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Densities of Water + Diethanolamine + Methanol and Water + *N*-Methyldiethanolamine + Methanol at Temperatures Ranging from (283.15 to 353.15) K

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Two vibrating tube densimeters have been used to measure the densities of two mixtures—water + diethanolamine + methanol and water + *N*-methyldiethanolamine + methanol—in the temperature range (283 to 353) K. The alkanolamines and methanol contents are respectively (between 20 and 50 and between 20 and 60) mass %. The experimental results have been correlated using the Redlich−Kister equation for the excess volume. A set of parameters for the Redlich−Kister equation has been determined using the densities of pure compounds and of binary systems available in the literature. The methodology has been extended to density calculations dealing with hybrid solvents.

Introduction

Aqueous alkanolamine solutions are of great interest as chemical solvents used in natural gas sweetening processes. A wide variety of alkanolamines such as monoethanolamine (MEA), diethanolamine (DEA), diisopropanolamine (DIPA), or methyldiethanolamine (MDEA) have been used industrially for a number of years.[1] MDEA and DEA are widely used in gas treatment because of their chemical properties. MDEA is generally used for selective removal of H_2S in the presence of CO_2, while DEA is a common solvent for total deacidification. These aqueous alkanolamine solutions have however generally quite low efficiencies when used for the removal of other sulfur species, especially mercaptans.

Moreover, when the acid gas impurities represent an appreciable fraction of the total gas stream, the cost for removing them by heat regenerable solvent absorption may be out of proportion to the value of the treated gas. This consideration has provided the major impetus for the development of processes employing nonreactive organic solvents as a treating agent. These materials dissolve physically the acid gases and are partially regenerated by merely reducing the pressure. Moreover, minor gas impurities such as carbonyl sulfide and mercaptans are quite soluble in most organic solvents and can be removed to a large extent together with the acid gases by a physical solvent.[2]

In contrast to the solvents mentioned previously, mixtures of chemical and physical solvents, often referred to as "mixed" or "hybrid" solvents, have been developed.[3−6] The absorption process resembles a conventional alkanolamine treating unit, but the presence of the physical solvent enhances the solution capacity, especially when the gas stream to be treated is at high pressure with large quantities of acid compounds and/or minor gas impurities such as carbonyl sulfide and mercaptans present.

As the gas reserves that natural gas field exploration and production have now to deal with are increasingly sour, Rojey et al.[7] have proposed a new sour gas treatment technology integrating dehydration, natural gas liquids (NGL) extraction, and acid gas removal steps with a single hybrid solvent (a mixture of methanol, water, and amine). This patented process produces sweet dry pipeline gas, sweet NGL, and dry pressurized acid gases. The process will be applicable to most sour to very sour, hydrocarbon-rich natural or associated gases.

This process is composed of two parts: a dew point section (used for dehydration and NGL extraction) and a sweetening section (used for acid gas removal). The solvent used in the sweetening section is a mixture of methanol, water, and an alkanolamine such as diethanolamine (DEA), which combines some of the advantages of physical solvent processes (high acid gas loadings, important affinity for COS and mercaptans) with those of chemical solvent processes (stringent specifications on H_2S and CO_2 in the treated gas easily achieved).

The physicochemical data of solvents required for the design of acid gas treatment equipment are generally solubility data, kinetic data, and additional data such as density, viscosity, and so forth. In the context of the development of this new process, particular attention was accorded here to the solvent density. In this work, densities of two different solvents, water + DEA + methanol and water + MDEA + methanol, were measured with two vibrating tube densimeters in the temperature range (283 to 353) K, for various compositions ranging from (20 to 50) wt % alkanolamine and from (20 to 60) mass % methanol. A simplified form of the Redlich−Kister equation was applied to represent excess molar volumes.

Experimental Section

Apparatus and Procedure. Numerous experimental data for alkanolamine aqueous mixtures densities have been reported in the literature.[8−14] Most of these previous works have used atmospheric apparatus, pycnometers, or vibrating tube densimeters.

