827	−0.357
19.992	985.8	0.390	0.778	−0.453	19.985	978.0	0.411	0.801	−0.400	19.987	970.1	0.432	0.825	−0.355
20.495	986.0	0.389	0.777	−0.452	20.939	978.4	0.409	0.799	−0.398	21.093	970.6	0.430	0.822	−0.353
		T/K = 342.92					T/K = 352.87					T/K = 362.73		
1.008	953.4	0.500	0.894	−0.358	1.039	945.0	0.526	0.918	−0.324	1.015	936.3	0.553	0.943	−0.285
2.004	953.8	0.498	0.891	−0.354	2.018	945.5	0.523	0.916	−0.321	2.010	936.7	0.550	0.940	−0.281
3.006	954.3	0.495	0.889	−0.353	3.005	946.0	0.521	0.913	−0.319	3.022	937.3	0.547	0.937	−0.280
4.000	954.8	0.493	0.886	−0.350	4.018	946.5	0.518	0.911	−0.316	3.997	937.8	0.544	0.935	−0.276
4.997	955.3	0.490	0.884	−0.347	5.000	946.9	0.515	0.908	−0.312	5.010	938.3	0.541	0.932	−0.275
5.996	955.7	0.488	0.881	−0.345	5.997	947.4	0.513	0.906	−0.311	6.002	938.8	0.538	0.929	−0.272
6.996	956.2	0.485	0.879	−0.343	7.007	947.9	0.510	0.903	−0.309	6.999	939.3	0.536	0.927	−0.269
7.993	956.7	0.483	0.876	−0.340	7.999	948.4	0.507	0.900	−0.306	7.992	939.8	0.533	0.924	−0.268
8.988	957.2	0.480	0.874	−0.339	8.994	948.9	0.505	0.898	−0.304	8.997	940.3	0.530	0.922	−0.264
9.983	957.6	0.478	0.872	−0.336	9.996	949.4	0.502	0.895	−0.301	10.028	940.9	0.527	0.919	−0.263
10.990	958.1	0.475	0.869	−0.334	10.996	949.8	0.500	0.893	−0.298	10.990	941.3	0.525	0.916	−0.260
12.003	958.5	0.473	0.867	−0.330	12.002	950.3	0.497	0.890	−0.296	11.996	941.8	0.522	0.914	−0.259
12.992	958.9	0.471	0.864	−0.327	13.000	950.8	0.495	0.888	−0.293	13.002	942.3	0.519	0.911	−0.255
13.996	959.4	0.468	0.862	−0.325	13.993	951.2	0.492	0.885	−0.291	13.994	942.8	0.517	0.909	−0.254
14.988	959.9	0.466	0.860	−0.323	15.004	951.7	0.490	0.883	−0.288	14.986	943.3	0.514	0.906	−0.251
15.995	960.3	0.464	0.857	−0.321	16.002	952.2	0.487	0.881	−0.286	15.995	943.8	0.512	0.904	−0.250
16.984	960.8	0.461	0.855	−0.320	16.989	952.6	0.485	0.878	−0.283	16.985	944.3	0.509	0.901	−0.247
17.995	961.2	0.459	0.853	−0.316	18.011	953.1	0.482	0.876	−0.282	18.007	944.8	0.506	0.899	−0.245
18.994	961.7	0.457	0.850	−0.315	18.989	953.5	0.480	0.873	−0.279	18.989	945.2	0.504	0.896	−0.242
19.993	962.1	0.454	0.848	−0.314	20.010	954.0	0.478	0.871	−0.278	19.988	945.7	0.501	0.894	−0.241
21.021	962.5	0.452	0.846	−0.310	20.989	954.4	0.475	0.869	−0.274	21.004	946.2	0.499	0.891	−0.238

Table 6. Ranges of Temperature, T, Pressure, p, and Density, ρ, Data Points, n, and Parameters for the Correlation Model for AMP and for AMP (1) + Water (2) Mixtures with Standard Deviations (SDV's)

	AMP	x_1 = 0.0480	x_1 = 0.0736	x_1 = 0.1188	x_1 = 0.1668
T_{min}/K	313.06	313.13	313.13	313.13	313.13
T_{max}/K	362.65	362.74	362.73	362.74	362.73
p_{min}/MPa	0.50	0.5	0.995	0.998	0.999
p_{max}/MPa	24.00	24.008	20.987	21.502	21.093
ρ_{min}/kg·m^{-3}	888.00	957.9	954.1	946.10	936.30
ρ_{max}/kg·m^{-3}	943.10	998.5	996.4	993.00	986.00
n	147	137	125	126	126
d_1/MPa·m^3·kg^{-1}	−7.208	−2.145	−12.131	−2.435	−9.141
d_2/m^3·kg^{-1}	−0.0259	−0.0038	−0.0260	−0.0054	−0.0215
d_3/MPa	−7651.2	−535.3	−3720.2	−1729.1	−7909.1
d_4/MPa·K^{-1}	−9.261	−7.356	−40.975	−5.716	−17.955
d_5/MPa·K$^{-1/2}$	−110.59	−219.85	−1192.50	−138.97	−375.8
d_6	−28.11	−4.6	−30.4	−6.30	−24.87
SDV/%	0.009	0.009	0.007	0.006	0.006