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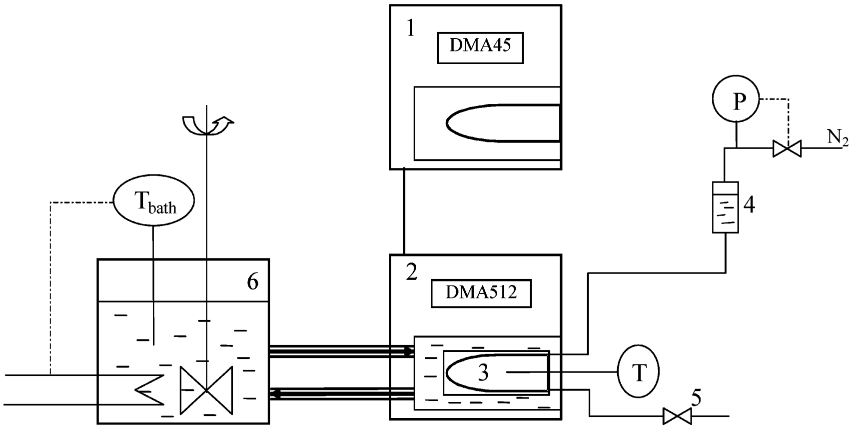

Figure 1. Experimental apparatus: 1, DMA45 densimeter; 2, DMA512 remote cell; 3, measuring cell; 4, solvent reserve; 5, stop valve; 6, thermostated bath.

In this work, two apparatuses in two different laboratories have been used to measure liquid densities. Both are vibrating tube densimeter type. The first one allows density measurement under pressure by using a special remote cell; the second one was a standard atmospheric apparatus similar to those described in the open literature. The consistency of the different experimental results was checked against any systematic error.

The first apparatus, manufactured by Anton Paar, is a vibrating tube densimeter type DMA512, which is a special remote cell for density measurement under pressure. The sample tube, made of stainless steel, was housed in a thermostated brass jacket. The measuring cell temperature was regulated to within 0.05 K with a HAAKE K15/DC30 liquid bath. The cell temperature was measured with a platinum probe calibrated within 0.01 K against a 25-Ω platinum probe type 1/622C manufactured by Rosemount. This remote cell was connected to an Anton Paar DMA45 densimeter used as a processing unit. Densities ρ were calculated from the period of vibration τ:

$$\rho = A + B\tau^2 \tag{1}$$

The constants A and B were determined as a function of temperature by calibrating the apparatus with reference fluids of known densities, taking into account the conclusions of Bouchot and Richon.[15] The DMA45 + DMA512 set was calibrated within 0.001 g·cm^{-3} with pure water and pure alcohol with the same process in the temperature range (293 to 353) K.

The following procedure was applied to apparatus calibration and density measurements. The liquid sample from the solvent supply was introduced into the vibrating tube of the DMA512 densimeter (Figure 1). All the tubing was filled with the liquid. The stop valve was closed. The liquid sample was then pressurized to 0.7 MPa with nitrogen. This procedure was used to prevent the appearance of gas bubbles in the measuring cell, which occurs at high temperatures. The gas−solvent interface was located in the solvent reserve, and the tubing length avoids the introduction of N_2 into the measuring cell by diffusion through the solvent during the time of the experiment.

For each sample, the vibration period was then measured at temperatures ranging from (303 to 353) K by successive temperature increments. This operation was performed with increasing and decreasing temperatures to prove that no hysteresis effects need to be considered with temperature changes. Densities are then calculated, and each reported value is the average of at least three measurements within an uncertainty of ±0.001 g.cm^{-3}.

Table 1. Experimental Conditions for Density Measurements

solvent	T/K	w_2	w_3	experimental method
	Water (1) + DEA (2) + Methanol (3)			
solvent 1	293−353	0.200	0.200	DMA45 + DMA512
solvent 2	293−353	0.200	0.400	DMA45 + DMA512
solvent 3	293−353	0.300	0.200	DMA45 + DMA512
solvent 4	293−353	0.300	0.300	DMA45 + DMA512
solvent 5	293−353	0.300	0.500	DMA45 + DMA512
solvent 6	293−353	0.300	0.600	DMA45 + DMA512
solvent 7	293−353	0.400	0.400	DMA45 + DMA512
solvent 8	278−353	0.301	0.199	DMA5000
solvent 9	278−353	0.400	0.200	DMA5000
solvent 10	278−353	0.401	0.397	DMA5000
	Water (1) + MDEA (2) + Methanol (3)			
solvent 11	293−353	0.200	0.200	DMA45 + DMA512
solvent 12	293−353	0.200	0.400	DMA45 + DMA512
solvent 13	293−353	0.300	0.300	DMA45 + DMA512
solvent 14	293−353	0.300	0.500	DMA45 + DMA512
solvent 15	293−353	0.400	0.200	DMA45 + DMA512
solvent 16	293−353	0.400	0.400	DMA45 + DMA512
solvent 17	283−353	0.200	0.401	DMA5000
solvent 18	283−353	0.302	0.396	DMA5000
solvent 19	283−353	0.303	0.495	DMA5000
solvent 20	283−353	0.398	0.301	DMA5000
solvent 21	283−353	0.400	0.398	DMA5000
solvent 22	283−353	0.399	0.495	DMA5000
solvent 23	283−353	0.496	0.300	DMA5000
solvent 24	283−353	0.498	0.397	DMA5000
solvent 25	283−353	0.399	0.301	DMA5000

The second apparatus used in this study is an Anton-Paar digital vibrating glass tube densimeter (model DMA5000), with a precision of 10^{-5} g·cm^{-3}. The temperature was determined with a platinum resistance thermometer with an accuracy of 0.001 K. The DMA5000 was calibrated with bidistilled and degassed water, and air. Uncertainty has been estimated to within ±0.0002 g·cm^{-3}.

The sample density was measured at thermal equilibrium after changing the temperature from (283 to 353) K following successive increments. This operation is performed twice for each solution. Then each reported density is the average of two measurements.

Solutions Preparation. Mixed solvents were prepared from water, methanol, and DEA/MDEA. Water was distilled and degassed under a vacuum. Methanol (99.8 mass % purity) from Merck was also degassed under a vacuum. DEA (99 mass % purity) was purchased from Aldrich, and MDEA (98 mass % purity) was purchased from Fluka. All chemicals were used without any further purification.

The solutions were prepared gravimetrically at ambient temperature in initially evacuated 20 cm^3 glass bottles (the resulting pressure is the vapor pressure of the mixed

Table 2. Density of (Water + DEA + Methanol) Solvents

solvent[a]	T/K	ρ/g·cm^{-3}	solvent[a]	T/K	ρ/g·cm^{-3}
1	293.15	0.990	7	293.15	0.962
	298.15	0.987		298.15	0.958
	303.15	0.985		303.15	0.954
	308.15	0.982		308.15	0.951
	313.15	0.978		313.15	0.947
	323.05	0.972		323.05	0.938
	333.05	0.965		333.05	0.929
	343.05	0.957		343.05	0.921
	352.95	0.950		352.95	0.912
2	293.15	0.950	8	278.15	1.0091
	298.15	0.947		283.14	1.0064
	303.15	0.944		288.14	1.0036
	308.15	0.940		293.15	1.0007
	313.15	0.936		298.15	0.9978
	323.05	0.928		303.14	0.9947
	333.05	0.919		308.14	0.9916
	343.05	0.911		313.15	0.9884
	352.95	0.902		318.15	0.9851
3	293.15	1.001		323.15	0.9818
	298.15	0.998		328.14	0.9783
	303.15	0.995		333.15	0.9748
	308.15	0.992		338.14	0.9712
	313.15	0.988		343.15	0.9674
	323.05	0.981		348.15	0.9636
	333.05	0.973		353.15	0.9597
	343.05	0.966		358.14	0.9557
	352.95	0.958	9	278.15	1.0162
4	293.15	0.980		293.15	1.0101
	298.15	0.977		303.15	1.0037
	303.15	0.974		308.15	1.0004
	308.15	0.971		323.15	0.9901
	313.15	0.966		328.15	0.9865
	323.05	0.958		333.15	0.9829
	333.05	0.950		338.15	0.9792
	343.05	0.942		343.15	0.9754
	352.95	0.934		348.15	0.9715
5	293.15	0.931		353.15	0.9676
	298.15	0.928	10	278.15	0.9736
	303.15	0.924		283.15	0.9700
	308.15	0.920		288.18	0.9664
	313.15	0.916		293.15	0.9628
	323.05	0.907		298.15	0.9591
	333.05	0.898		303.15	0.9554
	343.05	0.892		308.15	0.9517
	352.95	0.883		313.15	0.9479
6	293.15	0.903		323.15	0.9401
	298.15	0.900		338.15	0.9281
	303.15	0.895		343.15	0.9239
	308.15	0.892		353.15	0.9155
	313.15	0.887			
	323.05	0.879			
	333.05	0.869			
	343.05	0.861			
	352.95	0.851			

[a] See Table 1 for solvent composition.