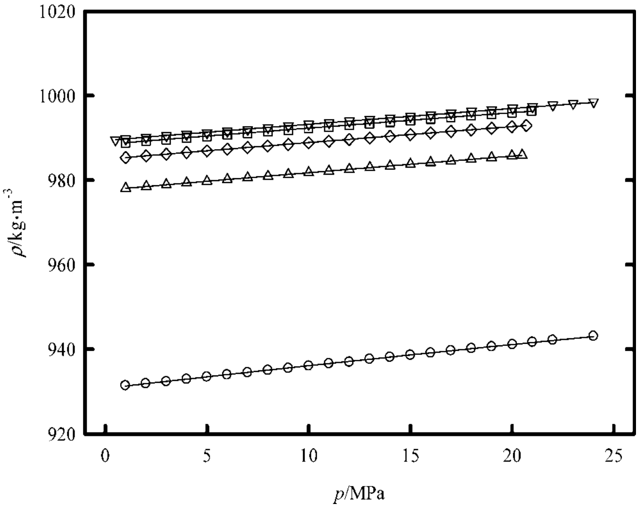

Figure 1. Experimental densities of AMP and of an AMP (1) + water (2) mixture at 313.13 K: ○, AMP; ▽, $x_1 = 0.0480$; □, $x_1 = 0.0736$; ◇, $x_1 = 0.1188$; △, $x_1 = 0.1668$. Solid lines are fits to eq 3 using the parameters at each composition reported in Table 6.

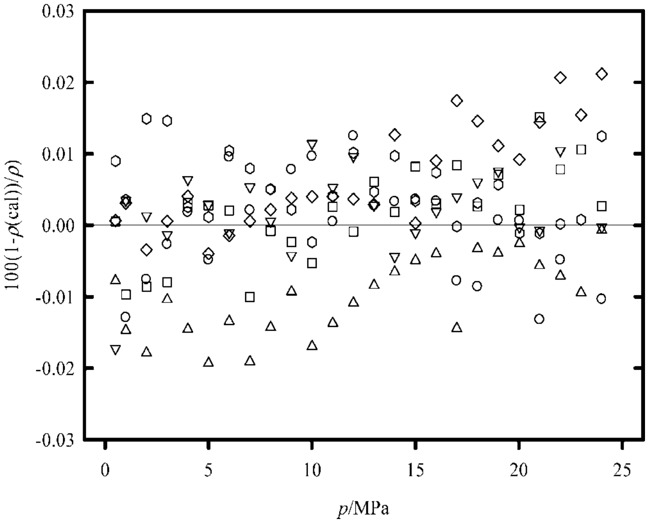

Figure 2. Relative deviations of experimental densities from this work (ρ) and values calculated [ρ(cal)] with the six-parameter equation using the parameters reported in Table 6 for AMP, at the following temperatures: ○, 313.06 K; ▽, 322.98 K; □, 332.91 K; ◇, 342.84 K; △, 352.79 K; ☆, 362.65 K.

The isothermal compressibilities for AMP are larger than those of mixtures, which can be seen in Figure 4. Values of the isothermal compressibilities for the mixtures increase as the AMP content increases in the mixture as depicted in Figure 4.

The isobaric thermal expansivity is defined as

$$\alpha_p = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{8}$$

as it was for the isothermal compressibility, and eq 3 along with the parameters reported in Table 6 is used to derive the isobaric thermal expansivity, yielding the following expression

$$\alpha_p/\mathrm{K}^{-1} = (2d_4 - d_5T^{-1/2})/[2(d_3 - d_4T + d_5T^{1/2} + d_6p)] \tag{9}$$

The calculated isobaric thermal expansivities for AMP and for each mixture are reported in Tables 1 to 5, and isobaric thermal expansivities as a function of pressure for AMP and for AMP (1) + water (2) at 313.13 K are shown in Figure 5. Isobaric thermal expansivities are larger for AMP, and for the mixtures, these values increased as the AMP content increased in the mixture, which is shown in Figure 5.

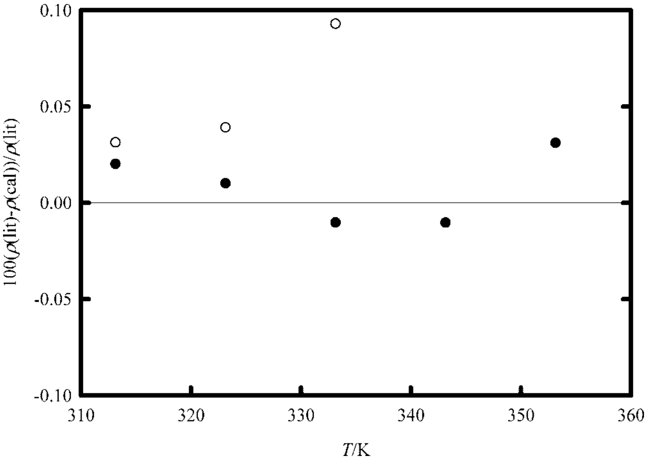

Figure 3. Comparisons of density literature data [ρ(lit.)] at atmospheric pressure with values calculated [ρ(cal)] with the six-parameter correlation, at the following compositions. ○, at $w_1 = 0.2$ (Li and Lie[7]); ●, at $w_1 = 0.4$ (Aguila et al.[9]).