Table 3. Density of (Water + MDEA + Methanol) Solvents

solvent[a]	T/K	ρ/g·cm^{-3}	solvent[a]	T/K	ρ/g·cm^{-3}
11	293.15	0.985	18	283.15	0.9512
	298.15	0.982		293.15	0.9437
	303.15	0.978		303.15	0.9363
	313.15	0.972		313.15	0.9286
	323.05	0.965		323.15	0.9206
	333.05	0.958		333.15	0.9122
	343.05	0.950		343.15	0.9036
	352.95	0.941		353.15	0.8946
12	293.15	0.945	19	283.15	0.9260
	298.15	0.941		293.15	0.9177
	303.15	0.938		303.15	0.9094
	313.15	0.929		313.15	0.9009
	323.05	0.921		323.15	0.8923
	333.05	0.913		333.15	0.8834
	343.05	0.904		343.15	0.8744
	352.95	0.894		353.15	0.8651
13	293.15	0.971	20	283.15	0.9799
	298.15	0.967		293.15	0.9724
	303.15	0.964		303.15	0.9645
	308.15	0.960		313.15	0.9564
	313.15	0.956		323.15	0.9481
	323.05	0.948		333.15	0.9396
	333.05	0.939		343.15	0.9309
	343.05	0.930		353.15	0.9218
	352.95	0.922	21	283.15	0.9541
14	293.15	0.920		293.15	0.9462
	298.15	0.916		303.15	0.9381
	303.15	0.912		313.15	0.9298
	313.15	0.904		323.15	0.9214
	323.05	0.895		333.15	0.9127
	333.05	0.886		343.15	0.9038
	343.05	0.877		353.15	0.8946
	352.95	0.867	22	283.15	0.9291
15	293.15	0.997		293.15	0.9211
	298.15	0.994		303.15	0.9129
	303.15	0.990		313.15	0.9045
	308.15	0.986		323.15	0.8959
	313.15	0.982		333.15	0.8871
	323.05	0.974		343.15	0.8780
	333.05	0.965		353.15	0.8687
	343.05	0.956	23	283.15	0.9803
	352.95	0.948		293.15	0.9725
16	293.15	0.946		303.15	0.9647
	298.15	0.942		313.15	0.9567
	303.15	0.939		323.15	0.9486
	308.15	0.935		333.15	0.9401
	313.15	0.930		343.15	0.9315
	323.05	0.922		353.15	0.9225
	333.05	0.912	24	283.15	0.9547
	343.05	0.903		293.15	0.9470
	352.95	0.894		303.15	0.9392
17	283.15	0.9509		313.15	0.9312
	293.15	0.9430		323.15	0.9229
	303.15	0.9348		333.15	0.9144
	313.15	0.9265		343.15	0.9055
	323.15	0.9180		353.15	0.8964
	333.15	0.9093	25	283.15	0.9799
	343.15	0.9005		293.15	0.9723
	353.15	0.8914		303.15	0.9645
				313.15	0.9564
				323.15	0.9481
				333.15	0.9396
				343.15	0.9308
				353.15	0.9218

[a] See Table 1 for solvent composition.

solvent) using a Mettler AT 200 balance with an accuracy of 10^{-4} g.

The procedure was the following: (1) the bottles were first evacuated with a vacuum pump; (2) the empty bottles were weighed; (3) degassed DEA or MDEA was introduced in the bottles by means of a syringe; (4) the bottles loaded with DEA or MDEA were weighed; (5) degassed water and degassed methanol were added successively, and the bottles were weighed after each addition. Finally, the composition of the solution was determined from the different masses. The solution was then transferred into the solvent reserve for DMA45 + DMA512 equipment (measurement under pressure) or directly introduced into the DMA5000 densimeter cell (measurement under atmospheric pressure). The compositions for each solvent, and the corresponding density measurement method, are reported in Table 1.

Results. The densities of the different solvents, water + DEA + methanol and water + MDEA + methanol, are reported in Tables 2 and 3, respectively, at several compositions and for temperatures ranging from (283 to 353) K.

We have compared for the similar solvent compositions the densities obtained with both sets of equipment (DMA45 + DMA512 and DMA5000) used in this study. As shown in Figure 2 the densities obtained through the two sets of equipment are in good agreement. Some differences appear at the higher temperatures. However, they generally remain within the uncertainties of the experimental methods. Moreover, they can be explained by the slight differences in the solvent compositions and by the different operating pressures, 0.7 MPa for the DMA45 + DMA512 and atmospheric pressure for the DMA5000.

Discussion

The density of water + alkanolamine + methanol systems was represented with a similar approach to those previously used by Rinker et al.[13] and Hsu and Li[16] for

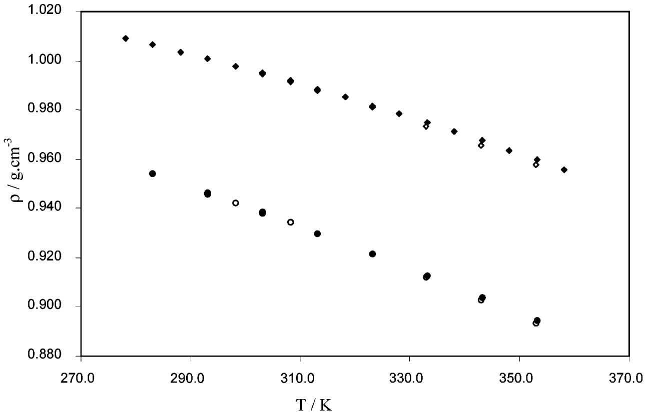

Figure 2. Comparison of the two experimental techniques: ◆, (50−30−20) mass % H_2O + DEA + MeOH; ◇, (50−30−20) mass % H_2O + DEA + MeOH; ●, (20−40−40) mass % H_2O + DEA + MeOH; ○, (20−40−40) mass % H_2O + DEA + MeOH.

Table 4. Density of Pure DEA and Pure MDEA

ref	T/K	no. of points	deviation[a] (%)
DEA			
20	293.15−353.15	4	0.11
21	298.15−333.15	8	0.03
22	298.15−393.15	6	0.09
23	293.15−361.15	5	0.09
13	298.15−363.15	5	0.24
18*	283.15−363.15	18	0.04
14*	183.15−373.15	10	0.03
8*	298.15−353.15	7	0.03
MDEA			
22	296.15−398.15	5	0.12
24	303.15−353.15	8	0.08
23	293.15−361.15	5	0.06
13	298.15−366.15	6	0.31
18*	283.15−363.15	17	0.06
14*	293.15−393.15	9	0.27
8*	298.15−353.15	7	0.05

[a] Deviation $U = (100/n)\Sigma((U_{exp} - U_{cal})/U_{exp})$.

Table 5. Density of Binary Systems

H_2O−DEA

ref	T/K	DEA mass %	no. of points	deviation[a] (%)
20	293.15−353.15	20−100	20	0.60
25	293.15−303.15	0−100	33	0.07
26	298.15	0−30	10	0.15
8*	298.15−353.15	0−100	119	0.05
12	298.15	10−40	4	0.06
16	313.15−353.15	20−30	12	0.06
13	293.15−373.15	10−100	22	0.11
14*	283.15−363.15	0−100	171	0.04

H_2O−MDEA

ref	T/K	MDEA mass %	no. of points	deviation[a] (%)
27	288.15−308.15	10−20	12	0.78
28	288.15−333.15	0−50	53	0.05
24	303.15−353.15	30	8	0.06
9	303.15−333.15	20−30	8	0.06
8*	298.15−353.15	0−100	126	0.10
29	303.15−323.15	30−40	5	0.05
11	283.15−353.15	50	5	0.06
12	298.15	30−60	4	0.24
13	333.15−373.15	10−100	18	0.16
14*	283.15−373.15	0−100	135	0.17

H_2O−Methanol

ref	T/K	methanol mass %	no. of points	deviation[a] (%)
open lit.	273.15−353.15	0−100	>700	0.19

[a] Deviation $U = (100/n)\Sigma((U_{exp} - U_{cal})/U_{exp})$.

Table 6. Binary Parameters of the Redlich−Kister Equation

binary pairs	A_0/cm^3·mol^{-1}	A_1/cm^3·mol^{-1}·K^{-1}	A_2/cm^3·mol^{-1}
DEA + H_2O	−5.398 20	6.321 9 × 10^{-3}	1.942 42
MDEA + H_2O	−10.462 2	0.011 22	4.079 36
DEA + MeOH	2.551 49	−1.948 42 × 10^{-2}	0.521 99
MDEA + MeOH	4.989 25	−0.011 38	−30.159 51
H_2O−MeOH	−0.437 07	−0.010 66	−0.328 74
DEA−MDEA	−11.152 59	0.034 82	0

water + alkanolamines binary and ternary systems:

$$\rho = \frac{M_m}{V_m} = \frac{\sum x_i M_i}{V_m} \qquad (2)$$

where M_m was the molar mass of the mixture, M_i was the molar mass of the pure compound i, and x_i was the mole fraction of component i. The molar volume of the liquid mixture V_m was calculated from eq 3:

$$V_m = \sum x_i V_i + V^E \qquad (3)$$

where V^E is the excess volume and V_i is the molar volume of component i.