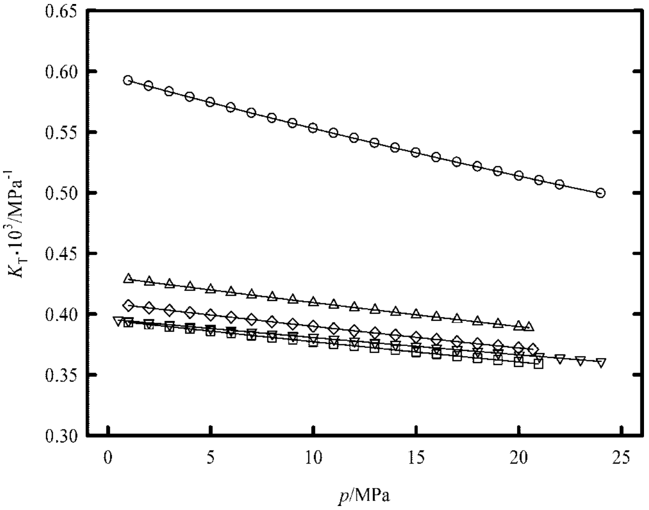

Figure 4. Isothermal compressibilities for AMP and for the AMP (1) + water (2) mixture at 313.13 K: ○, AMP; ▽, $x_1 = 0.0480$; □, $x_1 = 0.0736$; ◇, $x_1 = 0.1188$; △, $x_1 = 0.1668$. Solid lines are fits to eq 7 using the parameters at each composition reported in Table 6.

The effect of pressure and temperature on K_T and α_p for AMP and for AMP (1) + water (2) mixtures is similar, and it is as follows: K_T and α_p decreased as the pressure increased at a constant temperature, while K_T and α_p increased as the temperature increased at a constant pressure. These behaviors can be easily extracted from Tables 1 to 5.

The uncertainties of the calculated isothermal compressibilities and the calculated isobaric thermal expansivities were calculated with the law of propagation of errors.[22] In this case, the sensitivity coefficients are the parameters of the six-parameter equation, and the standard uncertainty refers to the number of significant decimals of the parameters of the equation as previously described.[23] The uncertainty for the isothermal compressibilities was estimated to be $\pm\, 3 \cdot 10^{-6}$ MPa^{-1}, and the uncertainty for the isobaric thermal expansivities was estimated to be $\pm\, 4 \cdot 10^{-7}$ K^{-1}.

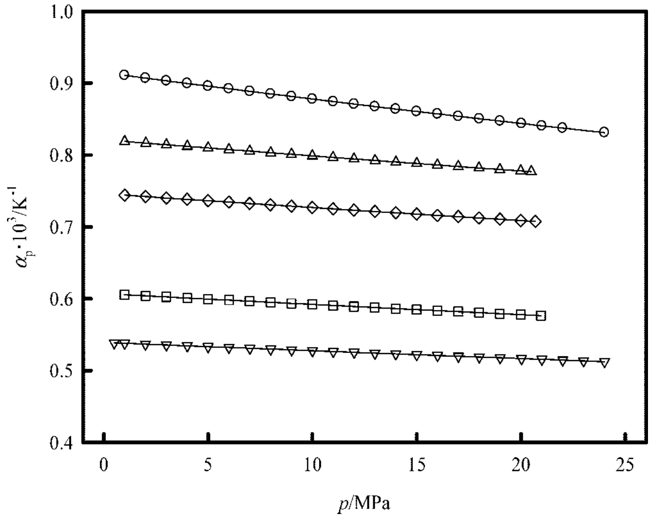

Figure 5. Isobaric thermal expansivities for AMP and for the AMP (1) + water (2) mixture at 313.13 K: ○, AMP; ▽, $x_1 = 0.0480$; □, $x_1 = 0.0736$; ◇, $x_1 = 0.1188$; △, $x_1 = 0.1668$. Solid lines are fits to eq 9 using the parameters at each composition reported in Table 6.

Conclusions

In this work, densities of AMP and AMP + water systems at high pressure were measured. The experimental densities were successfully correlated with a six-parameter equation. Good agreement was found between the correlations obtained at $w_1 = 0.1997$ and 0.4002 with literature data. For the remaining mixtures, comparisons were not performed because of differences in composition with literature data. Excess molar volumes were calculated for the mixtures studied in this work, and all exhibit negative deviations from ideality. The obtained correlations were used to calculate the isothermal compressibility and isobaric thermal expansivity.

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