A Redlich−Kister type equation was applied for the excess molar volume:

$$V_{12}^E/\text{cm}^3\cdot\text{mol}^{-1} = x_1 x_2 (A_0 + A_1 T/(\text{K}) + A_2 x_1) \qquad (4)$$

T is the temperature and A_0, A_1, and A_2 are binary parameters; cf. Table 6. The excess volume V^E of the liquid mixture for a ternary system was obtained from the excess molar volume of each binary system:

$$V^E = V_{12}^E + V_{13}^E + V_{23}^E \qquad (5)$$

The method was based on the molar volumes of each pure compound, as well as on the representation of the two water + alkanolamine and water + methanol binary systems. The binary parameters for these two systems were determined from experimental data. The representation of the ternary systems was then realized by fitting the parameters alkanolamine + methanol from the experimental data obtained for the ternary systems. Therefore, the developed model will not allow representing the density of the binary systems alkanolamine + methanol.

Representation of Molar Volumes of Pure Compounds. The molar volumes of water and methanol were obtained from the correlations of Rinker et al.[13] and DIPPR:[17]

$$V_{\text{methanol}}/\text{cm}^3\cdot\text{mol}^{-1} = 1000 \times \frac{0.27073^{(1+(1-[T/(\text{K})]/512.5)^{0.24713})}}{2.3267} \qquad (6)$$

$$V_{H_2O}/\text{cm}^3\cdot\text{mol}^{-1} = \frac{18.02}{0.753597 + (1.877465 \times 10^{-3})T/(\text{K}) - (3.563982 \times 10^{-6})T^2/(\text{K}^2)} \qquad (7)$$

For DEA and MDEA, we have selected the literature data which appear to be the most consistent with the temperature and composition ranges studied and according to the consistency of these data between each other.[8,14,18] These data are identified with an asterisk in Table 4. They have been obtained by means of a vibrating glass tube

Table 7. Density of Ternary Systems

H_2O−DEA−Methanol					
apparatus	T/K	DEA mass %	methanol mass %	no. of points	deviation[a] (%)
DMA45 + DMA512	293.15−353.15	20−40	0−60	64	0.09
DMA5000	278.15−353.15	30−40	0−40	54	0.04
H_2O−MDEA−Methanol					
apparatus	T/K	MDEA mass %	methanol mass %	no. of points	deviation[a] (%)
DMA45 + DMA512	293.15−353.15	20−40	20−50	51	0.13
DMA5000	283.15−353.15	20−50	30−50	64	0.20

[a] Deviation $U = (100/n)\sum((U_{\text{exp}} - U_{\text{cal}})/U_{\text{exp}})$.

densimeter, and they present experimental uncertainties lower than 0.001 g·cm^{-3} and a good consistency between the various sources. The following correlations were obtained from these data:

$$V_{\text{DEA}}/\text{cm}^3\cdot\text{mol}^{-1} = \frac{105.16}{1.2968 - (6.8008 \times 10^{-4})T/(\text{K})} \quad (8)$$

$$V_{\text{MDEA}}/\text{cm}^3\cdot\text{mol}^{-1} = \frac{119.16}{1.27462 - (7.9703 \times 10^{-4})T/(\text{K})} \quad (9)$$

Table 4 shows the deviation between these correlations and the literature data and contains the regressed data sources.

Representation of Water + Alkanolamine and Water + Methanol Binary Systems. The binary parameters for DEA + water and MDEA + water, were determined from literature data. As for the pure components, consistent data (displayed with an asterisk in Table 5) were selected in the open literature for the determination of the correlation parameters. The representation of the consistent data was achieved within an average absolute percentage deviation of 0.04% and 0.14%, respectively, for the water + DEA and water + MDEA systems.

More than 800 experimental data points are available in the open literature for the water + methanol system, over a large range of temperatures (163 to 353 K) and compositions. All of them are collected in the Dortmund Data Bank.[19] We have retained the more consistent data for the identification of the water + methanol binary parameters, in the temperature range (273.15 to 353.15) K (Table 5). All the determined binary parameters are reported in Table 6.

Representation of Water + Alkanolamine + Methanol Ternary Systems. As mentioned above, the representation of the ternary system was obtained by fitting the alkanolamine + methanol binary parameters from density data of ternary systems. This approach ensured a good representation of the water + alkanolamine + methanol system, within (0.07 and 0.16)% deviation for water + DEA + methanol and water + MDEA + methanol ternary systems, respectively, as shown in Table 7 and Figures 3 and 4.

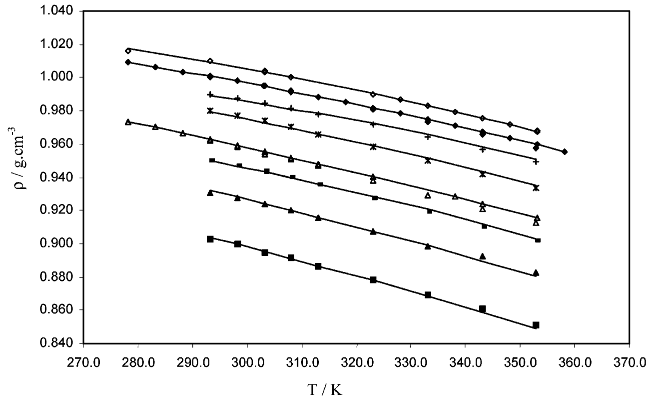

Figure 3. Density of the water + DEA + methanol system: □, (10−30−60) mass % H_2O + DEA + MeOH; small box, (40−20−40) mass % H_2O + DEA + MeOH; ▲, (20−30−50) mass % H_2O + DEA + MeOH; ∗, (40−30−30) mass % H_2O + DEA + MeOH; △, (20−40−40) mass % H_2O + DEA + MeOH; ◆, (50−30−20) mass % H_2O + DEA + MeOH; ◇, (40−20−20) mass % H_2O + DEA + MeOH; +, (60−20−20) mass % H_2O + DEA + MeOH; −, calculated values.

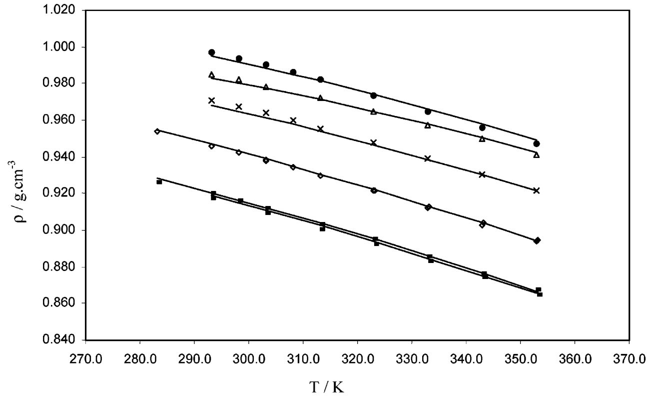

Figure 4. Density of the water + DEA + methanol system: ■, (20−30−50) mass % H_2O + DEA + MeOH; ◇, (20−40−40) mass % H_2O + DEA + MeOH; ×, (40−30−30) mass % H_2O + DEA + MeOH; ●, (40−40−20) mass % H_2O + DEA + MeOH; △, (60−20−20) mass % H_2O + DEA + MeOH; −, calculated values.

Conclusion

The densities of the solvent systems (water + DEA + methanol) and (water + MDEA + methanol) have been measured using two apparatuses, the first one for density measurement under pressure and the second one for density measurement under atmospheric pressure. Measurements were performed for temperatures ranging from (283 to 353) K and for several compositions. We obtained good reproducibility, and at temperatures below 353 K, we have observed an excellent agreement between the two methods within their estimated uncertainties. The densities of liquid mixtures have been correlated using a Redlich−Kister equation for the excess volume. On the basis of the densities of pure compounds and of binary systems available in the literature, a set of parameters in the Redlich−Kister equation was determined. The methodology has been extended to the density calculations for the hybrid solvents. Satisfactory results were obtained for the (water + DEA + methanol) and (water + MDEA + methanol) solvents, within an overall average absolute percentage deviation of 0.12%.

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